Network Coding-Based Capacity Optimization for Space Dynamic Network

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Abstract. Network coding (NC) scheme can effectively improve system capacity. Although NC has been widely studied and applied in terrestrial wireless networks, these researches are not suitable for space dynamic networks because of the dynamic topology and limited on-board resources. In order to make better use of on-board resource to improve the system capacity, a capacity optimization scheme is designed for space dynamic network based on network coding and power allocation. Firstly, considering a multicast scenario with single-source and multi-destination in a satellite network, and establishing a system transmission model based on linear network coding and limited power resources for the objective to maximize the multicast rate of the system. Through the analysis of the constraint conditions, the optimization problem is transformed into two sub-problems, which are to solve the maximum flow of each destination node and maximize the capacity of the key links. Finally we design a heuristic algorithm to solve these problems. Simulation results demonstrate the effectiveness of the proposed algorithm.

Keywords: Network coding · Multicast · Capacity · Power allocation · Satellite network

1 Introduction

The satellite network bears the important role of extending the ground network and expanding the communication range. Through the satellite network, it can achieve multi-dimensional coverage of air, space, ground and sea, and provide people with more efficient and comprehensive services.

However, the satellite network has the characteristics of dynamic changes in topological structure, long inter-satellite link (ISL) distance, high bit error rate, multi-hop connection, and limited resources on the satellite, which brings challenges to the research and improvement of satellite network transmission performance [1, 2]. Therefore, an efficient and reliable routing strategy is a necessary condition for achieving high-quality communication in satellite networks. In recent years, the emergence of network coding

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(NC) theory, especially the combination of coding perception ideas and network transmission technology [3–5], provides new ideas for the optimization of satellite network routing strategies.

Network coding is considered an extension of the traditional 'store-and-forward' routing technology. Before the advent of network coding, the only task of nodes in the network was to receive and forward data packets to maintain the integrity of the packets. The NC scheme allows the node to encode multiple received data packets into a single encoded packet before forwarding, which can effectively increase the transmission rate of the network [6, 7].

The existing literature on network coding is more focused on the ground wireless network environment research. However, there are big differences in the topological structure, change rules, link characteristics, etc. of the ground network and the satellite network, which leads to the fact that the existing network coding transmission scheme cannot be directly applied to the satellite network environment. In recent years, there have been some researches on the application of network coding in satellite networks. Xu *et al.* [8] introduced the DCAR scheme to the satellite communication network, and conducted a preliminary exploration of the two-layer satellite network using the coding-aware routing algorithm. Tang *et al.* [9] proposed NCMCR protocol, which uses intra-flow network coding to dynamically and coordinately transmit different parts of the same data flow along multiple disjoint paths. Giambene *et al.* [10] studied the combination of network coding and transmission protocol for mobile satellite applications. Godoy *et al.* [11] discussed the application of network coding in two typical satellite network scenarios, namely downlink multi-beam satellite network and multi-source multicast satellite network. However, the above work did not pay attention to the situation of limited power resources. When the total transmission power of a single satellite is limited, how to use network coding to increase the capacity of the satellite network is the focus of our research.

In this paper, we propose a network-coding based multicast capacity optimization scheme for satellite network. Firstly, we consider a multicast scenario with single source and multiple destinations in a satellite network. In this scenario, the source node needs to send the same piece of data to multiple destination nodes, and the destination nodes receive the data at the same rate which is called the multicast rate. This paper aims to maximize the multicast rate when the power resources of satellite nodes are limited. In order to solve this problem, the key links is defined and the problem is transformed into two sub-problems of seeking the maximum flow of each destination node and maximizing the capacity of the key links. Then solve them by utilizing the classic maximum flow algorithm and convex optimization tools. The performance of the proposed scheme is evaluated via simulations. The results demonstrate that the application of network coding in satellite networks is feasible, and the optimization method by combining network coding and power allocation can greatly improve the multicast capacity of satellite networks.

