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Multi-objective network optimization combining topology and routing algorithms in multi-layered satellite networks

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Dear editor,

In satellite communication studies, the multi-layered satellite network (MLSN) can take advantage of both wide coverage and low time delay. Furthermore, the issue of stable networking and dynamic reconstructing methods is still worth exploring. However, current studies rarely involve the combination of the routing algorithm and the network topology. In [1, 2], two MLSN designs are introduced, but the design of the inter-satellite link is ignored. Most routing algorithms in satellite networks concentrate on improving network performance, such as quality of service (QoS) [3], computation complexity [4] and load balancing [5], but most are based on a given static topology without considering topology dynamics. This study focuses on optimizing and reconstructing the MLSN under multi-objective QoS constraints by combining topology and routing algorithms. The feasibility of combing topology and routing is analyzed. Besides, a network initialization is completed to offer an initial topology for optimization. A multi-objective optimization (MOP) model is proposed to optimize multiple QoS parameters in the routing algorithm, and a network optimization combing topology and routing algorithm is introduced. A heuristic networking scheme balances the network cost and the requirement.

Satellite network architecture. This study uses a classic MLSN architecture [2]. Assuming the constellation has enough nodes and links, six low-Earth orbit (LEO) satellite nodes under one medium-Earth satellite's coverage in the MLSN are selected to form a network architecture.

Feasibility analysis. Most routing algorithms are based on a static topology [4, 5], thus, the network topology unidirectionally affects the routing algorithm, but the effect produced by the distribution of different time delays and network bandwidths is ignored. Besides, although an optimum solution can be obtained using certain routing algorithms, resources can be wasted without reconstructing the topology. Therefore, it is necessary to combine the topology and the routing algorithm to optimize the network.

In addition, the delay represents the routing characteristics, and the stability represents topological characteristics. As defined in [6], the average delay $\overline{D}$ is the ratio of the traffic transmitted on each path multiplied by the corresponding delay

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to the total network traffic demands, as follows:

$$\overline{D} = \frac{1}{c} \cdot \frac{\sum_{i,j=1}^{n} C_{ij} \cdot R_{ij}}{\sum_{i,j=1}^{n} R_{ij}}, \tag{1}$$

where c represents the speed of light, C_{ij} represents the link cost constituted by the distance between node i and node j, as depicted in Figure 1(a), R_{ij} represents the link demand which is the real-time traffic of the link between node i and node j, and n represents the number of nodes.

From (1), the average network delay is determined by network cost and requirements, and network cost is related to the topology. If using the shortest path matrix as the weight of the adjacency matrix to represent network cost, then by multiplying it to the network demand matrix, Eq. (2) is derived. Where, $P_{mn} = [P_{mn_i}]$ is the shortest path matrix of (m, n), $R_{n\times n} = [r_{mn}]$ is the requirement matrix, and d is the distance between nodes.

$$\overline{D} = \frac{1}{c} \cdot \left\{ \sum_{m=1}^{n} \sum_{k=1}^{n} \left\{ \sum_{m=1}^{n} \sum_{j=1}^{n} P_{mn_i} [d_{\min} - \ln a_{ij} (d_{\max} - d_{\min})] \cdot r_{mk} \right\} \right\} \Bigg/ \left\{ \sum_{m=1}^{n} \sum_{k=1}^{n} r_{mk} \right\}. \tag{2}$$

The stability of a network can be measured by natural connectivity and be denoted as $\overline{\lambda}$, where $\overline{\lambda} = \ln(\frac{1}{n} \sum_{i=1}^{n} \mathrm{e}^{\lambda_i})$, and λ_i represents the eigenvalue of adjacency matrix $A_{n\times n}$. Eq. (3) is further derived, where, d_{ij} represents the distance between node i and node j. In addition, when there is no link, $d_{ij} = +\infty$. $\widetilde{A}_{n\times n} = [\widetilde{a}_{ij}]$, $\widetilde{a}_{ij} = \mathrm{e}^{-\frac{d_{ij} - d_{\min}}{d_{\max} - d_{\min}}}$.

$$\overline{\lambda} = \ln \left(\frac{1}{n} \sum_{i=1}^{n} \mathrm{e}^{\lambda_i (\widetilde{A}_{n\times n})} \right). \tag{3}$$

The average delay in (2) reflects the network routing results, and the stability in (3) reflects the network topology, and both contain the link state. Once the network link state is given, the topology is determined, thus the stability and routing results are also determined. Consequently, the topology is consistent with network stability and routing characteristics.

Network initialization. A backbone network was first established, the Prim and the Dijkstra algorithm were designed to access all the nodes, the detailed process is presented in Appendix A.

