A topology-based optimization method for software-defined satellite network control

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Abstract. Satellite network is gaining significant attention, and software-defined networking architecture is more and more popular as applied in many traditional networking fields. In order to meet the diversified user service requirements and the continuously expanding application scenario requirements, the research of software defined satellite network combining satellite network and software definition has gradually become a research hotspot. Aiming at the problem of how to optimize the control function of software-defined satellite network, this paper proposes a control optimization method based on topological structure. By quantifying the controllability of the network structure and eliminating the special characteristic structure, the controllability of the network is improved, and then the control function of software-defined satellite network is optimized. The simulation results show that the controllability of the network is improved by the method.

1. Introduction

In recent years, with the continuous development of satellite network technology and next generation internet technology, software-defined satellite network (SDSN) has become a hot topic in satellite internet researches, which has considerable research value and development potential.

Compared with the traditional satellite system, the advantages of SDSN are more flexible and agile network configuration, new business launching and updating, more efficient resource management and control capability, and more customized services and wider network access for more users[1]. For SDSN, most of the existing researches focus on the architectural design[2][3] and deployment scheme[4]of software-defined satellite networks, or on the resources allocation[5][6][7]and link failure and recovery[8][9], while few researches focus on the enhancement of the control function of software-defined satellite networks with dynamic topology changes. Because the satellites nodes in the satellite network are in motion all the time, the communication links between satellites to satellites, satellites to the ground are not continuously connected, the topological structure of the satellite network is dynamically changed, which leads to the deterioration of the control capacity and reliability of the network. Therefore, it is of significance to study how to improve the network control capability and reduce the negative impact on network performance, service quality and reliability caused by the dynamic topology of SDSN.
In this work, in order to improve the control capability of SDSN, based on the analysis of SDSN architecture, we propose a topology-based network topology control capability measurement method, and a control capability improvement method by changing the topology of network.

2. SDSN model construction

2.1. The architecture of SDSN

Based on the typical GEO/LEO two-layer satellite network structure [10], a SDSN system based on SDN architecture was constructed.

As shown in Figure 1, the GEO layer is Geosynchronous Earth Orbit (GEO), generally composed of more than three Geo satellites, capable of achieving full coverage in low and medium latitudes. However, the data transmission process suffers from great loss and long delay. The LEO layer is Low Earth Orbit (LEO), consisting of several groups of low-orbit satellites, with small loss and short delay in data transmission. However, due to the small coverage area, short orbit cycle and fast speed, the effective communication time with the ground is usually only a few minutes. The bottom layer is the ground system, which consists of several ground station nodes and end-user nodes, among which the ground station nodes mainly include the ground gateway and the ground control center.

![Fig.1 GEO/LEO double-layered satellite network structure](image)

There are three kinds of bidirectional satellite communication links in the structure: the inter-satellite-link (ISL) is responsible for the satellite connection within the same level, the inter-orbital -Link (IOL) is responsible for the satellite connection between different levels, and the user-data-link (UDL) is responsible for the communication between the satellite and the ground gateway. In this networking mode, LEO satellites support user access services, GEO satellites are responsible for data relay services, and earth stations are directly connected to GEO satellites.

Since the control function and data forwarding function are separated in SDN, the control function of SDNS is deployed on GEO satellite layer, and the LEO layer is responsible for the data forwarding.
function, and the ground station is responsible for the coordination of the whole satellite system management and decision making.

2.2. The network model of SDSN

According to the nodes and edges of the satellite network, the network topology can be abstracted, and the connection of each node of the network is represented by the adjacency matrix $A$ of the network.

Let the number of network nodes be $N$, and the adjacency matrix $A$ can be expressed as:

$$
A = \begin{bmatrix}
    a_{11} & a_{12} & L & a_{1N} \\
    a_{21} & a_{22} & L & a_{2N} \\
    M & M & O & M \\
    a_{N1} & a_{N2} & L & a_{NN}
\end{bmatrix}
$$

(1)

The adjacency matrix $A$ is a square matrix of order $N$, numbering $N$ nodes in the network from 1 to $N$, then the element $a_{ij}(i, j \in (1, N))$ in $A$ represents the connection between node $i$ and node $j$.

For element $a_{ij}$ in $A$, $a_{ii} = 0$, $a_{ij} = a_{ji}$, and $a_{ij} = 0$ for $i = 1, N$.

Controllability was determined according to common methods: the basic rank criterion[11] and the PBH rank criterion[12].

3. Control capability improve method

3.1. Controllability of network

On the basis of the above model, we define network controllability, and then propose a method to improve network controllability by eliminating feature structure.

Definition 1. Network controllability is a quantitative index to describe the network control capability under the current network topology structure, and the index can be measurement by $n_d$, which is the ratio of the minimum number of control command input nodes $N_d$ to the total number of the nodes in network $N$[11]. It can represent as follow:

$$
n_d = N_d / N
$$

(2)

The basic rank criterion is the controllable criterion based on the following:

$$
\text{rank } [B AB A^2B \ldots A^{N-1}B] = N
$$

(3)

If the network system satisfies Equation (3), it is controllable; otherwise, it is not.

