

Topology Optimization of Heterogeneous Satellite Networks with Variable Time Slots

Huaiyu Liu^a, Yongqi Zhang^b, and Jihe Wang^{*c1}

^{*}School of Aeronautics and Astronautics, Sun Yat-Sen University, China.

ABSTRACT.

To deal with the frequently encounter link disconnections due to the rapid movement between the nodes in heterogeneous satellite constellations, different from traditional fixed time slot-based topology optimization method, this paper proposes a variable time slot-based topology optimization approach. The lengths of the variable time slots are based on the Jaccard similarity value of the visibility relation between neighboring initial fixed time slots. After determining the lengths of the variable time slots, a multi-objective topology optimization model is established, with total inter-satellite links distances and cluster coefficient of the satellite networks as optimization objectives. Genetic Algorithm is utilized to solve the proposed multi-objective topology optimization problem. Compared numerical simulations regarding to fixed time slot-based and variable time slot-based topology optimization have been conducted, and the results show that variable time slot-based topology optimization method can rapidly optimize the topology and better satisfy the constraints under the situation of drastic changes in inter-satellite visibility.

Keywords: heterogeneous constellations; topology optimization; inter-satellite links; time-varying network; genetic algorithms; adjacency matrices

1. INTRODUCTION

As an important part of 5G and future 6G technologies, satellite networks have already played a key role in aerospace. Most traditional satellite constellations are predominantly homogeneous, in recent years heterogeneous constellations have been increasingly utilized. Different types of satellites (e.g., communication satellites, remote sensing satellites, navigation satellites, etc.) in heterogeneous satellite constellations have different characteristics and functions, while the huge multi-layer heterogeneous satellite constellations pose significant challenges to the reliability and scalability of the network[1]. The BeiDou satellite constellation is a typical heterogeneous constellation, which uses the Walker-MEO satellite constellation as well as GEO and IGSO satellites[2] to provide global navigation, positioning and time services. Inter-Satellite Links (ISL), as an important part of the satellite network, provides an effective method for inter-satellite information transfer in the case of limited terrestrial networks[3,4]. As a result, scholars are currently working on inter-satellite links establishment and maintenance related research.

Due to the highly time-varying characteristics of satellite network inter-satellite relations and the extreme complexity of inter-satellite visibility, which will affect connection of ISL, the topology design method for fixed topology in terrestrial networks cannot be directly utilized to solve satellite network topology optimization problem. At present, most scholars use the idea of "limit" to deal with the inter-satellite topology design problem, and discretize the continuously changing topological relationship by segmentation, therefore, it can be transformed into a deterministic network topology design issue [5]. Werner M proposed the Discrete Time Dynamic Virtual Topology Routing (DT-DVTR) algorithm in 1997[6]. This algorithm is the first to propose a virtual topology method, using the concept of topology snapshot[7], to calculate routes according to certain rules on a static network topology. Chang et al.[8] employed the concept of Finite State Automaton (FSA) to partition the orbit of a LEO satellite system into equal time intervals. Within each interval, the inter-satellite topology remains fixed. With the optimization objective of reducing call blocking probability, they utilized simulated annealing algorithm (SA) to solve the link allocation problem. Korçak Ö et al. further proposed a virtual topology model with better performance based on the virtual node approach Multi-State Virtual Network (MSVN), this model allows seamless connectivity between satellite-earth networks[9]. Xu et al.[10] proposed an optimization problem with communication delay and inter-satellite ranging performance as the objectives and satellite relations as constraint conditions. To optimize the OISL (Optical Inter-Satellite Links) topology of future navigation satellites, Zeng et al.

^{1a}liuhy265@mail2.sysu.edu.cn, ^bzhangyq325@mail2.sysu.edu.cn, ^{*c}wangjihe@mail.sysu.edu.cn

proposed a multi-objective discrete binary particle swarm optimization algorithm considered the complex constraints of inter-satellite links[11].