The remainder of the paper is organized as follows. In Sect. 2, we describe the system model and problem formulation. The optimization algorithm is introduced in Sect. 3. The simulation results are analyzed in Sect. 4. Finally, we conclude this paper in Sect. 5.

2 System Model and Problem Statement

2.1 System Model

This paper considers a LEO satellite network consists of M parallel orbital planes and each plane is composed of N satellites. Adjacent satellites in the same orbital plane are connected by intra-plane ISLs, and adjacent satellites in different orbits are connected by inter-plane ISLs, as shown in Fig. 1. In our target environments, a source node s transmits data to the destination node set D through the ISLs. During transmission, the NC scheme is applied to process data packets to improve network capacity. When the transmission starts, the source node divides the original packets into multiple batches containing a fixed number of packets, and then linearly combines the original packets of each batch for transmission. After receiving the coded packets, the intermediate nodes perform a new linear combination of the coded packets to generate new coded packets and then send them out. Finally, the coded packets will not be forwarded after reaching the destination nodes. If the destinations receive a sufficient number of linearly independent packets, they can decode to get the original packets.

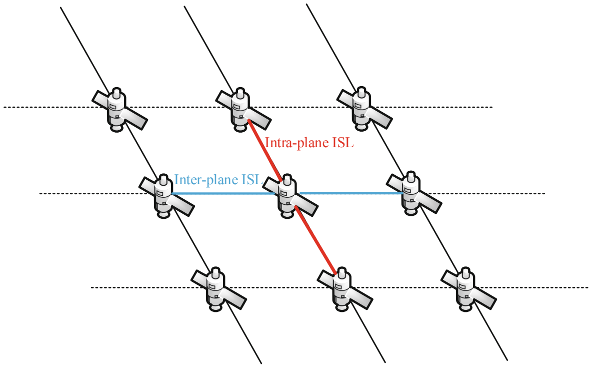

Fig. 1. A LEO satellite network topology

Moreover, we assume that all ISLs have the same bandwidth B and the total transmission power of each satellite P_{total} is the same. If the transmission power allocated to a ISL is $P < P_{total}$, the maximum transmission capacity of the link c can be calculated by Shannon Theory:

$$c = B \log_2(1 + \alpha P) \tag{1}$$

where α is the link quality factor, and we define it as follows:

$$\alpha = \frac{G}{kTBL_f} \tag{2}$$

where G is the total transmission gain containing the transmitting gain and the receiving gain, $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant, T is the Equivalent Noise

Temperature, and L_f is the free space transmission loss which is related to link length d and transmission frequency f:

$$L_f = (4\pi df/\mathcal{C})^2 \tag{3}$$

where $\mathcal{C} = 3 \times 10^8$ m/s is the speed of light.

In this paper, it is assumed that each ISL has the same parameters except the link length. Therefore, the link quality factor is determined by the link length d.

The method of time evolution graph is used to depict the dynamic changes of the satellite network in the static graph of discrete time slots. Therefore, in the research process, It is only necessary to study the general model in one time slot and then apply it in each time slot.

In a time slot, the satellite network can be considered as a static topology, and be modeled as a directed graph $\mathcal{G}(\mathcal{V}, \mathcal{E}, C)$, Where $\mathcal{V}$ is the set of satellites, $\mathcal{E} = \{(u, v)|u, v \in \mathcal{V}\}$ is the set of ISLs, and $C = \{c_{u,v}|u, v \in \mathcal{V}\}$ is the set of link capacity. If the ISL can be established between two nodes, there will be two parallel and opposite sides between them. Because the link capacity of the two sides may be different, a bidirectional link cannot be used between two nodes to represent two reverse edges.

