第38卷第6期
2019年12月

红 外 与 毫 米 波 学 报
J. Infrared Millim. Waves

Vol. 38，No. 6
December，2019

文章编号：1001-9014(2019)06-0706-10　　**DOI：10. 11972/j. issn. 1001-9014. 2019. 06. 005**

Robust dynamic topology control for ORS satellite laser communication networks

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Abstract： Inter-satellite laser links have the advantages of high data rate，long transmission distance and low probability of detection/intercept. It has become an important trend in satellite technology. The inter-satellite point-to-point laser links are high mobility，and have narrow beam width，which bring challenges to the PAT processes. Due to their high computational complexity and large delay，the existing free space networks（FSO）topology control strategies cannot be directly applied to satellite networks. In this article，an algebraic connectivity based network dynamic topology control scheme is proposed. With distributed construction and enhancement process，the network dynamic reconfiguration is accomplished. A modified edge perturbation method is developed，and proved to have lower computational complexity than existing methods. The scheme is distributed，self-organized and near real-time，it which meets the requirements of dynamic topology control well and will contribute to building operationally responsive space（ORS）satellite networks.

Key words： laser communication，dynamic topology control，algebraic graph theory，satellite networks
PACS： 42. 79. Sz，84. 40. Ua，02. 10. Ox

快速响应激光卫星通信网络的鲁棒动态拓扑控制

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摘要：星间激光通信具有传输速率高、传输距离远、抗干扰能力强的优点，已成为卫星组网的重要趋势.星间激光网络存在高移动、点对点、波束窄等特点，已有的自由空间网络(FSO)拓扑控制策略应用于星间激光通信，存在计算复杂度高、网络延迟大的不足，无法满足星间激光组网需求.文中提出了一种基于代数连通度的星间激光组网动态拓扑控制方案，通过分布式构建卫星网络连通图与网络增强方法，实现网络动态重构，并通过基于矩阵摄动理论的相关方法，降低了网络动态重构计算复杂度.该方案具有分布式、自组织、近实时的优点，可满足空间激光通信网络的动态拓扑控制需求，提高卫星快速响应能力.

关　键　词：激光通信；动态拓扑控制；代数图论；卫星网络
中图分类号：TN249，TN　711.6　　**文献标识码：**A

Introduction

Operationally responsive space（ORS）was proposed by the United States Department of Defense（DoD）in 2007. It was defined as assured space power，which timely satisfies the needs of Joint Force Commanders[1]. With micro-satellite networks，ORS can provide an economics scheme（both in time and cost）for urgent need in

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Received date： 2019-04-04，**revised date：** 2019-07-01　　**收稿日期：**2019-04-04，**修回日期：**2019-07-01
Foundation items：Supported by Chinese Academy of Sciences（ZDBS16ZRJ1）

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strategic mission level. The launching-on-demand is required, and then encourages developers to adopt advanced technologies. Also, the system provides better data integration, information sharing, and net-centricity, which enhance the quality of situational awareness and then improve the effectiveness of decision-making system. Thus, there is a pressing need to build ORS space backbone network for military missions, including data relay and earth observation. Optical inter-satellite links are regarded as an ideal choice for future satellite networks. Especially, with high data rates, it is a viable solution for data-sensitive military applications. Besides, with Low Probability of Intercept and Low Probability of Detection (LPI/LPD), the optical ISL (inter-satellite communication links) provides enhanced security for space mission[2]. This makes it more survivable in the future space confrontation, and more suitable for ORS military applications. The construction of optical constellations has been researched in many countries. In Europe Space Agency (ESA), the SILEX plan and EDRSS plan were proposed to build a relay satellite system, and two satellite SPOT-4 and ARTEMIS had been launched[3-4]. In United States, the 1st and 2nd generation (TDRSS) had been built by NASA, while another laser Satellite Data System[5] is under development since 1998 to the present[6-7]. In Japan, several laser satellites had been launched, including ETS-VI in 1994 and OICETS in 2005[8-10]. As for China, in order to conduct the Quantum Key Distribution Experiments at space scale, a satellite named "Mo-zi" was launched in 2016[11]. Also, another satellite named Xiangrikui-1, the first launching of CentiSpace plan, was developed by the Shanghai engineering center for microsatellites in 2018[12]. In this project, an 808/850 nm laser transceiver module is adopted, the laser transceiver module is shown in Fig. 1.

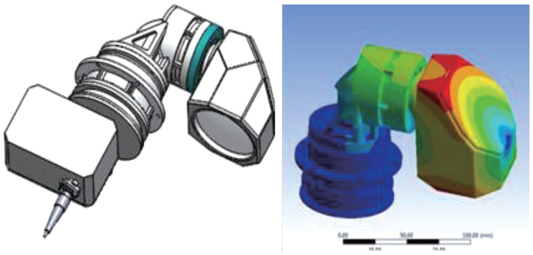

Fig. 1 Optical transceiver module in Xiangrikui-1 satellite
图 1 向日葵一号卫星的光学收发终端

One of the challenges in developing a robust optical satellite networks (OSN) is the high dynamic of the network. The high-speed movement of satellites leads to frequently topology change, which means the ISLs are continually broken and rebuilt. The constellation of a typical low earth orbit (LEO) satellite constellation NeLS is shown in Fig. 2. Also, due to the dynamic of satellite constellations, the relative position, especially the relative angle, of satellites in different panels are continuous changes. Thus, compared with traditional microwave ISL, the construction of an optical satellite link is more complicated. It needs acquisition, pointing and tracking (APT) process, which are time-consuming and energy-intensive. The relative position of two satellites in NeLS is shown in Fig. 3. As shown in Fig. 3, the building of a laser inter-satellite link subjects to the constellation dynamics. Also, the APT process is affected by multiple factors, including the vibration of satellite platform and high-energy particles in the space environment. Here, we will explain the topology control constraints with an ESA space mission SILEX. As shown in Fig. 4, the laser