If a static network topology constellation is used for the satellite network, the static links between satellites will inevitably be interrupted by the effects of Earth occlusion and finite laser antenna angular leading to degrade the network performance. Long-term interruptions in inter-satellite links within a constellation may have serious impacts on the performance of the entire constellation. Virtual topology strategy has been widely used in dynamic topology design for satellite networks. In the virtual topology strategy, the motion of the constellation is divided into many cycles, the constellations repeat the same motion in each cycle. Each cycle is divided into several time slots, and the inter-satellite visibility relations within each time slot do not change, and the visibility relations change only when the time slot is changed. In each time slot, the optimal inter-satellite link connection in each time slot is calculated based on the satellite visibility relationship.

However, the aforementioned methods have two drawbacks for heterogeneous constellations. First, the heterogeneous satellite network connectivity is frequently updated bringing a very large signaling overhead[12] leads to difficult satellite network management. Second, since the network topology is not updated within a fixed time slot, the connectivity relationships of satellite networks may not satisfy the visibility constraints in heterogeneous constellations. Therefore, to solve the aforementioned drawbacks, this paper proposes a variable time slot-based topology optimization approach.

The innovation of this method is to improve the fixed time slot in the virtual topology algorithm to variable time slot. In traditional virtual topology algorithm, the visibility within the previous time slot has no connection with the visibility in the next. In the proposed method, the Jaccard similarity[13] of the visibility matrices according to the visibility are calculated to determine the length of next time slot to adapt to changing inter-satellite visibility in heterogeneous constellations. The length of the time slot will become shorter with the drastic changes in inter-satellite visibility, and longer with gradual changes.

The rest of the paper is structured as follows: in section 2 the satellite network topology optimization problem is modeled. Section 3 explains the flow of the virtual topology method for variable time slots. Section 4 presents a simulation comparison between the proposed variable time slot-based topology optimization method and the conventional fixed time slot-based topology optimization method for this problem. Section 5 contains the summary.

2. PROBLEM DESCRIPTION OF TOPOLOGY OPTIMIZATION FOR SATELLITE NETWORKS

2.1 Modeling of Satellite Networks

The topological graph of the satellite network can be abstracted conveniently by using the theory related to complex networks[14]. Considering the satellite nodes as points in the graph and the inter-satellite links as edges in the graph, for a heterogeneous constellation with N satellites, then the graph $G = (V, E)$, V is the collection of points in the network graph, which corresponds to the set of satellite nodes; E composed of the satellites and inter-satellite links in the constellation is the collection of edges in the network graph, which corresponds to the set of inter-satellite links of the satellite network. Using the concept of adjacency matrix of a graph, for the visibility matrix V_{ij} of a satellite network graph, if satellite S_i and S_j are visible, the element v_{ij} in the matrix is 1; otherwise, v_{ij} is 0. The diagonal elements are always 0. The expression is as follows:

$$v_{ij} = \begin{cases} 1 & S_i \text{ and } S_j \text{ are visible} \\ 0 & S_i \text{ and } S_j \text{ are invisible} \\ 0 & i = j \end{cases} \quad (1)$$

For the connection matrix U_{ij} of a satellite network graph, if there is a connection between satellite S_i and S_j , the element u_{ij} in the matrix is 1; otherwise, it is 0. The diagonal element u_{ii} is always 0. The expression is as follows:

$$u_{ij} = \begin{cases} 1 & S_i \text{ and } S_j \text{ are connected} \\ 0 & S_i \text{ and } S_j \text{ are not connected} \\ 0 & i = j \end{cases} \quad (2)$$

2.2 Satellite Network Topology Optimization Model

2.2.1 Satellite network topology optimization objectives and constraints

$$\begin{cases} \text{Minimize}(\sum d_{i,j}) \\ \text{Maximum}(C) \end{cases}, s.t. \begin{cases} V_{i,j} = V_{j,i}, U_{i,j} = U_{j,i}, \forall i, j \\ u_{i,j}, v_{i,j,k} \in [0,1], \forall i, j \\ v_{i,j} = u_{i,j} = 0, i = j \\ u_{i,j} \leq v_{i,j}, \forall i, j \\ 3 \leq \sum_{i=1}^S u_{i,j} \leq 5, \forall j \end{cases} \quad (3)$$

The first optimization objective is minimizing sum of inter-satellite link distances $\sum d_{ij}$. The shorter the distance is, the smaller the transmission delay and the lower the transmission cost are[15]. The second optimization objective is maximizing the cluster coefficient of the satellite network. The larger the average cluster coefficient of the satellite network, the greater the connectivity of the network[16]. The cluster coefficient of a network with N nodes is shown in equation (4) as follows.

$$C = \frac{1}{N} \cdot \sum_{i=1}^N \frac{2E(i)}{k_i(k_i-1)} \quad (4)$$

k_i is the degree of node i (i.e., the number of edges connected to node i).

