Network Coding Based Efficient Topology Construction and Flow Allocation Method for Satellite Networks

Ruisong Wang[1], Wenjing Kang[1], Shengliang Fang[2], and Ruofei Ma[1](✉)

[1] School of Information Science and Engineering, Harbin Institute of Technology,
Weihai 264209, China
{kwjqq,maruofei}@hit.edu.cn
[2] School of Space Information, Space Engineering University, Beijing 101416, China

Abstract. As a key component of the sixth generation (6G) communication network, satellite network has attracted extensive attention due to its advantages of wide coverage and high capacity. However, the current limited resources are difficult to meet the growing data requirements. Therefore, this paper considers a multicast satellite network and uses network coding technology to improve the resource utilization of inter satellite links. Furthermore, we are committed to optimizing network topology and coding flow allocation to improve network capacity. The proposed optimization problem is formulated as an integer linear programming problem, which is difficult to solve. In order to improve computing efficiency, we propose a heuristic topology construction and flow allocation method. The flow allocation problem is equivalent to the maximum flow problem of multiple source-to-destination pairs for a given network topology. Based on this, the topology construction method is given by iteratively deleting the links that have the least impact on the overall performance. Finally, the simulation results indicate that the proposed method can significantly improve the network capacity compared with the traditional methods.

Keywords: Network Coding · Topology Construction · Flow Allocation Method · Satellite networks

1 Introduction

In the sixth generation (6G) communication network, global seamless coverage is expected to realize with the data transmission assisted by satellite network. Especially in some remote areas, it is more necessary to use satellite networks

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to access backbone networks because of the contradiction between the growing demand and the expensive ground network deployment. However, due to limited satellite network resources, traditional data transmission methods are difficult to meet the needs of large-scale user access. Combined with satellite multicast technology, linear network coding technology may provide a solution for large-scale data transmission on satellite networks. The transmitted data will be compressed after being encoded, so the occupation of satellite link resources and storage resources can be reduced. By using multicast technology, multiple satellites can receive the same coded packet in only one transmission, and the destination satellite can successfully decode when enough coded packets are received. The failure probability of random linear network coding (RLNC) has been analyzed in [1] and the results indicates that the partial network topology information may be beneficial for the failure probability of RLNC. The authors in [2] proposed to use RLNC to improve the security of data transmission. The author in [3] considered the design problem of linear network coding from the perspective of cost and provided two distributed algorithms to solve them efficiently. Similarly, the authors in [4] aimed to maximize the secure multicast rate and proposed a topology construction method based on Lagrangian relaxation method.

Although network coding technology can improve network capacity, the upper bound of capacity is closely related to network topology. However, the satellite network topology is time-varying due to the periodic motion of satellites, which brings difficulties to topology optimization. In order to reveal the temporal and spatial relationship of satellite networks, some characterization methods have been proposed, such as time expanded graph and time aggregation graph. In [5,6], the authors applied time expanded graph to characterize the inter satellite storage resources, communication resources, and the dynamic changes of satellites in a period of time. The authors in [7,8] proposed a more efficient time aggregation graph, in which the graph size does not change with time, so it is suitable for networks with large time scales.

Inspired by the above analysis, this paper aims to apply time expanded graph to characterize the dynamic changes of satellite network and the connection between network resources. Moreover, a multicast satellite network is taken into account that sends the same content to multiple destination satellites. On the one hand, the main idea is to apply network coding technology to reduce the occupation of communication resources and storage resources during data transmission. On other hand, the main idea is to further improve the network coding capacity through topology optimization and flow allocation methods. According to the simulation results, the network capacity is significantly increased when using network coding technology and the proposed optimization scheme.

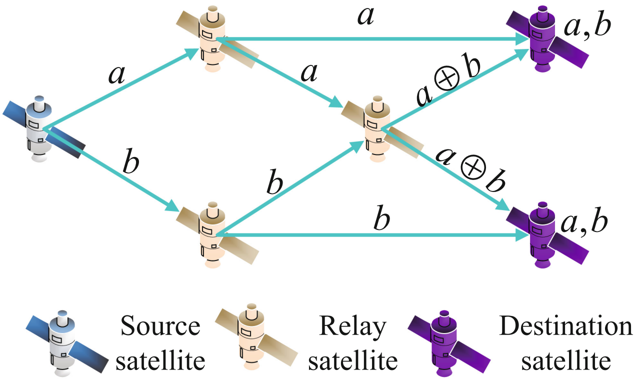

Fig. 1. System model of multicast satellite network with network coding.