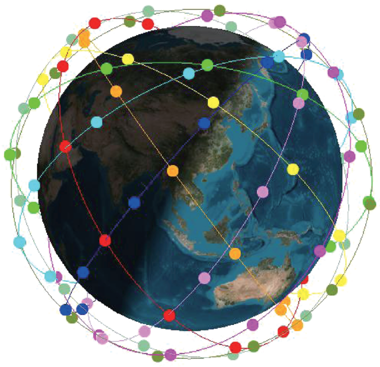

Fig. 2 The constellation of NeLS
图 2 NeLS 星座示意图

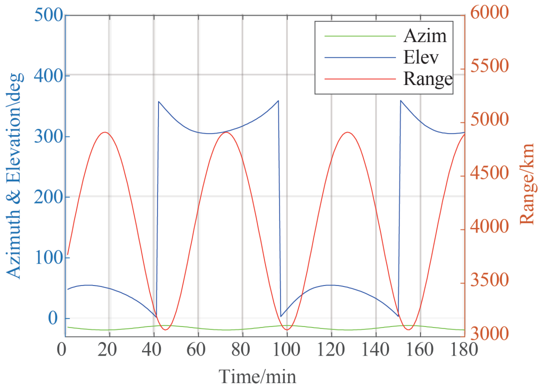

Fig. 3 Relative positions of two satellites on adjacent panels of NeLS
图 3 NeLS 星座相邻轨道两颗邻居卫星的相对位置变化图

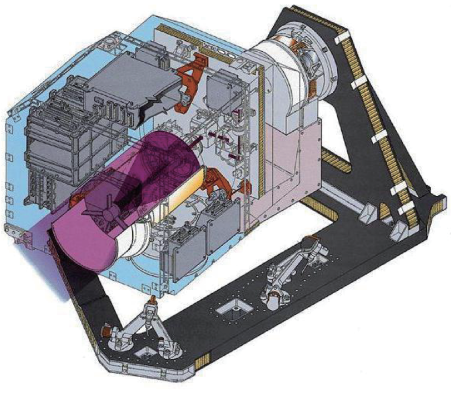

Fig. 4 Laser terminal PASTEL on SPOT-4
图 4 SPOT-4 卫星激光终端 PASTEL

Table 1Parameters of ASTEL on SPOT-4
表1 PASTEL性能参数

Acquisition	Range	
	Accuracy	
Pointing	Range	
	Time	130 s
	CCD	Pixels, 30 Hz
Tracking	Accuracy	238
	Control Bandwidth	148 Hz
	CCD	Pixels, 1/4/8 kHz

inter-satellite communication was performed between two satellites: ARTEMIS (GEO) and SPOT-4 [13], and the later carried a laser terminal named PASTEL[14]. The parameters of the PASTEL are given in the Table 1. As shown in Table 1, in the topology control of OSN, the acquisition range of the PASTEL fits the demand of Laser ISL switching well. However, the pointing process will cost more than two minutes. It will bring temporary interruption of the inter-satellite communication and then reduce the performance of the whole satellite networks. What's more, due to volume and weight limitation, the number of on-board optical transceivers is limited. In another word, the OSN is a dynamic degree-constricted network. Meanwhile, the on-board electric power of a satellite is limited. To sum up, the ISL building of OSN shows higher complexity and performs more recourse consuming than the traditional one. Thus, the number of times the transceiver moves should be considered in the topology control scheme design.

In the past decades, topology control problem in free space networks (FSO) had been studied by many research groups. Fang Liu first proposed a bootstrapping algorithm for Free Space Optical network[15]. Then, algebraic connectivity was adopted as robustness measure in building a k-degree constrained robust spanning tree[16]. Also, the problem was formulated into an integer linear programming (ILP) problem. A modified algorithm for this problem was proposed by Zhou[17], and the new scheme was proved to have a lower computational complexity and less transceiver movements. As for satellite networks, to deal with the mobility of satellites, the topology control of satellite networks has been studied as a part of routing strategy[18-20]. The schemes include the centralized virtual topology strategy proposed by Fischer[21-22], virtual node strategy by Mauger and Ekici[23-24], covering domain partition by Hashimoto. In recent years, the topology control of satellite networks start being treated as an independent problem, especially in OSN. Researchers from Air Force Engineering University of China investigated the topology control problem of optical satellite networks[25]. And a distributed minimum spanning tree (DMST) algorithm was proposed. Both single layer satellites system and multi-layer satellites system were considered. Also, the algebraic connectivity maximization for optical satellite networks was studied[26]. In this work, perturbation theory and convex optimization theory were adopted to solve the topology optimization problem. The schemes proposed by Zheng are centralized based, which need the support of word-spread ground stations. However, as indicated by academicians Zhang Nai-Tong, due to some political and economic reasons, unlike United States, it is difficult for China to build worldwide ground stations. Thus, a distributed scheme with self-organized ability needs to be developed.