The constraints are: the visibility matrix $V_{i,j,k}$ and the connection matrix $U_{i,j,k}$ must both be symmetry matrices, and the diagonal elements are all 0; the visibility relationship $v_{i,j,k}$ and the connection relationship $u_{i,j,k}$ between S_i and S_j take the value of 0 or 1; the value of the connection relationship of satellite $v_{i,j,k}$ is greater than or equal to the value of the link building relationship $u_{i,j,k}$, i.e., the satellite link building must satisfy the visibility constraints; for any S_i and S_j , the maximum number of connections per satellite is 5 and the minimum number of connections is 3.

2.2.2 Satellite network topology optimization using virtual topology algorithm

Using equation (3) as the optimization objective and optimization conditions within every time slot, the satellite network topology is optimized using genetic algorithm to obtain a series of optimal connection matrices U_1, U_2, \dots, U_n . The optimization results for the above problem using the virtual topology method are shown schematically in the figure below:

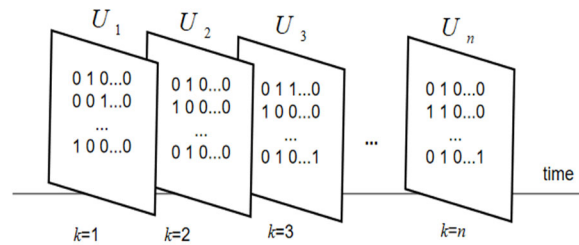


Figure 1 Schematic diagram of satellite network topology optimization results

3. VARIABLE TIME SLOT-BASED VIRTUAL TOPOLOGY OPTIMIZATION METHOD

Figure 2 shows the flowchart of the variable virtual topology algorithm, which is divided into the following steps:

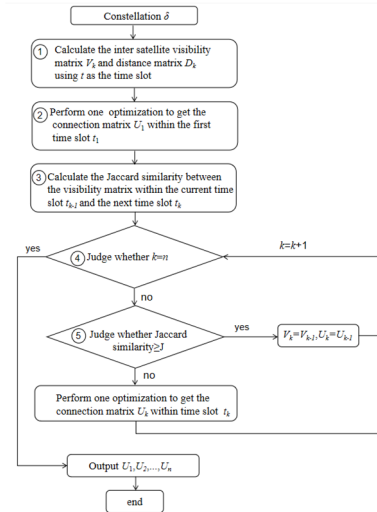


Figure 2 Flowchart of the virtual topology algorithm with variable time slots

1) Applying virtual topology strategy to divide the cycle of the constellation δ into n time slots, each of length t . The inter-satellite visibility matrix V_k and the distance matrix D_k within each time slot are obtained and used for the computation of steps 2), 3), 4), and 5).

2) Taking the link distance between satellites $\sum d_{i,j,1}$ and the cluster coefficient C_1 of the satellite network as the optimization objectives, genetic algorithm is used to optimize the topology of the satellite network within the first time slot to obtain the matrix U_1 that represents the constellation connectivity relationship in the first time slot t_1 .

3) Calculate the Jaccard similarity j_{12} between the visibility matrix V_1 in the second time slot t_1 and the visibility matrix V_2 in the first time slot t_2 .

4) Compare j_{12} with a specific value J . If j_{12} is greater than or equal to J , it means that there is no change in the visibility of the two, thus continuing the visibility matrix V_1 and connection matrix U_1 in the time slot t_1 . If j_{12} is less than or equal to J , update the visibility matrix of the constellation to V_2 and optimize it to get a new connection matrix U_2 .