2 System Model and Problem Formulation

2.1 System Model

As shown in Fig. 1, we consider a multicast satellite network, including a source satellite, some relay satellites, and multiple destination satellites. The source satellite stores some content of interest to the destination satellites and tries to deliver the content to the required destination satellites. The original information of the source satellite is first encoded and transmitted to the destination satellites through the relay satellites. After receiving the coded packets, the relay satellites will further encode these packets and forward them. Finally, after receiving enough coded packets, the destination satellites can successfully decode all the required information. In addition, due to the periodic motion of satellites, the network topology is time-varying and predictable. In order to describe the dynamics of satellite networks, we assume that the network is time-varying for a period of time, but the network can be reasonably considered as static when the time change is small. Therefore, the duration of information transmission T is divided into N time slots, in which the length of each time slot is $\tau = T/N$. The length of time slot is considered to be small enough that the change of network topology can be ignored. Let's denote the set of all satellites as $\mathcal{S} = \{s\} \cup \mathcal{R} \cup \mathcal{D}$ where s represents the source satellite, $\mathcal{R}$ denotes the relay satellites, and $\mathcal{D}$ is the set of destination satellites. Moreover, let's denotes the set of time slot as $\mathcal{N}$. Based on the above definition, the satellite network topology can be represented by a time expanded graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$. Specifically, $\mathcal{V} = \{v_i^{(t)} | v_i^{(t)} \in \mathcal{S}, t \in \mathcal{N}\}$ is the set of vertices and $v_i^{(t)}$ represents i-th satellite in the t-th time slot. The set of edges consists of two components, i.e., $\mathcal{E} = \mathcal{E}^{com} \cup \mathcal{E}^{sto}$ where $\mathcal{E}^{com} = \{e(v_i^{(t)}, v_j^{(t)}) | v_i^{(t)}, v_j^{(t)} \in \mathcal{S}, t \in \mathcal{N}\}$ is denoted as all communication edges and $\mathcal{E}^{com} = \{e(v_i^{(t)}, v_i^{(t+1)}) | v_i^{(t)}, v_i^{(t+1)} \in \mathcal{S}, t \in \mathcal{N}\}$

represents the storage edges. For each destination satellite, as long as all encoded data packets are collected within a given time, the data packet transmission is successful without losing timeliness. In fact, the vertices in graph $\mathcal{G}$ corresponding to the destination satellite in different time slots can be considered as one vertex. Therefore, we need to add some virtual vertices in the graph $\mathcal{G}$ according to this idea by letting $\mathcal{V} = \mathcal{V} \cup \widetilde{\mathcal{D}}$ where $\widetilde{d} \in \widetilde{\mathcal{D}}$ corresponds to the destination satellite $d^{(t)}$ in different time slots. After adding the virtual vertices, corresponding edges must be added to ensure the integrity of the graph. Let's denote the set of virtual edges as $\mathcal{E}^{vir} = \{e(v_i^{(t)}, v_j) | v_i^{(t)} \in \mathcal{S}, v_j \in \widetilde{\mathcal{D}}\}$ and add it to the edge set of graph $\mathcal{G}$ by setting $\mathcal{E} = \mathcal{E} \cup \mathcal{E}^{vir}$. Then, the multicast transmission problem from source satellite to destination satellites is equivalent to flow assignment problem of time expanded graph $\mathcal{G}$ between source vertex $s^{(1)}$ and destination vertex set $\widetilde{\mathcal{D}}$. Before formulating the proposed problem, we need to define the capacity of different types of edges in the graph. For the communication edges, the edge capacity should be defined as the throughput of the inter satellite link (ISL) between two satellites. Specifically, the capacity of edge $e(v_i^{(t)}, v_i^{(t+1)})$ is expressed as

$$C_{i,j}^{(t)} = \tau B \log(1 + p_{i,j}^{(t)} h_{i,j}^{(t)}) \tag{1}$$

where B is the ISL bandwidth, $p_{i,j}^{(t)}$ is the transmission power of i-th satellite in t-th time slot, $h_{i,j}^{(t)}$ is the gain-to-noise ratio (GNR) in t-th time slot. The GNR $h_{i,j}^{(t)}$ can be calculated as

$$h_{i,j}^{(t)} = \frac{\lambda^2 G^{tr} G^{re}}{(4\pi l_{i,j}^{(t)})^2 \kappa B \varGamma} \tag{2}$$

where λ is the wavelength, G^{tr} and G^{re} represent transmission gain and receiving gain respectively, $l_{i,j}^{(t)}$ is the distance between two satellites, κ is the Boltzmann's constant, and $\varGamma$ is the noise temperature.