In this article, a robust OSN topology control scheme for ORS applications is proposed. Especially, the topology control operation is divided into two processes, including a distributed initiation algorithm and a centralized reconfiguration algorithm. The rest of this paper is organized as follows. In Sect. 2, the related problem statements are given, and the weighted algebraic connectivity maximization problem is discussed. In Sect. 3, the distributed construction of OSN (DCOSN), modified network enhance algorithm (MNE) and dynamic network reconfiguration algorithm (DNR) are proposed. Also, their computation complexities are given. In Sect. 4, the proposed scheme is evaluated via simulations and results are discussed. Also, in Sect. 5, the effectiveness of the scheme is discussed, and several special cases are given, in which the proposed scheme does not work. At the end, Sect. 6 concludes this paper.

1 Problem statement

1.1 System model

The establishment of a satellite link is completed by optical beam transceiver. And the neighbor discovery is completed by modulated beacon hardware. Also, we assume that the transceivers are able to rotate 360 degrees. The beacon transceiver is omnidirectional, and can be used to exchange the location and other necessary information (such as IP address) of a satellite.

As mentioned, both the bootstrapping and the reconfiguration of the OSN are considered. First, the DCOSN forms a spanning tree with isolated satellite nodes. Then, the MNE extends the spanning tree to a better-connected graph with circle links. Since the final goal is to construct a dynamic robust network. At last, the reconfiguration process is completed in the DNR.

In ORS applications, there are several cases during the operation of an OSN:

- New satellites are launched
- One or more satellites fail (e. g. , by attack)
- Inter-Satellite link fails (e. g. , by attack or optical transceiver fault) or recoveries.
- The quality of a satellite link changes (e. g. , by orbit dynamics).

1.2 Problem formulation

The proposed algorithm is expected to handle all the dynamics of the OSN. As mentioned, since the PAT process is time and electric-power consuming, the total movements of the optical transceiver caused by link dynamic should be noted. Also, compared with other FSO networks on ground, an inter-satellite link covers a larger distance. Therefore, we should pay attention to the power consuming in the transmission process. What's more, due to the orbit characters of satellite networks, the movements of satellites are predicable, thus the visibility can be obtained during the operations.

To describe the OSN, let $G=(V, E)$ denote the weighted undirected simple graph and the vertices the satellite nodes, and $w=(v_i, v_j)$ (w_{ij}, for short) be the weight of an edge $v_i, v_j \in E$, which indicates the strength of an inter-satellite link. The details of the edge weight calculations will not be discussed here. Then, we get the adjacent matrix $\boldsymbol{A}$ of the OSN, and we have

$$a_{ij} = \begin{cases} w_{ij}, & \text{if node } i \text{ and node } j \text{ are connected} \\ & \text{by an edge } e_{ij} \text{ with weight } w_{ij}; \\ 0, & \text{if node } i \text{ and } j \text{ are not connected} \end{cases} . \quad (1)$$

And, the Laplacian matrix of the graph will be:

$$l_{ij} = \begin{cases} -a_{ij} & if\ i \neq j \\ \sum_{i=1}^{n} a_{ij} & if\ i = j \end{cases} . \quad (2)$$

In 1973, Fiedler firstly studied the second small eigenvalue of the Laplacian matrix[27], which was named as algebraic connectivity and denote as $\alpha(L)$ here. The algebraic connectivity reflects some connectivity characters of a graph. The eigenvectors correspond to algebraic connectivity are called Fiedler vectors, let $y=(y_1, y_2 \cdots y_n)$ be the eigenvectors, and each sub-value y_i is called the Fiedler value of the vertex v_i.

For a partitioned graph, its algebraic connectivity will be zero. Only when it is connected, the algebraic connectivity will be positive ($\alpha(L) > 0$) By improving the value of $\alpha(L)$ through topology control, we can get a better-connected network.

Usually, vertex connectivity ($K_v(G)$) and edge connectivity ($K_e(G)$) are used to indicate the robustness of a graph. And we have[16,28-29]:

$$\frac{4}{D \cdot |V(G)|} \leqslant \alpha(G) \leqslant K_v(G) \leqslant K_e(G) \leqslant \delta(G), \quad (3)$$

where D denote the graph diameter and $V(G)$ the nodes number. And the minimum degree of the graph was marked as $\delta(G)$.

In this article, the objective of the topology control is to maximize the algebraic connectivity of the OSN. We denote the degree constraint vector of a satellite by $D_v = \{d_i\}$, where d_i indicates the number of optical transceivers for satellite i.

At the beginning of network initiation, each satellite exchanges its orbit and status information with its neighbor satellites as proposed in FSM[16]. Thus, the visibility relationship between satellites can be obtained. Let E_{vis} be the set of potential inter-satellites links. The initiation of the satellite networks can be formulated as:

$$\begin{aligned} &\text{max imize} \quad \alpha(G) \\ &\text{subject to} \quad 1 \leqslant \sum\nolimits_{eij \in \delta(x)} x_{ij} \leqslant d_v \\ &\qquad\qquad E \subseteq E_{vis} \end{aligned} , \quad (4)$$

where $\delta(x)$ is the set of edges belongs to satellite v, and x is a boolean vector which indicates the adjacent set, then we have:

$$x_{ij} = \begin{cases} 1, & \text{if edge } (v_i v_j) \in E \\ 0, & \text{otherwise} \end{cases} \text{for all edges } (v_i v_j) \in E_{\text{vis}}. \quad (5)$$

Then, the initial problem will be:

$$\begin{aligned} &\text{max imize} \quad \alpha(G) \\ &\text{subject to} \quad 1 \leqslant \sum\nolimits_{eij \in \delta(x)} x_{ij} \leqslant d_v \\ &\qquad\qquad E \subseteq E_{vis} \\ &\qquad\qquad x_{ij} \in \{0,1\} \end{aligned} . \quad (6)$$

