



# A Load-Balancing Based Research on Inter-satellite Link-Building Planning for Navigation Satellite Network

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**Abstract.** Based on navigation satellite network constituted by phased array inter-satellite links, our research proposes to optimize rapidly changing inter-satellite links topology. In the beginning of our research, we establish the topological model of the navigation satellite constellation dynamic network, and clarify the routing strategy. Then according to the principle that the topology is uniquely determined, our research analyzes the asymmetric traffic characteristics of the navigation satellite network. Furthermore, a topological link optimization method based on predicting load balance is proposed to describe the calculation steps of the link-building optimization method. Moreover, we verify load-balancing performance of inter-satellite link-building optimization method by using average time delay, maximum time delay and cache occupancy as indicators. It is verified through simulation that the load-balancing based inter-satellite link-building optimization method is feasible, at the same time, it is a valuable reference for planning of building inter-satellite links of the global navigation systems.

**Keywords:** Navigation satellite network · Load-balancing · Link-building planning

## 1 Introduction

Global navigation satellite system applied inter-satellite links in distance measurement for self-contained navigation and communication for operation data, which achieved long-time autonomous running without earth-based station support or managing global satellite navigation system with a small quantity of earth-based stations. Based on phased array antenna, inter-satellite links feature short response time, high precision in link building and long service life. Moreover, it not only provides more inter-satellite distance measurement results, but also forms Delay Tolerant Network (DTN) with rapidly changing topology. Network time-division multiplexing link-building needs to consider the time evolution before and after the inter-satellite link switching in route planning. Targeting the routing problem of DTN, Zhao Yue proposed dynamic

planning routing algorithm based on inter-satellite allocation plan constructed by polling link-building mode, and Fraire presented using simulated annealing algorithm to solve link-building planning problem. All these algorithms did not think over load balancing of network flow. Focusing on load balancing, Jain proposed earliest delivery routing algorithm based on local queue and whole network queue, and Yan Hongcheng presented an earliest delivery routing algorithm using subnet queue. However, for above two algorithms, it has great time delay for DTN when queue information interacting between network nodes, so queue information is obsolete easily. In addition, load balancing using queue status should generate routes dynamically with fixed link building topology planning, which cannot guarantee that link building planning is optimal compared with random routing strategy. In navigation satellite network, the visible relationship between satellite and satellite or between satellite and earth-based station is periodically predictable, therefore, optimized link topology of navigation satellite network is also able to be pre-planned. Once network topology is determined, end-to-end shortest path can be calculated by graph routing algorithm, and then the loads of every satellite node are available in advance using path set. This paper premeditates loads of satellite nodes and asymmetry of operation when just starting building links and planning routes, and applies simulated annealing global optimal search algorithm to achieve solving link-building planning with multi-objective optimization which includes average time delay, maximum time delay and load balancing. Through verifying in the navigation constellation network simulation system, it can be revealed that the method proposed by this paper can achieve efficient and balanced transmission of operation information among satellite nodes.

## 2 Network Model and Optimization Objective

When the navigation satellite carries only one phased array transceiver, each satellite establishes at most one half-duplex inter-satellite link in the planned time slot to form a typical DTN. In order to ensure the fairness of the link building between satellite nodes, that is, the chances of establishing an inter-satellite link between this satellite and other satellite are relatively equal, the navigation constellation operation cycle is divided into several link-building periods  $T$ . In each link-building period  $T$ , one navigation satellite repeatedly establishes links with different satellites in sequence until satellite visibility changes. The constellation link state within the link-building period  $T$  can be considered as a finite state machine, where each state represents the link pairing relationship of the satellites within a certain time slot. Our research divide link-building period  $T$  in  $k$  time slots, which correspond to  $k$  states in the state machine. The followings are graph model of navigation satellite network based on time cost and link-building planning.