For the edge $e(v_i^{(t)}, v_i^{(t+1)})$, the edge's capacity is equivalent to i-th satellite's storage capacity ST_i. For the virtual edge $e(v_i^{(t)}, v_j)$, the edge's capacity is infinite because two vertices represent the same satellite.

2.2 Problem Formulation

It can be noted that the actual information flow has been compressed due to the encoding operation at each satellite. At this time, the inflow and outflow of each node are not necessarily equal. However, the amount of encoded flow to be sent to given destination satellite will follow the flow balance constraint at each node. Hence, we define $x(v_i^{(t)}, v_j^{(t)}, \tilde{d})$ as the amount of encoded flow of which the destination satellite is $\tilde{d}$ through the ISL $e(v_i^{(t)}, v_j^{(t)})$. Then, the flow balance constraint is expressed as

$$\sum_{v_j^{(t)} \in \mathcal{S}} x(v_i^{(t)}, v_j^{(t)}, \tilde{d}) = R_{\tilde{d}}, v_i^{(t)} = s, t = 1 \tag{3}$$

$$\begin{aligned}&\sum_{v_j^{(t)}\in\mathcal{S}} x(v_i^{(t)},v_j^{(t)},\tilde{d})+x(v_i^{(t)},v_i^{(t+1)},\tilde{d})\\=&\sum_{v_j^{(t)}\in\mathcal{S}} x(v_j^{(t)},v_i^{(t)},\tilde{d})+x(v_i^{(t-1)},v_i^{(t)},\tilde{d}),v_i^{(t)}\neq s,t\in\mathcal{N}\end{aligned}\tag{4}$$

$$\sum_{v_j^{(t)}\in\mathcal{D}} x(v_j^{(t)},v_i,\tilde{d})=R_{\tilde{d}},v_i=\tilde{d}\tag{5}$$

where the constraint (3) indicates that the outflow of the source satellite is equal to the total amount of data it will send, the constraint (4) means that the inflow and outflow of each node are equal, and the constraint (5) indicates that the coded data packets collected by the target satellite in a given time are sufficient.

Although satellites may be visible to multiple satellites, each satellite can only establish a limited number of ISLs due to the limited number of antennas. Hence, we define a binary variable $a(v_i^{(t)},v_j^{(t)})$ where $a(v_i^{(t)},v_j^{(t)})=1$ indicates that the ISL $e(v_i^{(t)},v_j^{(t)})$ has been established and otherwise $a(v_i^{(t)},v_j^{(t)})=0$. Then, we have

$$\sum_{v_j^{(t)}\in\mathcal{S}} a(v_i^{(t)},v_j^{(t)})\leq A_{out}\tag{6}$$

$$\sum_{v_j^{(t)}\in\mathcal{S}} a(v_j^{(t)},v_i^{(t)})\leq A_{in}\tag{7}$$

For a given ISL $e(v_i^{(t)},v_j^{(t)})$, the actual amount of data passing through is equal to the maximum amount of all encoded packets. Because the throughput of the ISL is limited, the actual data throughput cannot exceed the ISL throughput. Hence, we have

$$\max_{\tilde{d}\in\tilde{\mathcal{D}}} x(v_i^{(t)},v_j^{(t)},\tilde{d})\leq a(v_i^{(t)},v_j^{(t)})C_{i,j}^{(t)}\tag{8}$$

Similarly, if the code packet cannot be transmitted to other satellites in time, it can be temporarily stored in the current satellite, but the storage amount cannot exceed the maximum storage capacity. Hence, we have the following constraint.

$$\max_{\tilde{d}\in\tilde{\mathcal{D}}} x(v_i^{(t)},v_i^{(t+1)},\tilde{d})\leq ST_i\tag{9}$$