5) Starting from the second time slot t_2 , repeat steps 3) and 4) until the end of the cycle of the satellite constellation to obtain a series of the satellite network connection matrices U_1, U_2, \dots, U_n .

4. NUMERICAL SIMULATION

4.1 Simulation Parameters

The simulation environment is a heterogeneous constellation composed of MEO satellites, LEO satellites and IGSO satellites, in which the MEO layer adopts the Walker- σ 12/3/1 configuration, with an orbital altitude of 21528 km and an orbital inclination of 55° . The IGSO layer has an orbital altitude of 35786km, an inclination of 55° , an intersection longitude of 118° E, and three satellites are uniformly distributed in three orbital planes with a 120° difference in ascending intersection equatorial longitude. The LEO layer adopts the Walker- σ 12/3/1 configuration, an orbital altitude of 1400km, and an orbital inclination of 52° . The satellite on-board antenna adopts a simple cone type, the cone half angle is 70° , and the azimuth angle range is $-180^\circ \sim 180^\circ$. The simulation time is from UTC 2007/07/01 00:00:00 to 2007/07/01 00:06:00, totaling 360 s.

For the variable time slots method proposed in this paper, the initial length is set to 10s, and the time slots in the second and subsequent time slots are decided based on the Jaccard similarity relationship of the visibility matrices in the previous and subsequent time slots. For the traditional virtual topology method, the length of the time slot is set to 40s. For convenience hereinafter, the variable time slots topology method is referred to as variable method, and the fixed time slot method is referred to as fixed method. In order to compare the two methods. In order to more intuitively represent the difference between the optimization results of the two methods, this paper adopts the form of topological diagram for

comparison. The axes of the topological diagram are not the actual physical distances or logical relationships in the network, but a representation used to visualize the network topology.

4.2 Optimization Simulation Results of the Variable Method

Analyze the results of the 360s simulation scenario for the satellite constellation. Figure 3 shows the variation curve of Jaccard similarity value j from 0-360s:

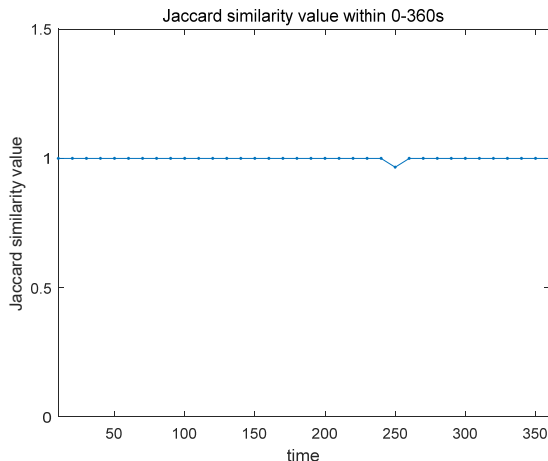


Figure 3 Curve of j -value change from 0-360s

From Figure 3, it can be seen that the visibility of the satellite network changes at 250s, and the satellite network remains unchanged at all other times. Figure 4.5 shows the satellite connection topology after optimization in 0~240s by the variable method. The node numbers in the figure represent the satellite numbers, where 1 to 12 are LEO satellites, 13 to 24 are MEO satellites, and 25 to 27 are IGSO satellites. The parameters for the genetic algorithm are set as follows: a population size of 100, a maximum iteration limit of 100, a crossover rate of 0.4, and a mutation rate of 0.1.

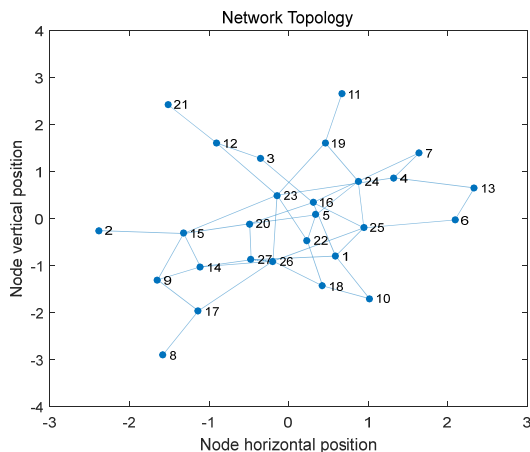


Figure 4 Connection topology of satellite network in 0~250s

As shown in figure 4, the connectivity relationship of the satellite network does not change in 0~250s. The Jaccard similarity of the satellite network visibility matrices $V_1 \sim V_{25}$ at 10s time slots within 0~250s are all 1, i.e., the visibility relationship does not change. As a result, the visibility matrix $V_1 \sim V_{25}$ within 0~250s with J set to 1 in this paper is not updated, inheriting the visibility matrix within the first time slot and connectivity topology map does not change.