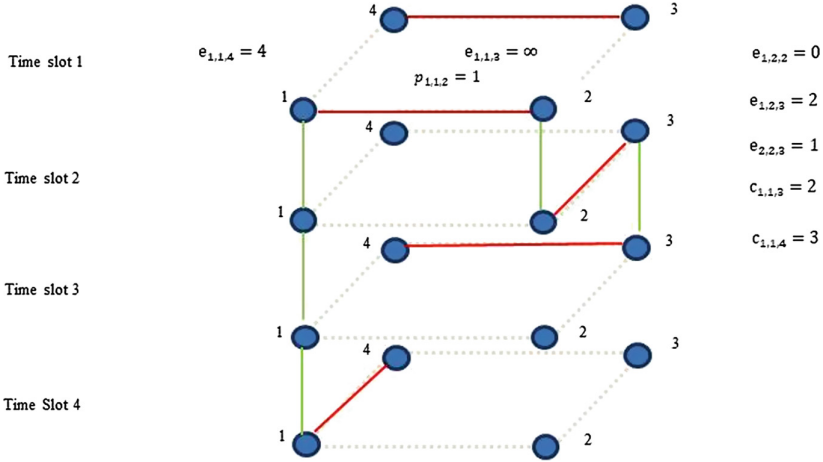


Fig. 1. Simplified model of navigation satellites network

- (1)  $v_{k,i,j}$  represents the visible relationship between the satellite  $i$  and the satellite  $j$  in the time slot  $k$ , where 1 represents visible and 0 represents invisible;
- (2)  $p_{k,i,j}$  represents the link-building relationship between the satellite  $i$  and the satellite  $j$  in the time slot  $h$ , where 1 represents linked and 0 represents unlinked;
- (3)  $e_{k,i,j}$  represents the edge cost between the satellite  $i$  and the satellite  $j$  in the time slot  $k$ , if  $p_{k,i,j} = 1$ , then  $e_{k,i,j} = 1$ , or if  $p_{k,i,j} = 0$  and  $p_{mod(k+t,T),i,j} = 1$ , then  $e_{k,i,j} = t + 1$ , otherwise  $e_{k,i,j} = \infty$ . That is, if the satellite  $i$  and the satellite  $j$  are directly linked in the time slot  $k$ , the cost of the edge between the node  $i$  and the node  $j$  in the figure only includes the communication time cost 1; if the satellite  $i$  and the satellite  $j$  are linked after  $t$  time slots, then the cost between the node  $i$  and the node  $j$  in the figure includes the communication time cost 1 and the delay cost  $t$ ; if the satellite  $i$  and the satellite  $j$  are not linked in the link-building period  $T$ , then the cost of the edge between the node  $i$  and the node  $j$  is infinite.
- (4)  $c_{k,i,j}$  represents the minimum cost between the satellite  $i$  and the satellite  $j$  in the time slot  $k$ .

A simplified network model is shown for ease of description in Fig. 1. The time-varying map structure of the navigation satellite network is described by four satellite nodes.  $v_{1,1,2}$  indicates that satellite 1 and satellite 2 are mutually visible in time slot 1,  $p_{1,1,2}$  indicates that satellite 1 and satellite 2 are established an inter-satellite link in time slot 1.  $e_{1,1,2}$  indicates that the cost of the edge between the satellite 1 and the satellite 2 is 1.  $c_{1,1,4}$  indicates that the minimum cost of the edge between satellite 1 and satellite 4 is 3. The shortest path from node  $i$  to node  $j$  at the time slot  $k$  is showed by  $l_{k,i,j} = \{(k + t_1, i, u_1)(k + t_2, u_2, u_2) \dots (k + t_n, u_n, j)\}$ , where  $u_n$  is the intermediate node. And  $l_{k+t_1+1,u_1,j} = \{(k + t_2, u_2, u_2) \dots (k + t_n, u_n, j)\} \in l_{k,i,j}$ , that is, if the shortest path from the satellite  $i$  to the satellite  $j$  arrives at the satellite  $u_1$  after  $t_1$  time slots, the shortest path from satellite  $u_1$  to satellite  $j$  in time slot  $t_1 + 1$  is necessarily same as the shortest path from the satellite  $i$  to the satellite  $j$  at the time slot  $k$ . Therefore, the end-to-