And short as:

$$\begin{aligned} &\text{max imize} \quad \alpha(G) \\ &\text{subject to} \quad 1 \leqslant \sum\nolimits_{eij \in \delta(x)} x_{ij} \leqslant d_v \quad \forall v \in V \\ &\qquad\qquad x_{ij} \in \{0,1\}^{|E_{vis}|} \end{aligned} . \quad (7)$$

Now, the original problem is formulated into a 0-1 mixed integer programming (MIP) problem, and it has been proved to be NP-hard [15,30]

In order to solve this problem with limited on-onboard computing resource. Here, we remove the 0-1 constraint, and replace with a liner constraint $0 \leqslant x \leqslant 1$. Also, the visible constraint is canceled, and then we have:

$$\begin{aligned} &\text{max imize} \quad \alpha(G) \\ &\text{subject to} \quad 1 \leqslant \sum\nolimits_{eij \in \delta(x)} x_{ij} \leqslant d_v \quad \forall v \in V \\ &\qquad\qquad 0 \leqslant x \leqslant 1 \end{aligned} . \quad (8)$$

The relaxed problem is a convex optimization problem. With a larger feasible set, it gives an upper bound solution of the original one. Also, it can be formulated as a semi -definite program as following.

$$\begin{aligned} &\text{max imize} \quad s \\ &\text{subject to} \quad s(I - \mathbf{1}\mathbf{1}^T/n) \leqslant L \\ &\qquad\qquad 1 \leqslant \sum\nolimits_{eij \in \delta(x)} x_{ij} \leqslant d_v \quad \forall v \in V \\ &\qquad\qquad 0 \leqslant x \leqslant 1 \end{aligned} . \quad (9)$$

As for the reconfiguration process, we already get a connected satellite network after the initiation process. In order to save the on orbit electric power and guarantee normal operation of the networks, here we assume that the total number of optical transceiver movement is limited. Which means a fixed number k of edge additions or deletions. Let E and $E\sim$ denote the edge set of the old and new graph, then we have

$$\begin{aligned} &\text{max imize} \quad \alpha(L) \\ &\text{subject to} \quad 1 \leqslant \sum\nolimits_{eij \in \delta(x)} x_{ij} \leqslant d_v \quad \forall v \in V \\ &\qquad\qquad E \oplus \hat{E} = \Delta E \\ &\qquad\qquad |\Delta E| = k \\ &\qquad\qquad x_{ij} \in \{0,1\}^{|E_{vis}|} \end{aligned} . \quad (10)$$

Similarly, the problem can be reformulated as

$$\begin{aligned} &\text{max imize} \quad s \\ &\text{subject to} \quad s(I - \mathbf{1}\mathbf{1}^T/n) \leqslant L \\ &\qquad\qquad 1 \leqslant \sum\nolimits_{eij \in \delta(x)} x_{ij} \leqslant d_v \quad \forall v \in V \\ &\qquad\qquad E \oplus \hat{E} = k \\ &\qquad\qquad 0 \leqslant x \leqslant 1 \end{aligned} . \quad (11)$$

For an OSN which has a small size, a standard SDP solver can be used to solve the optimization problem[31]. However, for on-board processor, it is still too complicated. Thus, several heuristic algorithms are developed to solve this problem, and the visibility constraint will be considered.

2 The heuristic algorithms

In the operation of ORS system, both the initiation and reconfiguration processes are important. In this section, these problems are solved separately. The initiation of the OSN starts from isolated nodes, while the reconfiguration starts with a connected graph.

2.1 Initiation of OSN

Distributed construction of OSN (DCOSN)

In order to construct a connected network as soon as possible, the initiation algorithm is divided into two phases. First, a degree constraint-spanning tree is formed. And then, network enhancing will be carried out. By releasing the idle degrees of satellite nodes, new edges are attached to the original network as shown in Fig. 5. After that, a better-connected satellite network will be established. As mentioned earlier, we assume that the neighbor information exchange is completed by the beacon hardware at the beginning.

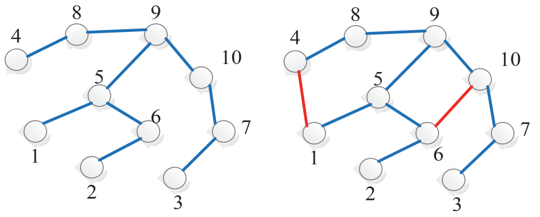

Fig. 5 Sketch maps of the modified network enhance algorithm (MNE), red edges are the new links.
图5 MNE算法效果示意图(红色边表示新增链路)

Here, we assume that no ground station is involved, thus the OSN is basically self-organized. Also, a satellite is appointed as the root satellite, the assignation may base on election or preset, the related details will not be discussed in this article. After launching, every satellite gets a unique identification and the following concepts are defined:

NetSAT, indicate a satellite already in the network

IdleSAT, indicate a satellite outside of the network

Visible, indicate a visible neighbor satellite

Candidate, indicate a Visible node still has idle transceiver

Active, indicate a status that a satellite has a Candidate neighbor.

Completely, indicate a status that a satellite link number equals to dv

NetlLink, indicate an ISL in the network

IdleLink, indicate an ISL outside of the network

And two operation processes are defined.