2.2 Problem Formulation

Based on the above description of the system model, it can be determined that the problem to be solved in our research is to utilize the linear network coding (LNC) scheme to improve the multicast capacity of the satellite network in a time slot under the condition of limited power. The specific description of the problem is as follows:

$$\text{Maximize} \quad R \tag{4}$$

Subject to:

$$\delta(u, v) = \delta(v, u) = \{0, 1\}, \quad \forall(u, v), (v, u) \in \mathcal{E} \tag{5}$$

$$c_{u,v} = B \log_2(1 + \alpha_{u,v} P_{u,v}) \cdot \delta(u, v) \tag{6}$$

$$\sum_{\{v:(u,v)\in\mathcal{E}\}} P_{u,v} \le P_{total} \tag{7}$$

$$\sum_{\{u:(u,v)\in\mathcal{E}\}} r^d_{u,v} - \sum_{\{w:(v,w)\in\mathcal{E}\}} r^d_{v,w} = \begin{cases} R^d, & v = d, \forall d \in D \\ -R^d, & v = s, \forall d \in D \\ 0, & v = \mathcal{V} - \{s, D\} \end{cases} \tag{8}$$

$$r^d_{u,v} \le r_{u,v}, \forall(u, v) \in \mathcal{E}, \forall d \in D \tag{9}$$

$$R \le R^d, \forall d \in D \tag{10}$$

$$0 \le r_{u,v} \le c_{u,v}, \forall(u, v) \in \mathcal{E} \tag{11}$$

$$0 \le r_{u,v}^{d} \le c_{u,v}, \forall (u, v) \in \mathcal{E} \tag{12}$$

Objective function (4) states that the target of our research is to maximize the multicast capacity of the system. Constraint (4) is the is the constraint of link building between satellite nodes. If the link between node u and node v exists, $\delta(u, v) = \delta(v, u) = 1$, and 0 otherwise. In this paper, we determine whether the link exists by determining the visible relationship between nodes. Constraint (6) is the constraint of link capacity, where B is the link bandwidth, $P_{u,v}$ is the transmission power from node u to node v. Constraint (7) is the constraint of satellite total transmission power, which means that the power of each transmission link of node u is limited by the total power. Constraint (8) is the network flow conservation constraint for each flow between source node s and each destination node. In our hypothetical scenario, the source node only sends packets but does not receive packets, and the destination nodes only receive packets but do not forward packets. Moreover, R^d is the reaching rate of destination node d, which denotes the capacity of each flow from s to each destination d. As shown in constraint (9), $r_{u,v}^{d}$ denotes the flow rate on the link (u,v) for the data delivery from s to the destination node d, and $r_{u,v}$ is the actual flow rate of the coded packets transmitted on link (u,v), which should be no less than $\max_{d \in D} r_{u,v}^{d}$. Constraint (10) combines with objective (4), which means $R = \min_{d \in D} R^d$ and R is the multicast capacity of the system. Constraint (11) and (12) show the constraint of link transmission rate.

The above optimization problem is a nonlinear integer programming problem with many complex variables and constraints, which means that it is difficult to solve. In this paper, we disassembled the optimization problem and transformed it into two less complex problems for solution.

3 Algorithm Design

Firstly, according to the constraint (10), objective (4) can be modeled as the following problem:

$$\begin{aligned} &\max \ \min_{d \in D} R^d \\ &s.t. \quad (5) - (9), (11) - (12) \end{aligned} \tag{13}$$

It denotes that the optimization goal is to maximize the unicast rate from the source node to each destination node. And then the multicast rate is the minimal unicast rate of the destination nodes. Because with LNC, the coded packets transmitted on each ISL are available to each destination node, the multicast rate is only limited by the one with the minimal unicast rate among the destination nodes. When the capacity of each link in the network is determined, the problem is a typical maximum flow problem which can be solved by using the traditional maximum flow algorithm.

It can be seen from constraints (8), (11) and (12) that the link transmission rate is limited by the link capacity, thus affecting the throughput from the source node to the destination node. Therefore, the key to optimizing the maximum flow of each destination node is to increase the link capacity on the maximum flow path from the source node to each destination node. Among these links, the system capacity is restricted by some links whose link capacity is fully used and the remaining capacity is 0.