end shortest path  $l_{k,i,j}$  calculated in any time slot  $k$  in a link-building period coincides with the end-to-end shortest path of other time slots, that is, the end-to-end information transmission path in the link-building period  $T$  is one and only. When improved Dijkstra algorithm is used to calculate the unique shortest path under the determined link-building plan, the routing strategy of the satellite node for the transferred information is also determined to ensure that all the information in the network can be transmitted along the optimal path. Therefore, under the premise of not considering the sudden asymmetric traffic, the process of routing load balancing to the navigation satellite network is the optimization process of the link-building planning. The navigation satellite network carries the telemetry service, the telecontrol service, and the autonomous navigation service. The telemetry service is forwarded from the non-access satellite through the network to the access satellite and then transferred to the earth-based station. The telecontrol service is uploaded to the access satellite through the earth-based station and then forwarded to the non-access satellite. Both of these make navigation satellite network be characterized of data flow long-term asymmetry. Access satellites are more loaded in the navigation satellite network as the connection hub between satellites and earth-based stations. Set  $Z = \{z_1, z_2, \dots, z_m\}$  as the set of  $M$  access satellites. When planning links, it should be preferential satisfied that the end-to-end path delay of one access satellites as the start point or the end point is minimum, which to achieve load balancing based on asymmetric service. In addition, the more times the satellite node  $u$  appears in the end-to-end shortest path set  $R$ , the greater the probability that the information flows through the satellite node  $u$ . So the shortest path set can be adjusted in advance through the link-building re-planning to realize the satellite-node-based load balancing.

### 3 Method of Link-Building Planning

The problem of satellite network link-building planning based on time-varying graph is essentially a global optimal solution search problem based on multiple optimization objectives. The first thing to do is to set objective function and calculate the optimal value. By continuously adjusting the link-building planning, the simulated annealing algorithm is used to get the global near-optimal solution. The key steps are as follows.

#### 3.1 Determining Evaluating Function Optimization Goal and Parameter Analysis

The objective function for solving the optimal link-building planning is  $f(x) = \alpha AD + \beta MD + \gamma AUD + \delta ADD + \varepsilon RMS$ .

$$AD = \frac{\sum_{k=1}^T \sum_{i=1}^N \sum_{j=1}^N C_{k,i,j}}{T \times N \times (N-1)}$$

indicates the average end-to-end time delay, where  $N$  is

the number of satellites in the navigation satellite network.

$$MD = \max_{\forall k,i,j} C_{k,i,j}$$

indicates the maximum end-to-end time delay.

$AUD = \frac{\sum_{k=1}^T \sum_{i \in Z} \sum_{j \in Z} c_{k,i,j}}{T \times M \times (N-1)}$  indicates the average end-to-end time delay in of the uplink telecontrol of the access satellites.

$ADD = \frac{\sum_{k=1}^T \sum_{i \in Z} \sum_{j \in Z} c_{k,i,j}}{T \times M \times (N-1)}$  indicates the average end-to-end time delay in of the downlink telemetry of the access satellites.

$RMS = \frac{\sum_{i=1}^N \frac{F_i - F_{avr}}{N}}$  indicates the load mean square deviation of satellite nodes under the optimal path, where  $F_i$  is the statistics of satellite  $i$  in the end-to-end shortest path set  $R$ , and  $F_{avr} = \frac{\sum_{i=1}^N F_i}{N}$  is the average statistics of all the satellites in set  $R$ .

For the weight adjustment factors of each indicator, which includes,  $\alpha, \beta, \gamma, \delta$  and  $\epsilon$ , when the asymmetric traffic is large, the value  $\gamma$  and  $\delta$  should be increased, however, when the asymmetric traffic is small, the values should be decreased. In this way, the problem of link-building planning translates into the problem of finding the global minimum of  $f(x)$ .

### 3.2 Shortest Path Calculation

In this paper, the Dijkstra algorithm is used to complete the calculation of the end-to-end shortest path from node  $s$  to the arbitrary destination node  $d$  in the time slot  $k$  of the network. The steps of the algorithm are as follows:

- (1) Set  $V$  as the constellation network nodes set.  $Q$  is the shortest path nodes set, in which every element represents whether a satellite node has been included in the shortest path  $L = \{l_{k,s,j}, j = 1, 2, \dots, N, j \neq s\}$ .  $T = V - Q$  shows the nodes that has not been included in the shortest path. Also, the path cost sets  $C = c_{k,s,j}, j = 1, 2, \dots, N, j \neq s$ .
- (2) Initialize the shortest path nodes set  $Q$  and the shortest path  $L$ , and let  $Q$  and  $L$  include the source node  $S$ . Initialize  $c_{k,s,j}$  as  $\infty$ .
- (3) Find the satellite node  $u$  with the shortest distance  $c_{k,s,u}$  from  $s$  in  $T = V - Q$  and add  $u$  to set  $Q$  and  $L$ .
- (4) Slacken the path  $L$  that the destination satellite node  $j \in T$ . If  $c_{k,s,j} > (e_{k+t,u,j} + c_{k,s,u})$ , add node  $u$  to  $l_{k,s,j}$  and modify  $c_{k,s,j}$ .
- (5) Repeat step (3) and step (4) until all satellite nodes are included in the shortest path node set  $Q$ , that is  $Q = V$ .