PBH rank criterion is a controllable criterion based on the following:

$$
\text{rank } [\lambda_k I - A B] = N \quad k = 1, 2, \ldots, N
$$

(4)

Where $\lambda_k$ is all the eigenvalues for the adjacency matrix $A$. If the network system satisfies Equation (4), the network system is controllable; otherwise, it is not.

According to the criterion matrix of Equation (3) or Equation (4), basic ideas can be provided for solving the minimum control input: for the adjacency matrix $A$, find the simplest matrix $B$ that satisfies $\text{rank}(Q) = N$ or $\text{rank}(P_k) = N$, then the corresponding control input of $B$ at this time is the minimum control input. The most direct method for the substitution method, that is, for all the nodes in the network, will be the control input by less up to traverse the combination, generating all possible cases of input matrix $B$, from simple to complex to perform Equation (3) or Equation (4) to test its rank, once appear, judged to be controlled, can the matrix $B$ to determine the minimum control input. However, for a network with $N$ nodes, the computational complexity of finding out all matrix $B$ is $O(2^{N-1})$.

The solution method of matrix $B$ can be obtained: firstly, calculate lambda $\lambda_k I - A$, and then carry out elementary column transformation without changing the row-related properties; According to row correlation, eliminate row correlation for $\lambda_k I - A$ by setting minimum $b_i$, so that all row vectors in the PBH matrix are irrelevant; Finally, all $b_i$ settings corresponding to $\lambda_k$ are integrated so that $b_i$ can eliminate the row vector correlation of all PBH matrices corresponding to $\lambda_k$, which satisfies Equation (4). In the end, the corresponding $b_i$ is the matrix $B$ corresponding to the minimum control input, and the number of nodes of the minimum control input is $N_d = \text{rank}(B)$. 


Then, the measurement index $n_d$ of network controllability can be obtained by Equation (2), and the quantitative analysis is done.

### 3.2. The improve method

According to eliminating the correlation of PBH decision matrix, the minimum number of control input nodes is reduced by increasing/decreasing network edges, thus improving the controllability of structure.

From the section mentioned above, it can be observed that the direct factor affecting the controllability of the network is the row correlation of $\lambda_d I - A$ in PBH matrix, while the row correlation of $\lambda_d I - A$ is jointly determined by adjacency matrix $A$ and $\lambda_d$, of which two eigenvalues of 0 and -1 have specific associations with the row correlation of $\lambda_d I - A$.

According to the adjacency matrix, the network nodes corresponding to three characteristic structures (i.e., the isolated feature structure, type I and type II) are found, and the edge adding operation is carried out on the isolated nodes, namely, the nodes within the reachable range are randomly connected; For type I and type II structures, the edges are increased or decreased according to the connection conditions of the nodes themselves. If the node degree becomes larger, the edges are randomly decreased, and if the node degree is smaller, the edges are randomly increased within the reachable range. Although the row correlation of $\lambda_d I - A$ can not be eliminated, the zero-vector correlation and the repeated correlation in the row correlation can be eliminated, thus reducing the row correlation of $\lambda_d I - A$ and improving the controllability of the network.

### 4. Simulation result

#### 4.1. Simulation parameters

We conduct simulation on the network with node number $N=100$, the connect probability between nodes is $P=0.99$. And the nodes in the network are uniform distributed in 500*500 units, which are represents the satellite nodes of SDSN. The maximum connection distance of any two nodes is set by 50 units, other links out of 50 units are removed, for which the initial topology of SDSN is done. After that, we could set dynamic nodes in three test networks by randomly generated the next position within 50 units away from the previous step, which are represent the dynamic satellite nodes in SDSN. The number of dynamic nodes in three test networks are 50, 70, 90, and follow the generation rule above, the links between dynamic nodes also within 50 units, otherwise remove the beyond ones.

Applying the control method mentioned in 3.2 on the three test networks. Firstly, calculating the controllability index $n_d$ of the initial network. Secondly, moving each dynamic node according to the motion trajectory of the dynamic network, calculating the distance between every two nodes, removing the links beyond 50 units, and adding the links within 50 units. Then, calculating the controllability index $n_d$ of the current test network by its topology structure. As for the results, repeat above steps 10 times on the three test networks respectively, and record the mean value of the controllability index $n_d$ of both initial network and current network controlled by our method.

#### 4.2. Results of simulation

The results of the comparison of the original network (initial network) and the controlled network (controlled by the method) are shown in Fig.2, and (a), (b), (c) respectively shows the test networks with dynamic nodes of 50, 70, 90.
It can be seen from Fig. 2 that the values of $n_d$ in controlled network is better than original network, which means the controllability of test networks are improved by the control method, and the validity of our control method is proved.

5. Conclusion
In this work, we proposed a topology-based optimization method that is applied on SDSN, the conclusions are summarized as below:

(1) A software-defined satellite network architecture is proposed, and the structure of which is explained in detail.

(2) To evaluate the control capability of SDSN structure, a quantitative index controllability of network structure is proposed.

(3) A controllability improvement method by changing the connection states in network topology is proposed, and the effectiveness of method is proved with experiment results.

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