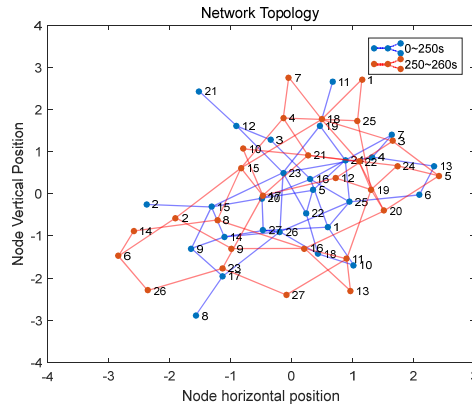


Figure 5 Comparison of connectivity topology of satellite networks in 0~250s and 250~260s

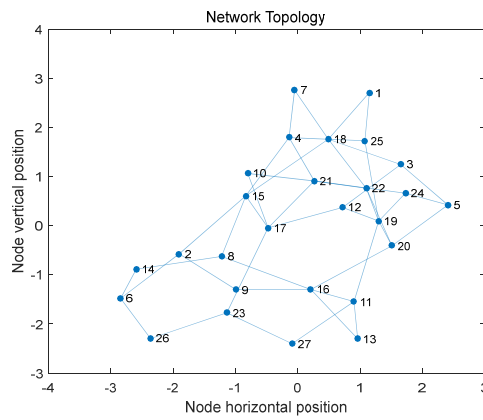


Figure 6 Connection topology of the satellite network in 260~360s

Figure 5 shows a comparison of the connection topology of the satellite network in 0~250s and 250~260s, it can be seen that the topology of the satellite network changes, and corresponds to the curve of j -value change in figure 6, where the visibility relation of the satellite changes at 250s.

Figure 6 shows the connection topology of the satellite network during 260~360s. Since there is no change in the satellite constellation visibility, there is no change in the satellite network connection during this period of time.

4.3 Optimization Simulation Results of Fixed Method

Figure 8 shows the connection topology of the satellite network for the fixed method from 0 to 280 s. The connection state of the satellite network does not change in 0~280 s.

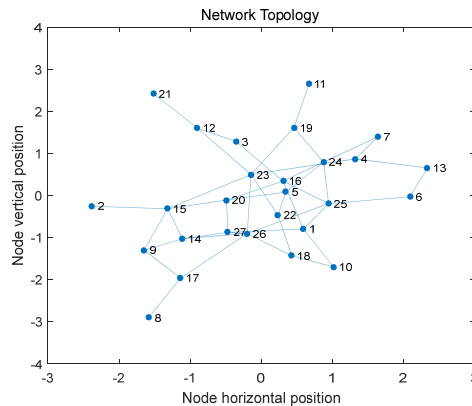


Figure 7 Connection topology of the satellite network in 0~280s

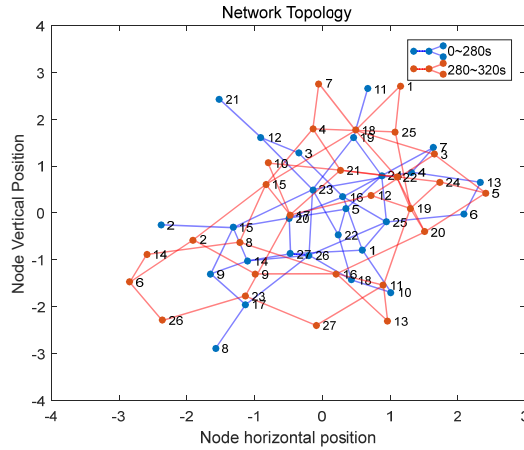


Figure 8 Comparison of connection topology of satellite networks in 0~280s and 280~320s