The purpose of this paper is to maximize the coding capacity by optimizing the establishment of ISLs $\mathbf{a}=\{a(v_i^{(t)},v_j^{(t)})\}$, the flow allocation $\mathbf{x}=\{x(v_i^{(t)},v_j^{(t)})\}$, and the coding capacity $\mathbf{R}=\{R_{\tilde{d}}\}$. According to the linear network coding theory, the coding capacity of satellite networks is equal to the minimum amount of the flow to different destinations. Overall, the optimization problem is given as follows.

$$\begin{aligned} &\max_{\mathbf{a},\mathbf{x},\mathbf{R}} \ \min_{\tilde{d}\in\widetilde{\mathcal{D}}} R_{\tilde{d}} \\ &\quad s.t.\ (3)-(9) \\ &\qquad a(v_i^{(t)}, v_j^{(t)}) \in \{0,1\} \end{aligned} \tag{10}$$

The proposed optimization problem obviously belongs to integer linear programming, so there is usually no efficient method to obtain the optimal solution. Therefore, this paper focuses on designing an efficient algorithm to obtain suboptimal solutions. Once the variable **a** is given, the optimization problem is transformed into a linear programming so that it is easy to solve. So we are committed to an efficient topology construction method to optimize variable **a**.

3 Heuristic Topology Construction Method

In this section, we propose a topology construction method that starts with a completed network topology and continues to delete the ISLs until a feasible network topology is obtained. The main idea of topology construction method is to delete the ISL that has the least effect on the overall performance. In order to evaluate the importance of different ISLs, we propose a weighting method by considering the characteristics of the encoded fow.

The proposed algorithm consists of three steps. The first step is to build a complete network topology, the second step is to define the weight of each ISL, and the third step is to iteratively delete redundant ISLs.

1) Complete network topology construction: It is assumed that the ISL can be established as long as two satellites are visible, which indicates that the variable **a** has been given. Then, the original optimization problem can be decomposed into several parallel subproblems.

$$\max_{\mathbf{x},\mathbf{R}} \ R_{\tilde{d}} \tag{11}$$

$$s.t. \sum_{v_j^{(t)}\in\mathcal{S}} x(v_i^{(t)}, v_j^{(t)}, \tilde{d}) = R_{\tilde{d}}, v_i^{(t)} = s, t = 1 \tag{11a}$$

$$\sum_{v_j^{(t)}\in\mathcal{S}} x(v_i^{(t)}, v_j^{(t)}, \tilde{d}) + x(v_i^{(t)}, v_i^{(t+1)}, \tilde{d}) \tag{11b}$$

$$= \sum_{v_j^{(t)}\in\mathcal{S}} x(v_j^{(t)}, v_i^{(t)}, \tilde{d}) + x(v_i^{(t-1)}, v_i^{(t)}, \tilde{d}), v_i^{(t)} \neq s, t \in \mathcal{N} \tag{11c}$$

$$\sum_{v_j^{(t)}\in\mathcal{D}} x(v_j^{(t)}, v_i, \tilde{d}) = R_{\tilde{d}}, v_i = \tilde{d} \tag{11d}$$

$$x(v_i^{(t)}, v_j^{(t)}, \tilde{d}) \leq a(v_i^{(t)}, v_j^{(t)}) C_{i,j}^{(t)} \tag{11e}$$

$$x(v_i^{(t)}, v_i^{(t+1)}, \tilde{d}) \leq ST_i \tag{11f}$$

It can be seen that the optimization problem (11) is equivalent to the maximum flow problem from the source satellite s to the destination satellite $\tilde{d}$, so it can be solved well with the current method. Then, aiming at the pairs $\langle s, \tilde{d}\rangle$ of different source satellite and destination satellite, we can get the amount of maximum flow $R_{\tilde{d}}$ and corresponding coding flow allocation $\mathbf{f}$ through different ISLs.