As shown in Fig. 2, node *S* has three paths through relay nodes *R1*, *R2* and *R3* to transmit data to node *D*, where the black arcs denote the link capacity, and the blue arcs denote the maximum flow multipath routing. Assuming that the initial link capacity of each link is 10, and in the maximum flow path, the amount of data transmitted by the source node to *R1*, *R2* and *R3* is 10, 5 and 8 respectively. Obviously, the available link capacity from node S to *R2* and *R3* is left and the available link capacity to *R1* is 0. It denotes that in the case of transmitting as much data as possible to the destination node, links (*S*, *R2*) and (*S*, *R3*) still have redundant capacity, while link (*S*, *R1*) may not have enough capacity. If the capacity of the link (*S*, *R1*) is increased, it may be able to transmit more data to the destination node. So the maximum flow from *S* to *D* is limited by the upper limit of the link capacity of (*S*, *R1*). Only by increasing the link capacity of *R1*, it is possible to improve the throughput from *S* to *D*. In this paper, we define these links as *key links*.

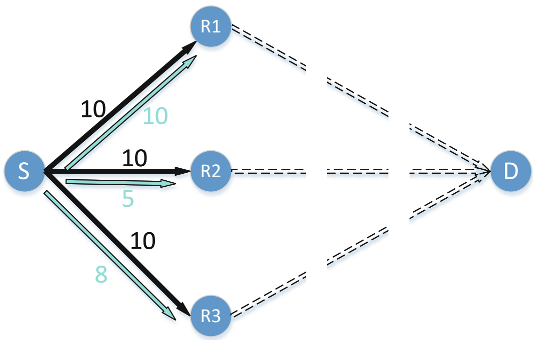

Fig. 2. An example of key links

Let *L* be the set of key links from the source node to the destination nodes. Then the problem can be transformed into:

$$\begin{aligned} &\max \sum_{\{v:(u,v)\in L\}} c_{u,v} \\ &s.t.\ \ c_{u,v} = B\log_2(1+\alpha_{u,v}P_{u,v}), \\ &\qquad \sum_{\{v:(u,v)\in \mathcal{E}\}} P_{u,v} \le P_{total} \end{aligned} \tag{14}$$

It denotes that the power resources of each satellite node should tend to be more allocated to the key links, so that the link capacity of the key links can be improved, and the bottleneck restricting the increase of the system capacity can be broken. Therefore, the problem is transformed into a typical power allocation optimization problem.

For the solution of this problem, it can be specifically divided into 3 cases:

The transmit links of a node are all in the set of key links. It means that there is no remaining power resource for this node, so there is no need to re-allocate it.

There is only 1 key link in the transmit links of a node. It means that the power resources of the other transmission links of the node are excessive. Under the condition that the transmission rate of other links is not lower than the current value, all the remaining power resources are allocated to the key link.

There are more than one key links in the transmission link of a node, and one or more links *have remaining capacity.* Let the maximum transmission rate of key links be $RK_i(i = 1, 2, ..., N)$, where N is the number of the key links. And let the maximum transmission rate of the links which have remaining capacity be $RE_j(j = 1, 2, ..., M)$, where M is the number of the links. The transmission rate of these links in the max-flow multipath routing is $RE_j^{\min}$. Then the remaining power resources are allocated to the key links under the condition that the maximum transmission rate of other links is not lower than $RE_j^{\min}$. We have:

$$\max \sum_{i=1}^{N} RK_i \tag{15}$$

Subject to:

$$RE_j = RE_j^{\min}, \forall j \in \{1, 2, ..., M\} \tag{16}$$

$$\sum_{i=1}^{N} P_i + \sum_{j=1}^{M} P_j \le P_{total} \tag{17}$$

$$RK_i = B \log_2(1 + \alpha_i P_i), \forall i \in \{1, 2, ..., N\} \tag{18}$$

$$RE_j = B \log_2(1 + \alpha_j P_j), \forall j \in \{1, 2, ..., M\} \tag{19}$$

According to the constraints (16) and (19), we can obtain P_j. Then (14) is simplified to:

$$\max \sum_{i=1}^{N} RK_i \tag{20}$$

Subject to:

$$\sum_{i=1}^{N} P_i \le P_{total} - \sum_{j=1}^{M} P_j \tag{21}$$

$$RK_i = B \log_2(1 + \alpha_i P_i), \forall i \in \{1, 2, ..., N\} \tag{22}$$

Under the condition that the transmission power of a satellite is limited and the transmission link state is known, the capacity of the key links can be maximized based on the water filling algorithm [12]. The optimal power distribution is as follows:

$$P_i = \max(\mu - \frac{1}{\alpha_i}, 0) \tag{23}$$

where is a constant that is determined by the power and the link quality factor:

$$\mu = \frac{P_{total} - \sum_{j=1}^{M} P_j + \sum_{i=1}^{N} \frac{1}{\alpha_i}}{N} \tag{24}$$

In the specific solution, we solve it by heuristic algorithm. The algorithm steps are as follows:

Algorithm 1: Algorithm for Solving Multicast Capacity based on Network Coding

1: **Input**: ISLs matrix, Inter-satellite distance matrix, source node *s*, destination nodes set *D*, link bandwidth *B*, transmission frequency *f*, total transmission power P_{total} of a satellite;
2: **Output**: system multicast capacity *R*;
3: **for** each node $u \in \mathcal{V}$ **do**
4: Obtain the number of transmission links of *u*, and then Evenly distribute the total transmission power of the node;
5: **end for**
6: According to Equation (6), to obtain the link capacity matrix *C*;
7: **for** each $d \in D$ **do**
8: $c_{d,v} = 0, \forall v \in \mathcal{V}$;
9: **end for**
10: Use the link capacity matrix as the weight matrix to construct a directed graph *G*;
11: **for** each $d \in D$ **do**
12: Obtain the capacity of the max-flow R^d and the multipath routing link set E^d from *s* to *d* in *G* by utilizing Edmonds-Karp method;
13: **end for**
14: According to the weight in the link set E^d, calculate the remaining capacity matrix *C_Re*;
15: Obtain the *key links* set *L*;
16: According to problem (14), optimize the capacity of key links and update the power allocation scheme of each node;
17: Re-execute steps 6-13 to update R^d;
18: $R = \min_{\forall d \in D} R^d$;

4 Simulation

In this section, we consider a LEO satellite network, which contains three parallel orbital planes with an orbital inclination of 60°, and each orbital plane is distributed with 3 LEO satellites with a height of 1500 km, as shown in Fig. 3.

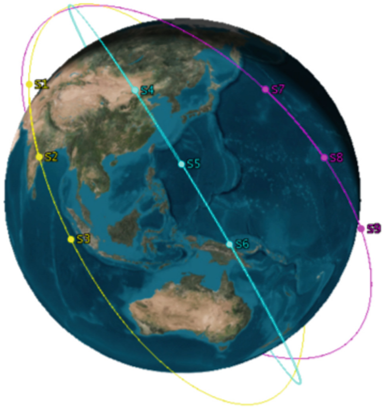

Fig. 3. A LEO satellite network

Through the simulation software STK, the visible relationship and distance between satellites can be analyzed, so as to establish the inter-satellite link building matrix and the inter-satellite distance matrix.

In this simulation experiment, we assume that the bandwidth of all ISLs equal to B, and each satellite node has the same total transmission power P_{total}. In addition, the transmission gain, antenna equivalent noise temperature and transmission frequency of each satellite are all equal, and the free space transmission loss is only determined by the distance between the satellites. The specific simulation parameters are shown in Table 1.