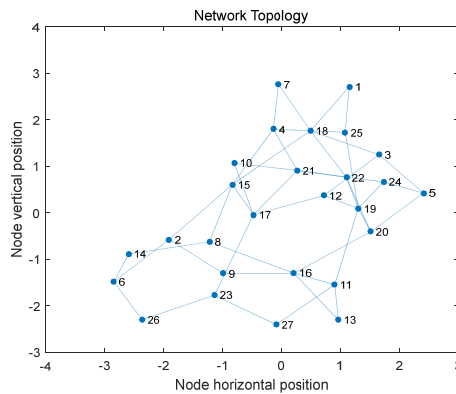


Figure 9 Connection topology of the satellite network in 320~360s

Figure 8 shows a comparison of the connection topology of the satellite network for the fixed method from 0 to 280s and from 280s to 320s, and it can be seen that the connection state of the satellite network changes at 280s.

Figure 9 shows the connection topology of the satellite network during 320~360s for the fixed method and there is no change in the connection relationship of the satellite network

4.4 Comparison of the Simulation Results of the Two Methods

During 0~360s, according to the change curve of Jaccard similarity, it can be seen that the visibility of the constellation is unchanged from 0~250s, changed at 250s and unchanged from 250s~360s. The trend of connection topology of both methods is from fixed to changing to fixed throughout the time period. However, the connection topology change time of the two is different, the fixed method takes 40s as a time slot, the time slot is updated at 240s, and the 250s is inside the seventh time slot unable to perceive the change of visibility relation so the connection topology changes at 280s. In contrast, the variable method takes 10s as a time slot, and by calculating the Jaccard similarity of the visibility within the before and after time slots, the time slot is updated at the 250th time slot, and thus the visibility can be perceived to have changed, altering the topological connection.

Analyze the optimization results for both approaches and compare them against the optimization constraints. Use the 7th equation of Equation (3) within every time slot $v_{i,j,k} \geq u_{i,j,k}, \forall i, j, k$ to determine whether the optimization results satisfy the current visibility constraints, if $v_{i,j,k} - u_{i,j,k} \geq 0, \forall i, j, k$ that is, the difference between the visibility matrix and the connection matrix are both non-negative, it can be proved that the connection matrix meets the visibility constraints. It is verified that the variable method, $v_{i,j,k} - u_{i,j,k} \geq 0, \forall i, j, k$, satisfies the visibility constraint in 360s, and the fixed method at $k = 5, 6, 7$ of the fixed method does not satisfy $v_{i,j,k} - u_{i,j,k} \geq 0, \forall i, j, k$. Therefore, the connection topology changes at 250s for the variable method and at 280s for the fixed method. Compared with the fixed method, the variable method is able to perceive the change of the visibility, the variable method has better dynamics. In 0-360s, the variable method only

performs two optimization operations in 0~360s, which are the 0th and 240th respectively, and the fixed method performs nine optimization operations, and the variable method is able to reduce the number of optimization operations in the time period where the change of satellite visibility is small. Table below shows the comparison graph of the two methods.

5. SUMMARY

In this paper, with respect to the time-varying network design problem of heterogeneous satellite constellations composed of LEO, MEO and IGSO, a variable time slot-based topology optimization approach is proposed. Topology optimization model is established with the shortest inter-satellite connection distance and cluster coefficient of the satellite network as the optimization objectives, and solved by genetic algorithm. The proposed variable time slot-based topology optimization method judges the Jaccard similarity of the before and after time slots when the time slot is changed, and if it is greater than or equal to a specific value it will not update the connection matrix, otherwise, it will update the connection matrix. Simulation results show that when the topology of the satellite network changes, variable time slot-based topology method is able to perceive the change in the visibility of the satellite network faster and thus better satisfy the visibility constraints. Meanwhile, if the visibility of the satellite network changes slowly, the variable time slot-based topology method can reduce the number of network optimization times resulting in reducing a certain amount of computation.

6. ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China under Grant U21B2008.

7. REFERENCES

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