Information Topology Control Technology of Cluster Satellite Network

Jingling Li(✉), Jun Li, Tao Cui, Wei Liang, and Yi Zhang

National Key Laboratory of Science and Technology on Space Microwave, CAST, Xi'an 710100, China
ljlspirit@foxmail.com

Abstract. Currently, high dynamic topology and heterogeneous information in cluster satellite network pose new challenges to the topology control at the information level. Because of the topology control of traditional networks can not been directly applied to cluster satellite network, many new topology control technologies used in satellite network have been proposed. Due to the unique flexible networking characteristics of cluster satellite network, further research is needed based on the existing satellite network topology control technology in cluster satellite network. The connotation of information topology control in cluster satellite network is proposed. And based on the in-depth analysis of the characteristics of cluster satellite network, a general information topology model is constructed. Then the existing satellite topology control algorithms are introduced in detail, and its existing problems are analyzed. Finally, according to application requirements, the development trends of cluster satellite network topology control technology are proposed as reference.

Keywords: Cluster satellite network · Information topology control · Heterogeneous information · High dynamic topology

1 Introduction

With the further development of aerospace technology, all kinds of space missions and scientific missions undertaken by satellites are becoming more and more complex. First, from the perspective of solving missions, the traditional space mission solution that relies on a single powerful large satellite is not only expensive, but also inflexible, difficult, and long development time, which cannot fully meet the growing and complex requirements of the new missions; and the currently proposed space networks such as Space-ground integrated network, spatial information network, and so on, have complete functions and large scale, which can deal with space/scientific missions around the world. But these types of network have long deployment period and fixed preset mission requirements. When solving certain needs or responding to certain types of emergencies, the network has limited scalability and flexibility [1, 2]. Secondly, from the perspective of space security, satellite platform or payload damage may cause the satellite to fail to operate normally, and the security and invulnerability of the whole network become weaker.

B. Li et al. (Eds.): IoTaaS 2020, LNICST 346, pp. 392–402, 2021.
https://doi.org/10.1007/978-3-030-67514-1_32

A variety of cluster satellite networks have been proposed for different application scenarios [3–8], among which [3–5] consider the cluster satellite network to be a multi-purpose network composed of heterogeneous satellites, reference [6] considers the cluster satellite network is a system in which multiple small satellites work together. Reference [7] conducts theoretical analysis on small satellite networks with limited resources. Reference [8] believes that cluster satellite networks have loose topological characteristics. And multiple satellite connections with the same or different functions become an organic whole, realizing the dynamic sharing and flexible configuration of information and resources in the cluster.

Due to the advantages of the cluster satellite network in terms of development cost, flexibility and security, it will become an important network system of the space network in the future [8], the schematic diagram of cluster satellite information network is shown in Fig. 1, which includes EOS, DRS and other heterogeneous satellites. For the high dynamic topology and autonomous control characteristics of the cluster network, the topological characteristics of the cluster satellite network are different from other satellite networks and the ground networks. How to optimize the network node status and information connection method is an important basic problem of the cluster satellite network, which is also the main problem solved by topology control technology. The topology control technology of the cluster satellite network includes two levels of connotation: firstly, from the perspective of topology, design and control the spatial layout of network nodes; and secondly, from the perspective of information transmission, for the information topology formed by information transmission perform information logic control. This article mainly discusses the second point of information topology control.