2) Weight design method: When a ISL is deleted, the amount of maximum coding flow corresponding source-destination pair will be reduced. Specifically, for the source-destination pair $\langle s, \tilde{d}\rangle$, the amount of maximum coding flow will be decreased to $R_{\tilde{d}} - f(v_i^{(t)}, v_j^{(t)}, \tilde{d})$. Then, according to linear coding theory, the actual network throughput is expressed as $\min\limits_{\tilde{d}\in\widetilde{\mathcal{D}}}\{R_{\tilde{d}} - f(v_i^{(t)}, v_j^{(t)}, \tilde{d})\}$ after deleting the ISL $e(v_i^{(t)}, v_j^{(t)})$. In addition, the original network throughput is $\min\limits_{\tilde{d}\in\widetilde{\mathcal{D}}}\{R_{\tilde{d}}\}$ before deleting the ISL $e(v_i^{(t)}, v_j^{(t)})$. Moreover, the weight of ISL $e(v_i^{(t)}, v_j^{(t)})$ can be defined as the difference between the original throughput and the modified throughput. Hence, we have

$$w_{i,j}^{(t)} = \begin{cases} \min\limits_{\tilde{d}\in\widetilde{\mathcal{D}}}\{R_{\tilde{d}}\} - \min\limits_{\tilde{d}\in\widetilde{\mathcal{D}}}\{R_{\tilde{d}} - f(v_i^{(t)}, v_j^{(t)}, \tilde{d})\}, & \text{constraints (6) and (7) are met;} \\ \infty, & \text{otherwise.} \end{cases} \tag{12}$$

In fact, the proposed weight design method actually shows the decreasing degree of the overall performance when the link is deleted. It is worth noting that the storage edge and virtual edge are not deleted in the time expanded graph because the satellite storage resource always exists, while the virtual edge does not exist in the actual satellite network.

3) Iterative ISL deletion process: According to the weight design method, it is obvious that $w_{i,j}^{(t)} \geq 0$. In particular, $w_{i,j}^{(t)} = 0$ indicates that the ISL $e(v_i^{(t)}, v_j^{(t)})$ has no effect on the overall network performance and hence can be removed.

The coding flow balance constraint is no longer valid due to deleting a ISL. To ensure that the flow balance constraint is still satisfied, we need to update the flow allocation results of the existing ISLs. We define $\Phi(v_i^{(t)}) = \{v_j^{(t)} | a(v_j^{(t)}, v_i^{(t)}) = 1, v_j^{(t)} \in \mathcal{S}\}$ to represent the satellites corresponding to incoming edges of i-th satellite in the t-th time slot. Similarly, we denote $\Psi(v_j^{(t)}) = \{v_i^{(t)} | a(v_j^{(t)}, v_i^{(t)}) = 1, v_i^{(t)} \in \mathcal{S}\}$ as the satellites corresponding to outgoing edges of j-th satellite in the t-th time slot. Furthermore, we define a matrix $\mathbf{z} = \{z(v_i^{(t)}, v_j^{(t)}, \tilde{d})\}$ to represent the degree of coding flow reduction on each ISL. Naturally, we know $z(v_i^{(t)}, v_j^{(t)}, \tilde{d}) = f(v_i^{(t)}, v_j^{(t)}, \tilde{d})$ if the ISL $e(v_i^{(t)}, v_j^{(t)})$ is deleted. Then, the amount of flow on different ISLs that should be reduced is calculated as follows.

$$z(v_k^{(t)}, v_i^{(t)}, \tilde{d}) = \frac{f(v_k^{(t)}, v_i^{(t)}, \tilde{d})}{\sum\limits_{v_k^{(t)}\in\Phi(v_i^{(t)})} f(v_k^{(t)}, v_i^{(t)}, \tilde{d})} z(v_i^{(t)}, v_j^{(t)}, \tilde{d}), v_k^{(t)} \in \Phi(v_i^{(t)}) \tag{13}$$

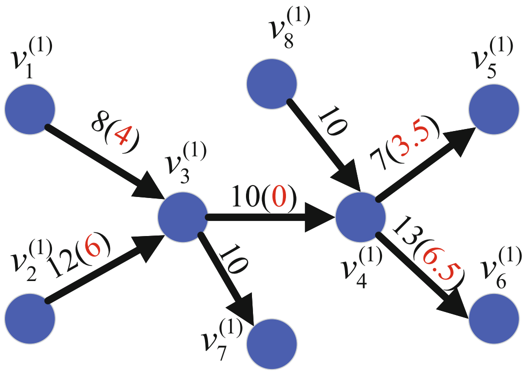

Fig. 2. Example of coding flow update method.