Initial, the Root Satellite Node wakes up and then tries to waken its neighbors. After then, every satellite node exchange orbit and link information with its neighbors, and create neighbor satellite set Visible <V_1, V_2⋯ V_n> and Constellation set <$NetSat_1$, $NetSat_2$⋯, $NetSat_m$>

Extending, Execute in the root satellite node. First, form a cycle with an **IdleLink** and delete another ISL, then turn this **IdleLink** into **NetLink**. Repeat the previous steps until this satellite node are connected and marked as NetSat.

The operation process of DCOSN is given in Fig. 6.

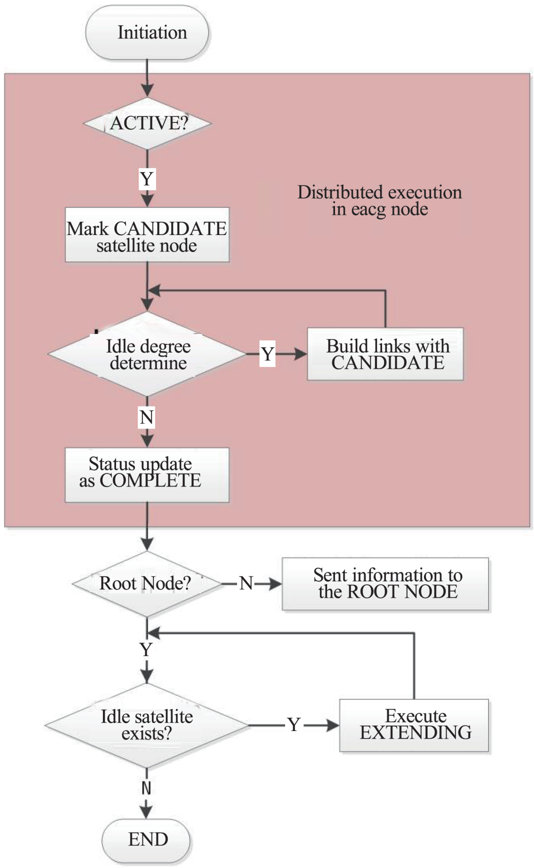

Fig. 6 Process of the DCOSN
图6 激光卫星网络的分布式初构过程

Modified network enhancing (MNE)

In this section, we try to maximize the algebraic connectivity with least transceiver movements. Enhancing edges set is proposed to describe the potential ages. For every satellite node, there are several potential edges that not included in the spanning tree described in Fig. 6. The details of the modified network-enhancing algorithm are presented in Table 2.

Table 2 The process of the MNE algorithm
表2 改进网络增强算法

Modified Network Enhancing Algorithms
Sort satellite node with their idle degrees (remaining transceiver number)
IF (Node is an Articulation)
Choose a link which gives a branch with
the minimum
ELSE
Choose another link with max
END
END

By adding the enhancing edges to the connected spanning tree, we can improve the algebraic connectivity of the OSN with least on-board resource. For each satellite node, when there are more than one enhancing edges, the operation is determined as follows:

The perturbation of unweighted graph was analyzed by Ghosh[31], and a heuristic algorithms based on Fielder Vector was proposed. Here, we prove that the similarly rules can be extended to the weighted case.

Let $\alpha(G)$ denote the algebraic connectivity of a weighted graph G, according to Ghosh, we have:

$$\alpha(G)=\min_{\substack{Y\in R^n\backslash\{0\}\\ Y^Ten=0}}\frac{Y^{\mathrm{T}}L(G)Y}{Y^{\mathrm{T}}Y}\quad,\qquad(12)$$

and

$$\alpha(G)=v^{\mathrm{T}}L(G)v\quad,\qquad(13)$$

where V is a normalized eigenvector corresponding to algebraic connectivity, and usually be called “Fiedler Vector”. And Y is a $n\times1$ column Vector.

In this section, we mainly concern about the change of $\alpha(G)$ when edges are added to the existing network. When edge e is added, the increase of $\alpha(G)$ can be determined by its partial derivative with respect to variable x_e According to Eq. 13, we have

$$\frac{\partial}{\partial x_e}\alpha(G)=v^{\mathrm{T}}\frac{\partial L(x)}{\partial x_e}v\quad.\qquad(14)$$

The weighted Laplacian matrix of a weighted graph is:

$$L=L_0+\sum\nolimits_{e=1}^{e=m}x_e\cdot w_e\cdot h_e\cdot h_e{}^{\mathrm{T}}\quad.\qquad(15)$$

Combine Eqs. 14-15. Since the original Laplacian matrix $\boldsymbol{L}_0$ is unrelated with x_e, we can obtain:

$$\begin{aligned}\frac{\partial}{\partial x_e}\alpha(G)&=v^T\frac{\partial L(x)}{\partial x_e}v\\&=v^T\frac{\partial\left(\sum\nolimits_{e=1}^{e=m}x_e\cdot w_e\cdot h_e\cdot h_e{}^{\mathrm{T}}\right)}{\partial x_e}v\\&=v^{\mathrm{T}}(w_e\cdot h_e\cdot h_e{}^{\mathrm{T}})v\\&=w_e(v^{\mathrm{T}}h_e)(h_e^{\mathrm{T}}v)\\&=w_e\left(v_i-v_j\right)^2\end{aligned}\quad.\qquad(16)$$

The formula above gives the derivative of $\alpha(G)$ with respect to x_e. Let v_i denote the i_{th} items of the Fiedler Vector. Among the remaining edge candidates, if we choose the edge that gives the maximal $w_e(v_i-v_j)^2$ every time, then we can always have the most robust network during the operations. The details of the heuristic search based algorithm MNE is listed in Table 2.