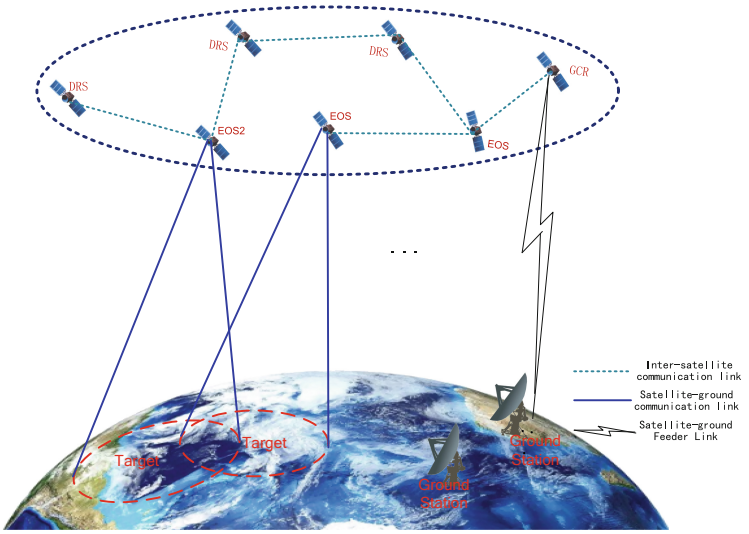

Fig. 1. Schematic diagram of cluster satellite information network

2 Concept and Connotation of Information Topology Control in Cluster Satellite Network

The cluster satellite network mainly includes satellite operating status information (e.g. relative position information, three-dimensional attitude information, relative operating speed, space time/frequency synchronization information, etc.), network control information (e.g. track, track location, etc.) and mission-based data information with large capacity. This article categorizes the satellite control information and status information as basic information, and categorizes mission-related large capacity information as data information. Since basic information and data information have different generation mechanisms, functions, and transmission paths, the two types of information are heterogeneous. As shown in Fig. 2 is a schematic diagram of a satellite heterogeneous information network, in which the satellite basic information is used to ensure the connectivity of the cluster satellite network, and the satellite data information is transmitted according to the mission requirements, which may be the interconnection between some nodes.

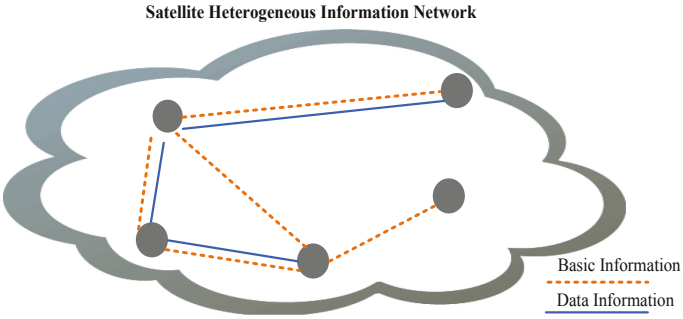

Fig. 2. Schematic diagram of satellite heterogeneous information network

During the process of performing collaborative tasks, the information obtained by each satellite is partial information of their local positions. The information of all satellites in the cluster is merged into global information, which is provided to the decision-making system for task division and Scheduling. When a satellite fails, the cluster satellite system can timely reconstruct the network information topology and dynamically adjust the connection relationship between system members, thereby improving system reliability and fault tolerance.

The information topology control technology in the cluster satellite network is used to connect the relationship between the physical layer and the network layer, which ensures that the network is connected and optimized, as the basis of the upper layer routing protocol. Another important role of topology control is to maintain the generated topology, or to rebuild the topology. In general, topology control technology can optimize the selection method of neighbor nodes according to different application scenarios under the premise of ensuring network connectivity and coverage, and finally form a stable and efficient network structure to complete scheduled tasks.

In order to reflect the "information-oriented" connotation, information topology control can be considered from two aspects. One is to implement topology control based on information of different types of attributes, maintain network connectivity, and optimize network lifetime; the second is to enable the network to better support the transmission of business information and improve network throughput through topology control technology. As shown in the Fig. 3 is a schematic diagram of the complete flow of information topology control technology, where the dotted frame is the content of the topology control technology, and the others are related discovery algorithms and monitoring mechanisms.

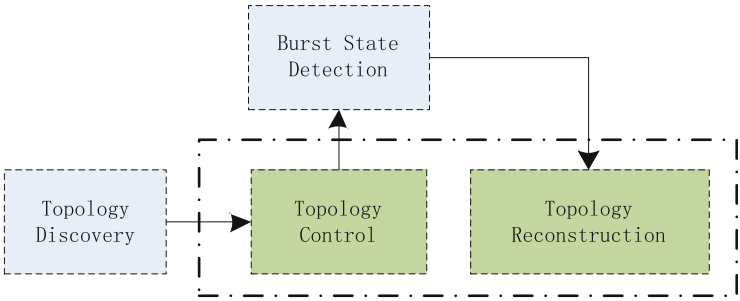

Fig. 3. Schematic diagram of the complete flow of information topology control technology

3 Information Topology Model of Cluster Satellite Network

Since the information topology control technology is strongly related to the information topology of the network, the model of the cluster satellite network needs to be discussed first. In this paper, based on the characteristics of information topology in the cluster satellite network [9, 10], the realization of the comprehensive algorithm, the information topology model of the cluster satellite network is set as follows.