$$z(v_j^{(t)}, v_k^{(t)}, \tilde{d}) = \frac{f(v_j^{(t)}, v_k^{(t)}, \tilde{d})}{\sum\limits_{v_k^{(t)} \in \Psi(v_j^{(t)})} f(v_j^{(t)}, v_k^{(t)}, \tilde{d})} z(v_j^{(t)}, v_k^{(t)}, \tilde{d}), v_k^{(t)} \in \Psi(v_j^{(t)}) \tag{14}$$

Then, for the satellites $v_k^{(t)} \in \Phi(v_i^{(t)})$ and $v_k^{(t)} \in \Psi(v_j^{(t)})$, we can reconstruct their incoming set Φ and outgoing set Ψ and then recalculate the decrement according to formula (13). Finally, each ISL needs to update the flow allocation result. Hence, we have

$$f(v_i^{(t)}, v_j^{(t)}, \tilde{d}) = f(v_i^{(t)}, v_j^{(t)}, \tilde{d}) - z(v_i^{(t)}, v_j^{(t)}, \tilde{d}) \tag{15}$$

To better understand the proposed flow update method, an example is given to show the process in Fig. 2 where the black number represents the amount of the original coding flow and the red number represents the amount of the updated coding flow. Suppose that the ISL $e(v_3^{(1)}, v_4^{(1)})$ is deleted and corresponding amount of coding flow on this ISL is $f(v_3^{(1)}, v_4^{(1)}, \tilde{d}) = 10$. By the definition of $\Phi(v_3^{(1)})$ and $\Psi(v_4^{(1)})$, we can know that $\Phi(v_3^{(1)}) = \{v_1^{(1)}, v_2^{(1)}\}$ and $\Psi(v_4^{(1)}) = \{v_5^{(1)}, v_6^{(1)}\}$. Then, based on two formulas (13) and (14), the decreasing amount of coding flow is calculated as follows.

$$\begin{aligned}
z(v_1^{(1)}, v_3^{(1)}, \tilde{d}) &= \frac{8}{8+12} * 10 = 4 \\
z(v_2^{(1)}, v_3^{(1)}, \tilde{d}) &= \frac{12}{8+12} * 10 = 6 \\
z(v_4^{(1)}, v_5^{(1)}, \tilde{d}) &= \frac{7}{7+13} * 10 = 3.5 \\
z(v_4^{(1)}, v_6^{(1)}, \tilde{d}) &= \frac{13}{7+13} * 10 = 6.5
\end{aligned} \tag{16}$$

Then, the flow allocation can be updated by using the formula (15).

$$\begin{aligned} f(v_1^{(1)}, v_3^{(1)}, \tilde{d}) &= 8 - 4 = 4 \\ f(v_2^{(1)}, v_3^{(1)}, \tilde{d}) &= 12 - 6 = 6 \\ f(v_4^{(1)}, v_5^{(1)}, \tilde{d}) &= 7 - 3.5 = 3.5 \\ f(v_4^{(1)}, v_6^{(1)}, \tilde{d}) &= 13 - 6.5 = 6.5 \\ f(v_3^{(1)}, v_4^{(1)}, \tilde{d}) &= 10 - 10 = 0 \end{aligned} \tag{17}$$

Now, we have completed the whole algorithm design and summarized this process in Algorithm 1.

Algorithm 1. The Proposed Topology Construction Algorithm

```
Input: The visual relationship between satellites within a given time and the ISL
    throughput.
Output: The topology construction result a.
Solve optimization problems (11) in parallel to obtain the coding flow allocation f
    and coding capacity R.
Define the weight of each ISL according to the formula (12).
while $w_{i,j}^{(t)} == 0$ do
    Delete the ISL $e(v_i^{(t)}, v_j^{(t)})$ by letting $a(v_i^{(t)}, v_j^{(t)}) = 0$.
end while
while $\min_{i,j,t} w_{i,j}^{(t)} \neq \infty$ do
    $(i^*, j^*, t^*) = \arg\min_{i,j,t} w_{i,j}^{(t)}$.
    Delete the ISL $e(v_{i^*}^{(t^*)}, v_{j^*}^{(t^*)})$ by letting $a(v_{i^*}^{(t^*)}, v_{j^*}^{(t^*)}) = 0$.
    Calculate the decreasing amount of coding flow on each ISL by using formulas
        (13) and (14).
    Update the flow allocation result by using formula (15).
    Update the weight of each ISL by using formula (12).
end while
```

4 Simulation Results and Discussions

In this section, we provide simulation results to evaluate the effectiveness of the proposed topology construction method. We have established a LEO satellite network consisting of 3 orbits and 45 LEO satellites, of which the constellation is delta type Walker constellation and each orbit contains 15 LEO satellites. The source and destination satellites are randomly selected from 45 LEO satellites. All the simulations are the average results after 300 iterations. The parameters involved in the paper are listed in the Table 1 if there is no special description.