Table 1. Table captions should be placed above the tables.

Parameters	Value
Transmission frequency (f)	10 GHz
Bandwidth of ISLs (B)	100 MHz
Transmission gain (G)	50 dB
Equivalent Noise Temperature (T)	290 K
Total transmission power of a satellite (P_{total})	[50 W, 300 W]

The simulation examines the situation of multicasting data from one source node to two destination nodes. The total transmission power of a single satellite varies from 50 W to 300 W in steps. The source node and the destination node are randomly selected from all nodes with equal probability, and the scene corresponding to each transmission power is simulated for 1000 times and then the average value is taken.

In Fig. 4, other conditions are the same and the network coding scheme is used, and only different power allocation schemes are compared. It can be observed that with the increase of the total transmission power of the satellite, average system multicast capacity is increasing. Under the same total transmission power, the system capacity after power allocation optimization has increased by 7%–13% relative to the one with the average power allocation scheme.

In Fig. 5, other conditions are the same and the same power allocation optimization scheme is adopted, only the impact of the application of network coding on the system's multicast capacity is checked. It can be seen that with the same power, the system multicast capacity with the network coding scheme has increased by about 100% compared to the one with non-network coding scheme.

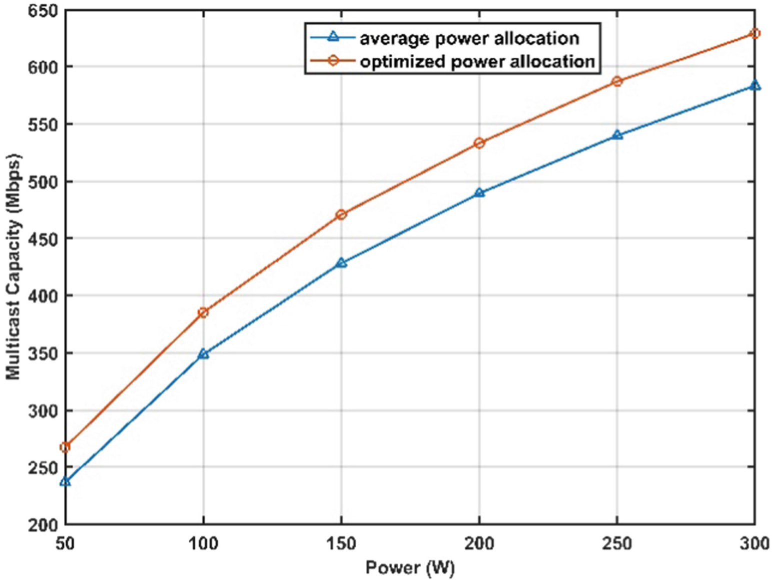

Fig. 4. Performance of optimized power allocation

The above experiments are all based on the situation where one source node multicasts to two destination nodes. In order to explore the influence of the number of destination nodes on the system capacity in the case of single source multicast, we designed a larger satellite Network, including 5 orbital planes, 5 satellites on each orbital plane, a total of 25 LEO satellites. In the simulation, we set the maximum transmission power of a single satellite to 100 W, and other parameters remain unchanged. The source node and destination nodes are randomly selected from all satellite nodes. The number of destination nodes is selected from 2 to 15, and the scenarios corresponding to each number of destination nodes are simulated 1000 times.