In real operation of the satellite networks, the calculation for perturbation action is time-consuming, and the decision-making requires global topology information. Since the topology is always in dynamic and the distance between satellites is long, the global topology information gathering is resource consuming and the delay caused by data transformation may up to several hundred milliseconds. According to some research results in linear algebra [28-29], the calculation of the Feidler Vector can be simplified in some specific situations.

Let $\boldsymbol{v}$ be a point of articulation, also named cut point, in weighted graph $\boldsymbol{G}$. And let $C_1,C_2,\cdots,C_k$ denote the connected components of $\boldsymbol{G}$ at $\boldsymbol{v}$. Let $C=U_{l=1}^{j}C_{il}$, where i_1. $i_1,\cdots,i_1\in\{1,2,\cdots,k\}$ Let M be the bottleneck matrix of C. By replacing C with a single connected component $\tilde{C}$, we got a new bottleneck matrix $\tilde{M}$ and form a new graph $\tilde{C}$. And let $\alpha(G)$ and $\alpha(\tilde{G})$ be the algebraic connectivity of the old and new graph.

According to theorem 2. 4 and 2. 5 in Ref. 31, if $(L(C))^{-1}=M>\tilde{M}$, then we have $\alpha(G)\leqslant\alpha(\tilde{G})$

To sum up, if we can find the branches, which includes both the articulation and candidate edges. And choose a branch, which gives a smaller bottleneck matrix. Then we will get a graph with lager algebraic connectivity.

Let p_{ij} be the path for node i to j. The set of a bottleneck matrix is defined as: $\sum\nolimits_{e\in p(i,j)}1/w(e)$. Where $p(i,j)$ represents the set of the ages both on the p_{iv} and p_{jv} [17]. Here we assume node i is the candidate node in another side of an candidate edge $p(i,v)$.

If the candidate node $\boldsymbol{i}$ is on the path p_{jv}, then the change of $\sum\nolimits_{e\in p(i,j)}1/w(e)$ will be the same with $\sum\nolimits_{e\in p(i,i)}1/w(e)$:

$$\Delta\sum\nolimits_{e\in p(i,j)}1/w(e)=\Delta\sum\nolimits_{e\in p(i,i)}1/w(e)\quad.\qquad(17)$$

Otherwise, the $\sum\nolimits_{e\in p(i,j)}1/w(e)$ will remain the same. In this way, for every candidate edge, we only need to calculate the $\sum\nolimits_{e\in p(i,i)}1/w(e)$ instead of the whole bottleneck matrix.

2. 2 Dynamic network reconfiguration

The reconfiguration of the OSN is expected to handle both the on-orbit failure and network dynamic caused by the satellite movement. When link failures or node failures happen in a small scale, new links are built with the heuristic algorithm as described in Fig. 6. In the case of link recovery of satellite launching, the same actions are taken.

Also, due to the dynamic of satellite constellation, the qualities of ISLs are continually changed. Here, we assume that threshold Q_t, indicates the tolerance value that the quality change can be ignored. If the quality of an edge drops beyond the threshold, a new edge will be established to replace it. The edge replace process is shown in Fig. 7. The dot line indicates a candidate edge, which replaced the original edge (solid line in the left) and become a new inter-satellite link (solid line in the right).

When the on-orbit failure happens in a wide range,

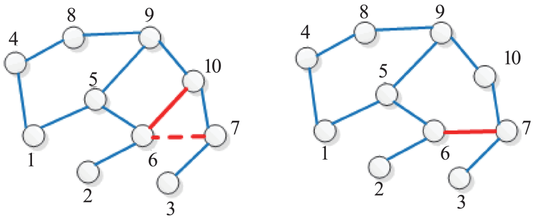

Fig. 7 The process of DNR
图7 网络动态重置过程示意图

which means many satellites are destroyed due to some external reasons (e. g. military attack), then the initiation phase will be executed. In the case of large number of satellite launching at the same time, the same action will be taken.

The process of the DNR algorithms are described in Table 3.

Table 3The process of DNR
表3 激光卫星网络动态重构算法过程

Dynamic Network Reconfiguration of OSN
For (All satellites)
If (ISL fails or link quality change exceeds)
Choose another edge with the max $w_e(v_i - v_j)^2$
IF new satellite launched
Choose an edge from the candidate edges
with the max $w_e(v_i - v_j)^2$
Else if (many satellite launched / failed or many ISL fails)
Execute the network initiation process as
described in Fig. 6.
End

2. 3 Complexity analysis

The complexity of the OSN initiation phase is $O(V^3)$. In this phase, the computational complexity of the DCOSN algorithm is $O(V*E*\Lambda)$. Where Λ denotes the maximum number of visible neighbor nodes for a single satellites. In the network enhancing process, the complexity of the MNE algorithm is $O(V^3)$. For a particular satellite node, the calculation of its bottleneck matrix takes $O(V^2)$ and the eigenvector $O(V)$.

The complexity of DNR algorithm is $O(E*V)$. For a link failure, it takes $O(V)$ to find a candidate link. Since the calculation of the eigenvector takes $O(V)$.

3 Simulations and results discussion

3. 1 Simulation setting

In this section, we evaluated the proposed algorithms and compared them with existing schemes [25-26]. Four typical LEO constellations are considered and their original microwave based inter-satellite links are replaced with optical links. Their parameters are shown in Table 4.