(1) The network contains three types of information: mission information, status information, and control information. Status information and control information are network management and control information that needs to be sensed by the entire network, while task information is only transmitted on specific links.
(2) The network has two types of antennas, omnidirectional antennas are used to transmit status information and control information (low speed); and directional antennas are used to transmit mission information (high speed).
(3) Shared satellite node status information throughout the network: each satellite in the access satellite cluster network regularly shares its status information with other satellite nodes, including the 3-dimensional attitude in the reference system of navigation information, relative position, relative speed and space/time/frequency synchronization information, etc.
(4) The communication protocol on each satellite has an ideal MAC layer, that is, any two satellites can establish a communication link as long as they are within their respective communication ranges.

(5) Each satellite only runs according to its own orbit, which operating status can be predicted.
(6) It does not consider the perturbation effect of celestial bodies other than the earth on the satellite.

4 Analysis of Information Topology Control Technology

There are many different classification methods for network topology control technology. Literature [8] proposed to classify these methods based on algorithm fault tolerance. The control algorithms without fault tolerance are mainly single-connected topology algorithms, and the control algorithms with fault tolerance can be roughly divided into two categories: k-connectivity and topology autonomous restoration. Literature [11] proposed a satellite network topology control strategy based on static or dynamic topology. At present, there are two kinds of mainstream algorithms for topology control: centralized algorithms and distributed algorithms. Centralized topology control algorithms [12–14] relied on the central node in the network for calculating and controlling the entire network topology. This topology control method can obtain the global optimal topology control results, by adopting the method of sending control information from ground station to satellite cluster, it can avoid a large amount of control information overhead and the difficulty of algorithm convergence problems in satellite cluster network. The distributed topology control algorithm [14–16], in which each node can obtain the relevant information of the surrounding nodes, relied on the mutual cooperation between the nodes to complete the topology control, without core node.

The problem faced by this type of algorithm was that the local information obtained by each node cannot optimize the performance of the entire network through topology control, which may lead to deterioration of network connectivity in some cases.

The function and status of each node in the satellite network using centralized topology control technology is different, and the method of hierarchical topology structure can be adopted. And the satellite network using distributed topology control technology can adopt two types of topology control methods: hierarchical and planar (also called non-hierarchical) according to the formed topology, as shown in Fig. 4. Among them, the status of the nodes in the planar topology is the same, while the status of the nodes in the hierarchical topology is different. The hierarchical topology can be further refined into two types: tree topology and cluster topology. Strictly speaking, the cluster topology is also a tree topology, but because of its obvious cluster head nodes, it is classified as a single category.

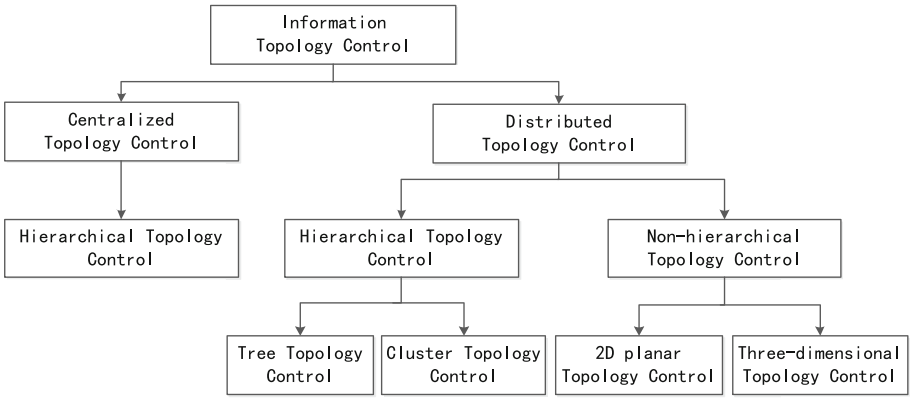

Fig. 4. Satellite network topology control technology classification

4.1 Distributed Satellite Topology Control Technology

The cluster spacecraft network constructed in [17] is similar to the wireless sensor network, and has the characteristics of self-organizing network such as network centerless, multi-hop information transmission, and time-varying topology. Based on the analysis of the advantages and disadvantages of the network hierarchical structure and the plane structure, combined with the characteristics and functional requirements of the cluster spacecraft, the plane structure is used as the basic configuration of the cluster spacecraft research. The paper believes that all modular spacecraft in the network have the same network-wide information routing table. This paper proposes an improved topology control algorithm based on the FLYG algorithm, which combines the expected value of network communication distance with the characteristics of cluster spacecraft. The algorithm optimization goal is to improve the performance of the topology control algorithm, thereby effectively reducing the energy consumption of network data transmission and extend the network life cycle. This paper assumes that the entire cluster spacecraft network is a homogeneous network, and each module spacecraft has the same parameters, including the maximum communication distance, the energy carried, etc., which is not suitable for heterogeneous cluster satellite networks.