The proposed method is evaluated by comparing it with existing fair contact plan (FCP) methods and the case without network coding. The performance

Table 1. Parameters in Simulation.

Parameters	Value
Channel bandwidth B	20 MHz
Wavelength λ	0.125 m
Duration of time slot $\varDelta T$	30 s
The noise temperature $\varGamma$	354.81 K
Transmission antenna gain G^{tr}	10 dB
Receiving antenna gain G^{re}	10 dB
Maximum number of transmission antennas A_{out}	2
Maximum number of receiving antennas A_{in}	2
Altitude of satellite orbit	1400 km
Inclination of satellite orbit	60°

evaluation includes two aspects: one is that the network coding capacity is equal to the objective function value of the original optimization problem (10), and the other is that the total network capacity is equal to the sum of the throughput of all destination satellites, i.e., $|\widetilde{\mathcal{D}}| \min\limits_{\tilde{d} \in \widetilde{\mathcal{D}}} R_{\tilde{d}}$. Specifically, for the case without network coding, the network coding capacity refers to the minimum amount of data received by each destination satellite, and total network capacity refers to the sum of data received by all destination satellites.

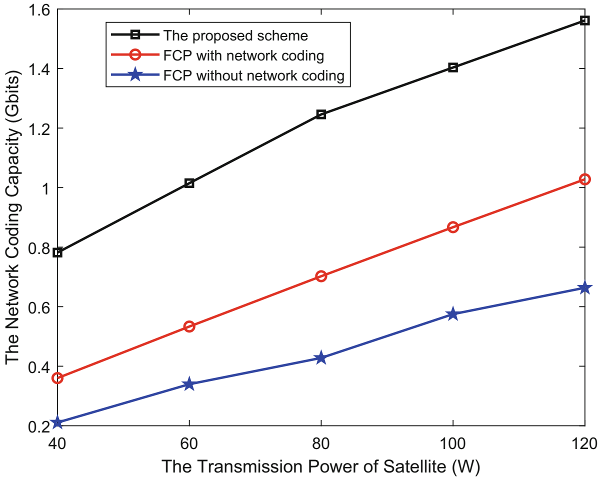

Fig. 3. Network coding capacity versus transmission power of satellite.

Figure 3 has shown the performance of network coding capacity with respect to the transmission power of satellite. It can be seen that the network coding capacity is improved with the increase of satellite transmission power. The reason is that increasing the satellite transmission power will increase the throughput of the ISLs, so more encoded packets can be passed in each time slot. Compared with the two benchmarks, the proposed topology construction algorithm has obvious advantages on improving network coding capacity. By taking the satellite transmission power of 100 W as an example, the network coding capacity with our proposed scheme is improved by 62.8% than FCP with network coding and improved by 145.6% compared with FCP without network coding.

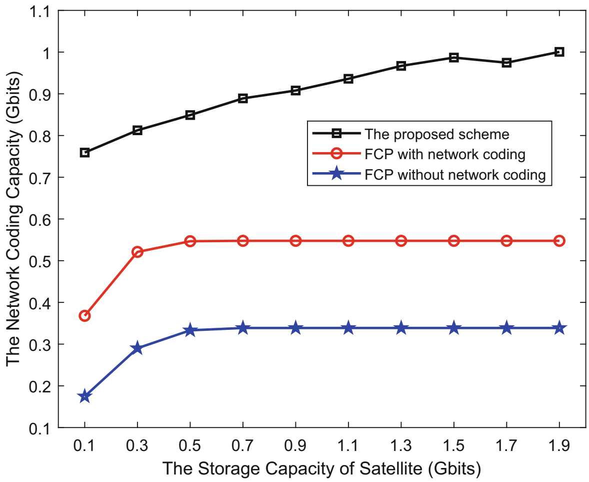

Fig. 4. Network coding capacity versus the storage capacity of satellite.