Table 4 Constellations used in the simulation
表4 仿真中用到的LEO星座

Constellations	Globalstar-like (2nd Gneration)	Iridium-like	NeLS-like	Teledesic-like
Panels	8	6	10	12
Satellites Number	48	66	120	288
Inclination/deg	52	86. 4	55	97. 7
Altitude/km	1414	780	1200	700

Since this work aims at the OSN topology control for ORS missions. Here we assume that the OSN is under attack, thus, the number of transceivers on each satellite is non-uniform distributed. This means the network model is not a regular graph, so the nodes' degrees are randomly distributed from 2 to 6 to describe the damaged situation. Also, the link weights are randomly chosen between 0. 5 and 1. The relative distance and visible relationship between satellite nodes are exported from STK. The rest of the simulation was implemented with MATLAB. In the Teledesic constellation, values are the averages of results from 20 simulations. In the other constellations, we repeat the simulations 50 times.

3. 2 Simulation results

As shown in Fig. 8, the network construct method DCOSN performs approximate transceiver movements with the exists scheme. Compared with the method in[23], the transceiver movements rose 17% in the Globalstar constellation, and 22% in the Iridium , 37%in the NeLS, 28% in the Teledesic. Note that in this part, the proposed scheme is distributed based. Due to the limit of local information, invalid link brings unnecessary link establishment and Link removal. Also, we find that the constellations with smaller inclinations (e. g. 52,55/deg) will generate more invalid ISLs.

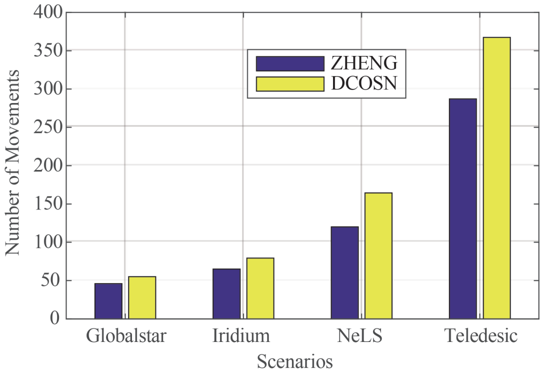

Fig. 8 Comparison of transceiver movements in different scenarios
图8 不同星座下两种方法光学终端建立链次数对比

As shown in Fig. 9, the MNE algorithm works well in the four scenarios. The algebraic connectivity mainly depends on the network size. Compared with a small one, a larger network has a much smaller algebraic connectivity. Also, a network with larger average degree will always have a larger connectivity. Especially, in the end of the network enhancing, its algebraic connectivity continually increases since a large average degree allows more edge adding. The number of edges in a network seems contributes most to the connectivity. Also, it is related with the distribution of the edge weight. In this simulation, the edges' weight are uniform distributed, and have a small difference in value. The more uneven the distribution, the more it impacts on algebraic connectivity.

The algebraic connectivity of NeLS is demonstrated

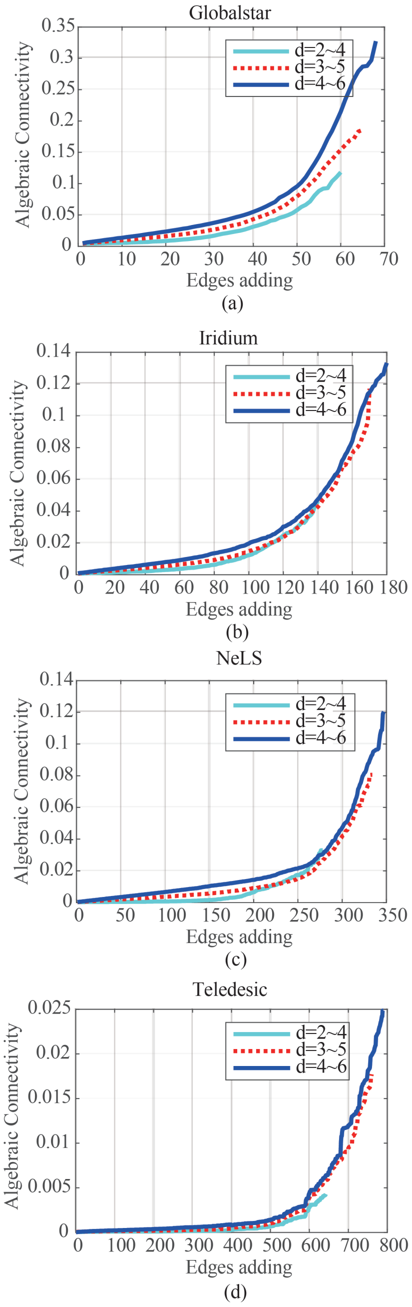

Fig.9 the MNE algorithm on deferent constellations
图9 MNE算法在不同星座上的效果

in the Fig. 10. The results show that the proposed DNR algorithm can handle the topology dynamic well and guarantee the connectivity during the operation process. As mentioned earlier in the Fig. 3, the orbit cycle of NeLS is about 100 minutes. Without loss of generality, the 3 hours' simulation can indicate the effectiveness of the proposed method well.

As shown in Fig. 11, compared with the two existing schemes, when the node degrees vary between 2~6, and the satellite number is below 80, the proposed scheme performs slightly better. In larger size networks (node number 80~200), the proposed scheme performs significant superiority. In this article, the performances are measured by algebraic connectivity, a larger algebraic connectivity indicates a better connected network.