Literature [18] describes a distributed cluster satellite network, which can provide flexible space scenarios that guarantee service quality. In such a multi-satellite heterogeneous system, a reasonable power control scheme can improve system performance. This paper establishes a network power control model by analyzing the characteristics of the distributed cluster satellite network and the difficulties of power control, and proposes a power control method based on prediction. The method mainly adjusts the network neighbor nodes by controlling the power of the satellite nodes, and requires the small satellites of the cluster satellite network to have the power adjustable ability, which is difficult to implement.

The cluster spacecraft studied in the literature [19] is a new type of space distributed system, in which the satellites move at high speed in orbit and the inter-satellite

links frequently switch, which fully reflects the high dynamics and periodicity of the cluster spacecraft network topology. This paper sets in the network model that each satellite can perceive the dynamic topology of the entire cluster network and the orbit data of other satellites, and can calculate the distance between each other at any time, so each satellite participates in the information topology in real time calculation and maintenance. And from the perspective of network energy consumption balance, the idea of star cluster network management is proposed, the main satellite node selection mechanism is set according to the energy consumption of nodes, and the network topology update strategy of dynamically changing the main satellite is adopted to avoid excessive energy consumption of the main satellite node. However, the network model constructed by this method is too ideal. In the actual network environment, it is difficult to establish wireless links between satellite nodes, and it is not always possible for each satellite to perceive the status changes of the entire network in real time.

In view of the characteristics of laser inter-satellite links, literature [20] takes into account the high-speed communication and high-precision measurement requirements of the navigation satellite inter-satellite links, and makes the link utilization rate, end-to-end transmission delay, link space geometric configuration and other parameters to be the optimization goal of the topology control algorithm. This paper converts the topology planning problem of laser inter-satellite link as a multi-objective function optimization problem under multiple constraints.

The article assumes that if two satellites meet the condition of continuous visibility in a certain FSA state in the network, the two satellites are considered to be visible in this state. By improving the multi-target simulated annealing algorithm (MOSA), a method is designed to avoid the conflicting link cross update algorithm, through the cross conversion of the link building matrix and the visible matrix, prevents the link switching from conflicting with the constraint conditions, and optimizes the multi-source minimum delay routing algorithm to improve the efficiency of the algorithm. When a certain satellite or a certain laser link is unavailable, the topology can still be dynamically optimized, and then the global optimal topology can be solved. However, this algorithm only discusses the solution method of the established function, and there is no specific analysis of the satellite network scenario and specific description of the topology control update mechanism.

4.2 Centralized Satellite Topology Control Technology

Literature [21] elaborated on the topology control scheme of dynamic link establishment of two types of heterogeneous satellites in Walker constellation. Since the movement trajectory and information link of the satellite in the satellite constellation network change periodically, the topology table can be generated on the ground to plan the network topology in advance. Therefore, the ground is used as the topology control center of the network.

Literature [22] is oriented to a heterogeneous satellite network composed of Earth Observation Satellite (EOS), Ground Station Communication Satellite (GSC) and Data Routing Satellite (DRS), and expands the functions of the entire network through the collaborative work between heterogeneous satellites. This paper constructs a three-dimensional satellite information topology model according to the set network

scenario, and proposes a centralized topology control strategy. The cluster regularly calculates all possible network links through a satellite, and then distributes the results to other satellites. The process of topology control strategy mainly includes two parts:

(1) Topological matrix calculation and its distribution. The calculation of the topology matrix means that one of the data routing satellites is responsible for analyzing the network link connection and obtaining the topology optimized for reliability;
(2) Information distribution. That is, the satellites with the link relationship distribute the information, and then in a topology update cycle, the network changes the link connection according to the topology matrix.