In Fig. 4, the effect of storage capacity on the performance of network coding capacity is given. It is obvious that the network coding capacity also increases when the storage capacity of satellites increases. The reason is that the storage capacity of the satellite is increased so that more data packets not transmitted are stored in the satellite to wait for a better time slot to transmit. From the perspective of time expanded graph, increasing the capacity of storage edge can increase the connectivity of network topology between different time slots, so it is possible to avoid some link bottlenecks and thus increase the network capacity. In addition, increasing storage capacity can not increase network coding capacity indefinitely. The reason is that network coding capacity is related to storage capacity and link throughput. When the storage capacity is particularly large, the link throughput becomes the limit of the network coding capacity. In terms of performance improvement, the proposed topology construction algorithm is superior to FCP with network coding and FCP without network coding.

Figure 5 has shown the change trend of network coding capacity with respect to the number of destination satellites. It can be seen that the network coding capacity decreases when the number of destination satellites increases. According to the linear network coding theory, the network coding capacity depends on

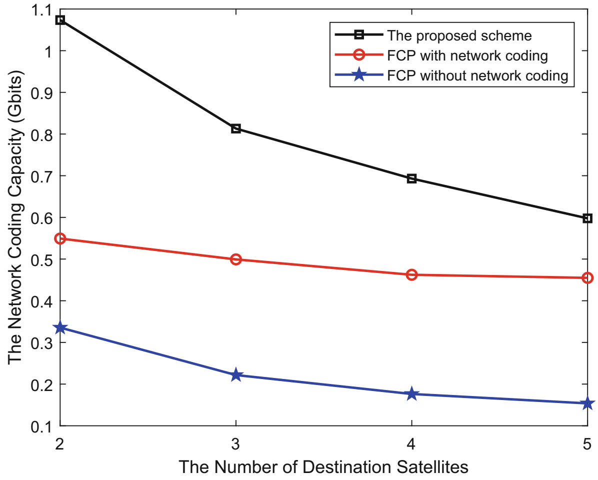

Fig. 5. Network coding capacity versus the number of destination satellites.

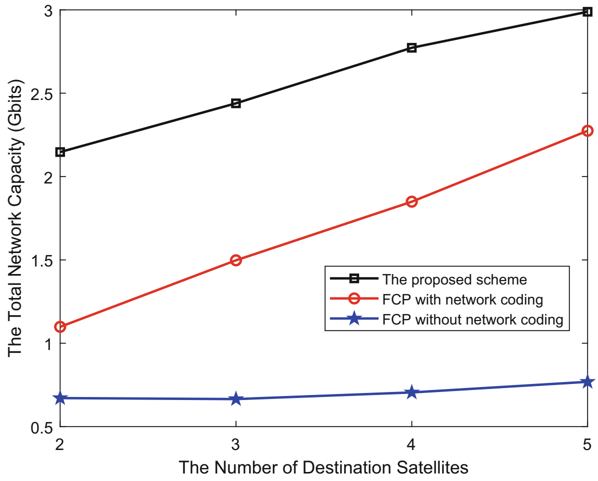

Fig. 6. Total network capacity versus the number of destination satellites.

the minimum capacity between multiple source-to-destination pairs. If the number of destination satellites is added, there is a greater possibility of encountering a link bottleneck, which will lead to the reduction of network coding capacity.

In Fig. 6, the relationship between the total network capacity and the number of destination satellites is given. It can be seen that the total network capacity increases by increasing the number of destination satellites for the case of applying network coding. The reason is that network resources are fully utilized through network coding technology, and the higher the number of destination satellites, the higher the resource utilization. However, when network coding is not used, the total network coding capacity is almost unchanged because the utilization rate of network resources is fixed, so the total network throughput is also fixed.

5 Conclusions

This paper studies the application of network coding technology in satellite multicast networks to improve network capacity. By performing the encoding operation, multiple data flows can be compressed on the satellite, thus reducing the occupation of communication resources and storage resources. Moreover, we propose a heuristic topology construction method and flow allocation method in order to improve the efficiency of network coding. From the simulation results, the network capacity is significantly improved after the network coding technology is adopted. In addition, the proposed optimization method is more effective than the traditional optimization method.

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