It is different from Dijkstra algorithm in continuous link network topology, due to the time evolution characteristics of the time-varying graph, when the non-optimal path is slackened, the edge cost of the intermediate node  $u$  to the destination satellite  $j$  should be  $e_{k+t,u,j}$  rather than  $e_{k,u,j}$ , in which the time delay  $t = c_{k,s,u}$ .

### 3.3 Link-Building Planning Adjustment

When the results of the objective function are not optimal, it is necessary to make minor adjustments to the link-building planning. This paper adopts the random link exchange method. The steps are as follows:

- (1) Generate the time slot  $k$ , the source node A of link 1 and the source node C of link 2;
- (2) Due to the original link-building planning, our research obtain satellite B pointed by satellite A and satellite D pointed by satellite C;
- (3) If  $B \neq C$ ,  $v_{k,a,c} = 1$  and  $v_{k,b,d} = 1$ , a link should be built between A and C and another link should be built between C and D; if  $B \neq C$ ,  $v_{k,a,d} = 1$  and  $v_{k,b,c} = 1$ , a link should be built between A and D and another link should be built between B and C, otherwise, go to step (1).

### 3.4 Simulated Annealing Optimization

Compared with genetic algorithm, it is more efficient to use simulated annealing algorithm to solve optimal path problem based on the characteristics that the network link path genes are only related to time and node data flow. The optimization steps are as follows:

- (1) Form initial link-building planning and evaluation function value  $f(x_{old})$  with initial temperature  $T = 1$ . The number of adjustment times for every temperature  $T$  is  $L$ ;
- (2) Adjust and generate new link-building plans;
- (3) Recalculate to get new evaluation function value  $f(x_{new})$ ;
- (4) Calculate the increment  $\Delta f = f(x_{new}) - f(x_{old})$ ;
- (5) If  $\Delta f < 0$ , we accept the new link-building plan, otherwise, accepting the new plan with the probability  $e^{-\frac{\Delta f}{T}}$ ;
- (6) If the link-building plans are not accepted for 20 consecutive times, the algorithm ends. If the adjustment times are less than 20, the process goes to step (2).
- (7)  $T = T \times \mu$ , if  $T > T_{min}$ , the process goes to step (2).

The speed of temperature dropping in simulated annealing and the number of adjustment  $L$  at each temperature depend on the rate of changing of the evaluation value during the link-building optimization process. If the evaluation function value can converge quickly, and  $L$  can be set to a smaller value.

## 4 Performance Simulation

### 4.1 The Parameter Setting of Simulation Scene

The navigation satellite network uses the constellation of 24MEO+3GEO+3IGSO, in which the configuration of MEOs is selected walker24/3/1, and each satellite carries one inter-satellite link. The STK simulation scenario is constructed based on the network parameters, and the inter-satellite visibility is obtained to form a link-building planning. The node transmission simulation platform for navigation satellite network is built by MATLAB. And the simulation results are used to compare the average time delay, maximum time delay, satellite cache occupancy and the number of dropped frames (Tables 1 and 2).

**Table 1.** The parameters of navigation satellite

Parameters	Settings
Number of satellite nodes	30
Number of inter-satellite nodes	1
MEO/IGSO inclination angle	55
Type of constellation	Walker24/3/1
MEO constellation period	7 days
Number of access satellite	6
Number of satellite nodes	30
Number of inter-satellite nodes	1
MEO/IGSO inclination angle	55

**Table 2.** Simulation parameters of navigation satellite network transmission

Parameters	Settings
Simulation duration (seconds)	3600
Inter-satellite bandwidth (frames/time slot)	50
Autonomous navigation frames generation rate (frames/time slot)	1
Telecontrol frames injection rate (frames/time slot/satellite)	12
Telemetry generation rate (frames/time slot/satellite)	5
Terminal node cache size (frames)	400
Routing node cache size (frames)	800
Maximum hop count	10
Simulation duration (seconds)	3600

## 4.2 Optimization Objectives Analysis

In the navigation satellite network, the link-building planning method forms link-building configuration Fig. 1. And the setting values of the adjustment factors are shown in Table 3.