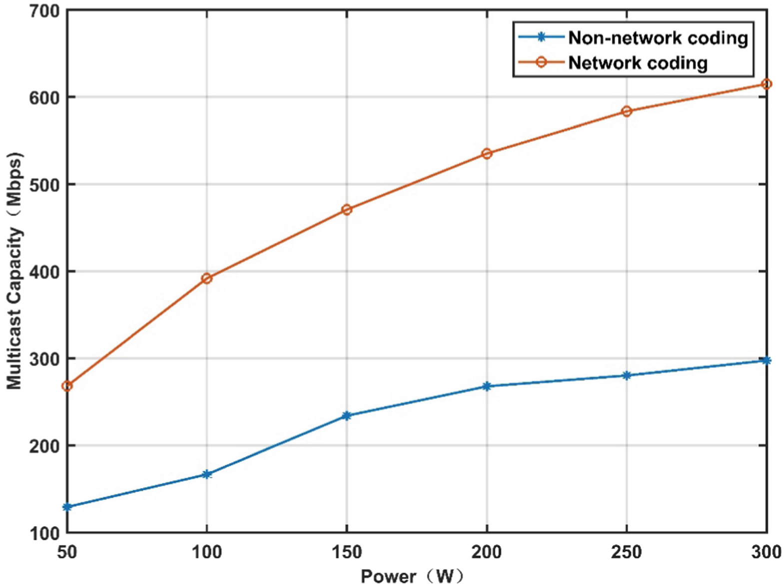

Fig. 5. Performance of network coding

The simulation results are shown in Fig. 6. With the increase in the number of destination nodes, the multicast capacity of the system continues to decrease. Because the destination nodes only receive data and do not relay data, with the increase of destination nodes, the number of relay nodes available in the network decreases, and data forwarding becomes difficult, resulting in a decrease in system capacity. But the network coding scheme has obvious relief to this kind of data congestion. It can be seen from the figure that the network coding scheme has a very obvious improvement in the system multicast capacity compared with the non-network coding scheme. Within a certain range, the more destination nodes, the higher the capacity increase rate of the network coding scheme. It fully proves the significance and practical value of the network coding scheme for the utilization of link resources in the multicast of the satellite network system.

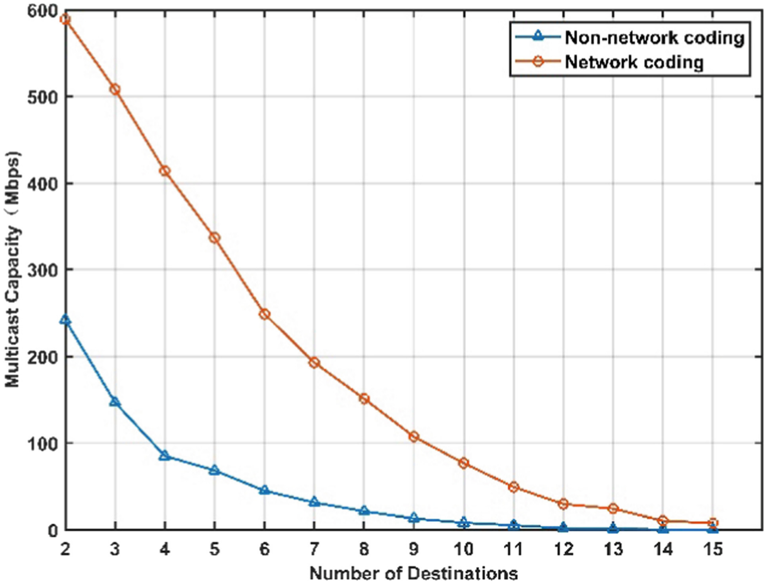

Fig. 6. Performance when the number of destinations is different

5 Conclusion

In this paper, an optimization scheme based on linear network coding and power allocation is proposed to improve the multicast capacity of satellite network. We establish a single-source multicast satellite network model based on linear network coding and power constraints. The key link is defined to solve the power allocation optimization problem, and the multicast capacity based on network coding is obtained by the method of seeking the minimal unicast max-flow. The simulation results show that in the case of limited power resources, the optimization scheme that uses a combination of network coding and power allocation can increase the system multicast capacity by about 100% compared with non-network coding schemes. Moreover, the more the number of multicast destination nodes in a certain range, the greater the improvement of the multicast capacity by the proposed scheme.

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