The disadvantage of this algorithm is that it does not analyze the complexity of the algorithm and the algorithm convergence time, and the centralized algorithm also lacks network robustness analysis. If the central computing node fails, how should the network recover and recalculate the network information topology.

4.3 Hybrid Algorithm Topology Control Technology

Literature [23] is different from the traditional centralized control algorithm and distributed control algorithm. It uses a hybrid method to divide the spatial information network into a series of autonomous domains according to the node attributes. Each autonomous domain adopts an independent control strategy. Different autonomous domains realize the exchange of control information through boundary nodes. Each autonomous domain can be divided into the next level of sub-autonomous domains as needed to build a hierarchical autonomous domain network structure. Through this division, the spatial information network, which is highly dynamic as a whole, is decoupled into a quasi-static sub-network composed of similar types of nodes with weak dynamic changes in its parts, thereby simplifying the complex problems of network topology control.

The spatial information network targeted by this paper has the characteristics of many types of nodes, three-dimensional multi-layer distribution, heterogeneous nodes, and large dynamic differences. Although the cluster satellite network also has high dynamics and heterogeneous characteristics, its network level is not complicated, and its satellites are mostly small satellites, with limited computing power, and are not suitable for overly complex topology control algorithms.

5 Research Direction of Information Topology Control Technology

At present, researches on topology control algorithms in satellite networks such as spatial information networks, navigation satellite networks, constellation networks, and cluster satellite networks have gradually increased, focusing on the characteristics of high dynamics of satellite networks, heterogeneous networking, and limited network energy. The network topology update strategy of dynamically changing the main satellite, the link cross update algorithm to avoid conflicts, the algorithm based on

centralized and distributed hybrid control, and many other topology control algorithms with multiple optimization objectives are proposed. Because cluster satellite networks have stronger flexibility and self-organizing characteristics, they face more problems compared with other types of satellite networks and require further research.

(1) First, facing the demand for high-speed transmission, it is necessary to further study the cluster satellite network directional sensing technology to obtain the set of reachable neighbor nodes. Due to the complexity of the satellite link building process, the inter-satellite link resources are very limited. In this case, it is difficult to assume that each satellite can perceive the state of all neighboring nodes and obtain neighbor node information. The literature [24] proposes A neighbor discovery method based on directional antennas, through the Q-Learning mechanism to determine the receiving/transmitting mode of each neighbor scan, and determine the return value according to the current scan result, learn the experience in the scan, and achieve the goal of improving the efficiency of neighbor discovery. However, this method takes a long time to search for neighbor nodes, and further research is needed for the high dynamic characteristics of cluster networks.
(2) Secondly, it is necessary to further study the influence of heterogeneous information on key nodes and topology strategies of the cluster satellite network. Literature [6] proposed to design the distributed satellite system communication network architecture into two logically independent sub-networks, namely the on-orbit operation control data control sub-network (operation control sub-network) and the high-speed load data transmission sub-network (data transmission sub-net). Among them, the operation control sub-net is mainly responsible for the transmission of control data required for network operation, using omnidirectional transmission; the data transmission sub-net is mainly responsible for the transmission of load data, using directional high-speed transmission.
(3) Finally, it is necessary to further solve the problems of self-organized storage, update and calculation of information in the cluster satellite network. The networking trend of cluster satellite network is the form of self-organizing network [8]. It can connect multiple spacecraft with the same or different functions into an organic whole, and can flexibly realize variable tasks by sharing information and resources in the cluster. In the future, topology control technology can be used to spontaneously respond to emergencies, adjust the network task structure or spatial topology structure, and independently maintain network security and dynamic stability. In this case, it is necessary to comprehensively consider the fault tolerance, convergence time and computational complexity of the satellite topology control algorithm. At present, there are few literatures for comprehensive analysis and research on this problem.

6 Conclusions

At present, cluster satellite networks have played an important role in the fields of earth observation, communication, scientific exploration, space surveillance, and space attack and defense. Since the strict distributed configuration of cluster satellite network

is very difficult to realize, the future cluster satellite network is more inclined to the network topology form of loosely coupled configuration, which requires higher flexibility and dynamics of information topology. Research on information topology control technology can help accelerate the realization of a new generation of cluster satellite distributed networking, further improve the flexibility, scalability and effective life cycle of the network. In the future, the cluster satellite network will bring greater advantages to specific space applications such as rapid observation and deployment in local areas, rapid assessment of natural disasters, etc.

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