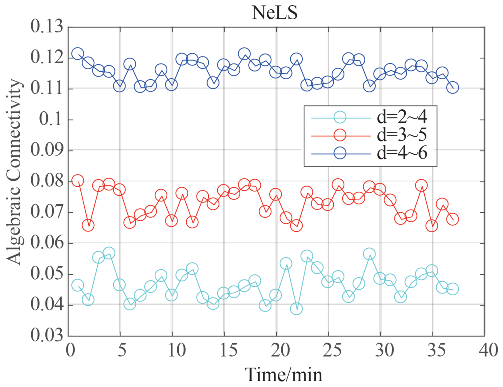

Fig. 10 The algebraic connectivity of NeLS with DNR algorithm
图10 DNR算法作用下,NeLS星座的代数连通度

4 Effectiveness and special cases

The effectiveness of the proposed scheme subject to the parameters of the satellite constellations and on-board laser terminal.

When the satellite network has a small size and satellites are sparse distributed, the link switching is limited. For example, if a satellite constellation has only 2 panels, 8 satellites on each panel, and 45-degree inclination, in most cases, the satellites in this constellation have only one or even zero inter-panel neighbors, thus, the proposed topology control cannot be performed.

As for large constellations, the key factor is the APT performance of the on-board laser terminal, especially the pointing speed of the Coarse Tracking System and Fine Aiming System. If the pointing process takes too long, it will cause serious network interruption or even real-time data loss. The judgment depends on the satellite handover period. For a satellite network which has an 8*12 polar orbit and 1200 km altitude, when the pointing phase last longer than 547 seconds (orbit period is 109 min 25 seconds, handover period=orbit period/12), the performance of the proposed Topology control method will be greatly reduced

During this work, we also find that in some special cases, the proposed algorithms cannot work effectively.

Let G be a graph, add an edge to G, and then we get $G+e$. Also, we have the eigenvalues of the two graphs:

$$\mu_n(G)\leqslant\mu_n(G+e)\leqslant\mu_{n-1}(G)\leqslant\mu_{n-1}(G+e)$$
$$\leqslant\mu_{n-2}(G)\cdots\leqslant\mu_1(G)\leqslant\mu_1(G+e)\quad, \tag{18}$$

As shown above, if $\mu_{n-2}(G)=\mu_{n-1}(G)$, then we have $\mu_{n-1}(G)=\mu_{n-1}(G+e)$.

In this case, the algebraic connectivity cannot reflect the operations of the topology control. This situation happens when the satellite network has a ring or star topology[32]. In this case, other robust measures (for example: Centrality and Kirchhoff index etc.) should be considered.

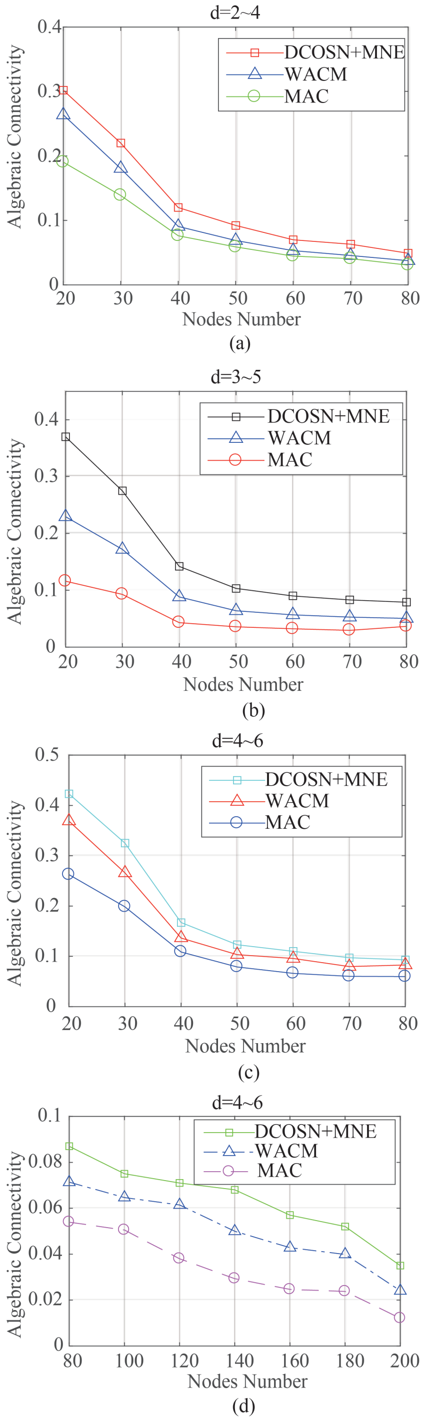

Fig. 11 Comparison of the proposed scheme with two existing schemes
图11 本文方案与两种已有方案的对比

5 Conclusions

In this article, we studied the dynamic topology control of optical satellite networks for ORS application. In order to maximize the network algebraic connectivity, a scheme, which includes both initiation and reconfiguration processes, was proposed. The formulated problem is proved to be NP-hard. Therefore, a distributed algorithm DCOSN and two centralized algorithms MNE and DNR were proposed.

As shown in the simulations, compared with the centralized schemes, the proposed bootstrapping algorithm performs approximate overhead through a distributed method. Also, during the network enhancing and dynamic reconfiguration process, the proposed algorithms have lower computational complexity. What's more, the effectiveness and limitation of the proposed methods are discussed. The impact of the laser terminal parameters on the methods' performance are discussed. Also, the inapplicable situations are indicated and alternative measures are given. The scheme proposed in this article will effectively improve the topology robustness of the satellite laser communication network, and will contribute to building a flexible and robust ORS system.

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