**Table 3.** The adjustment factors of evaluation function indicator weights

Parameters	Settings
$\alpha$	1
$\beta$	1
$\gamma$	1
$\delta$	1
$\varepsilon$	10

The minimum average end-to-end time delay is used as the optimization target to form the link-building configuration Fig. 2. The link-building configuration schemes are respectively deployed on the node transmission simulation platform for navigation satellite network, and the simulation results are shown in Figs. 2, 3, 4 and 5.

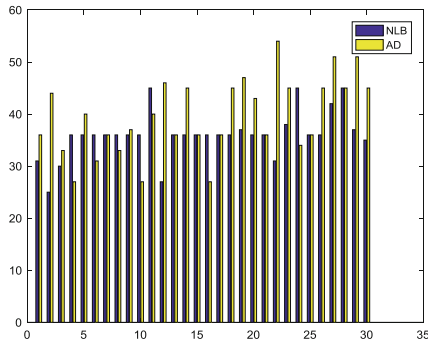


Fig. 2. Time delay comparison of link-building plans

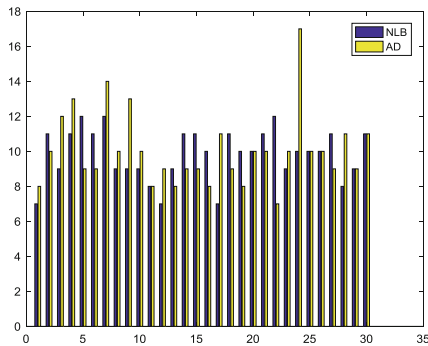


Fig. 3. Node cache occupancy of link-building plans

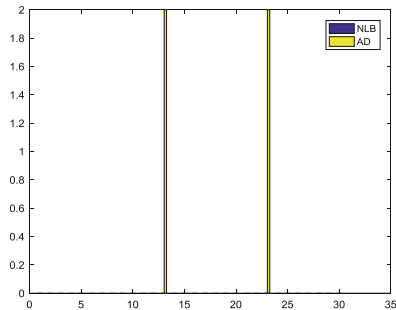
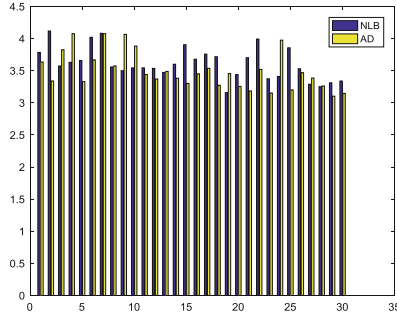


Fig. 4. Dropped frame numbers comparison under full load circumstances



**Fig. 5.** The average time delay comparison of link-building plans

In the management and control scenario of the traffic asymmetric navigation satellite network, the link-building configuration scheme based on the load-balancing link-building planning method is better than that targeting minimum average end-to-end time delay on the indicators of maximum time delay and the balance of the node cache occupancy. Under full load, the number of dropped frames in the network after load balancing is significantly smaller than that of the non-load-balancing scheme. However, the difference of the average end-to-end time delay between the two schemes is less than 1. In summary, the load balancing based DTN link-building planning scheme effectively achieves the load balancing among the satellite nodes of the navigation satellite network without affecting the average end-to-end time delay.

## 5 Conclusion

This paper establishes a time-division multiplexed network model for navigation satellite constellation. According to the uniqueness of the optimal routing path under the fixed link-building topology and the asymmetric characteristics of the navigation satellite network service information path, this paper proposes a method to improve the load balancing performance of network routing in topological link-building planning. The simulation results show that the topological link-building optimization method based on load balancing is better than that targeting minimum average end-to-end time delay, which can support the link planning of the inter-satellite links of the global navigation system. The next step in this study will consider more influencing factors in the link-building planning. For instance, satellite visibility changing will lead to the switch of link-building planning, so the optimal path will change during the information transmission process. Under this circumstance, it is necessary to ensure that the network time delay performance will not decrease during link-building planning switching. In addition, autonomous navigation requires more ranging links between navigation satellites, and also requires better geometric accuracy factors. Moreover, when selecting ground access nodes, it is necessary to consider the impacts of satellite elevation angle, satellite-ground connection duration and the number of accessed satellites.

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