The MOP model. A routing algorithm with multiple parameters as link weight is defined as a MOP problem [7]. In this article, improving network delay, residual bandwidth, and stability are the optimization goals. Therefore, the problem became a three-objective optimization, as follows:

$$\min(C_{n\times n} \cdot A_{n\times n}, (B_{n\times n} - \widetilde{B}_{n\times n}) \cdot A_{n\times n}, -\overline{\lambda})^{\mathrm{T}} \tag{4}$$

$$\text{s.t.} \begin{cases} n - 1 \leqslant n_l \leqslant \frac{1}{2} n \cdot (n-1), \\ C_{ij} \leqslant C_T, \\ R_{ij} \leqslant R_T, \ (i,j) \in p_k, \ k \in \left[1, \frac{1}{2} n \cdot (n-1)\right], \\ \lambda_T \leqslant \overline{\lambda} \leqslant 1, \end{cases}$$

where $C_{n\times n}$ represents cost matrix, $B_{n\times n} = [b_{ij}]$, $\widetilde{B}_{n\times n} = [\widetilde{b}_{ij}]$ represents the bandwidth threshold and real-time bandwidth of network link, n_l represents the link number, C_T represents the threshold of a path cost, R_T represents the threshold of a path requirement, λ_T represents the stability threshold, and p_k represents the path set of the network. The vector function can be presented as

$$f(x) = (C_{n\times n} \cdot A_{n\times n}, (B_{n\times n} - \widetilde{B}_{n\times n}) \cdot A_{n\times n}, -\overline{\lambda})^{\mathrm{T}},$$
$$g(x) = (C_{ij} - C_T, R_{ij} - R_T, \lambda_T - \overline{\lambda})^{\mathrm{T}}. \tag{5}$$

If $R = \{x \in E^n | g(x) \leqslant 0, n - 1 \leqslant n_l \leqslant \frac{1}{2} n \cdot (n-1), \overline{\lambda} \leqslant 1\}$, the above problem becomes $\min_{x\in R} f(x)$. The problem can be further simplified to a single-objective problem: there exists a solution interval $R_a = \{x \in E^n | f_i(x) = a_i, i = 1, 2\}$, so that $f_3(x)$ obtains the optimum solution, namely, $\min_{x\in R_a} f_3(x)$. If the values a_i of $f_i(x)$ $(i = 1, 2)$ also satisfy their optimum conditions, the solution of the single-objective optimization problem is also the solution of the MOP problem. Hence, abandon the inefficient solutions in R_a, and the remaining solutions comprise the efficient solution set.

The networking optimization combining topology and routing algorithms. To optimize the network, a factor p was adopted balancing the cost and requirement, and a heuristic networking scheme was proposed as follows:

$$\min(C_{n\times n} \cdot A_{n\times n}, (B_{n\times n} - \widetilde{B}_{n\times n}) \cdot A_{n\times n}, -\overline{\lambda})^{\mathrm{T}} \tag{6}$$

$$\text{s.t.} \begin{cases} n - 1 \leqslant n_l \leqslant \frac{1}{2} n \cdot (n-1), \\ \Delta C_{ij}^{p} \cdot R_{ij}^{1-p} \geqslant (\Delta C_T^{p}) \cdot R_T^{1-p}, \\ \lambda_T \leqslant \overline{\lambda} \leqslant 1, \end{cases}$$

where ΔC_{ij} represents the amount of the cost reduction of path (i, j) after optimization and ΔC_T represents the threshold amount of the cost reduction of path (i, j) after optimization. The steps of the optimization are as follows.

Step 1, traverse the hop matrix H calculated by Dijkstra algorithm, and select the node pair (i, j) with maximum hops. Step 2, if $(\Delta C_{ij}^{p}) \cdot R_{ij}^{1-p} \geqslant \Delta C_T^{p} \cdot R_T^{1-p}$, create a new link between (i, j) , and update the value of $H(i, j)$ to 1. Else, go to step 3. Step 3, separate (i, j) into (i, k) and (k, j), and

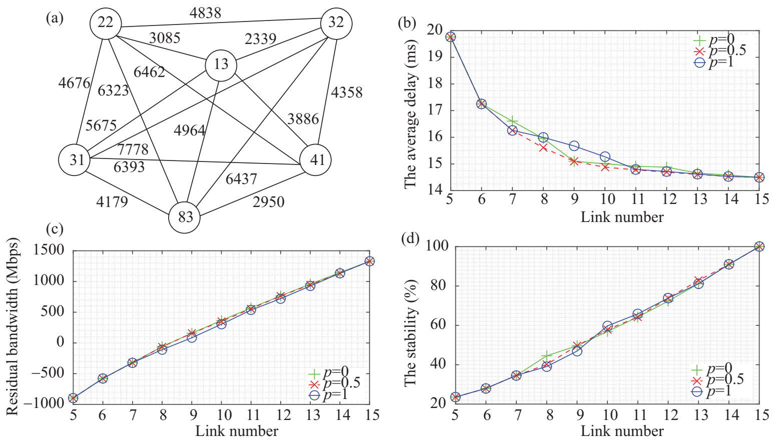

Figure 1 (Color online) (a) The network cost matrix; (b) the average delay (in ms) under different p values; (c) the residual bandwidth (in Mbps) under different p values; (d) the stability under different p values.

minimize (k, j), where (i, k)'s hop is 1 and is in the same row or column with (i, j). Let $H(i, j) = 0$, meanwhile, add $R(i, j)$ to $R(i, k)$ and $R(k, j)$. Step 4, repeat steps 1 through 3, until all the hops in H is less than 2. Then, calculate the natural connectivity $\overline{\lambda}$ and compare it with the threshold λ_T. If $\overline{\lambda} < \lambda_T$, then choose the two nodes with maximum values that are less than the threshold R_T in R, and create a new link; meanwhile, update $H(i, j)$ to 1 and $R(i, j)$ to R_T. Then, perform the iterations until $\overline{\lambda} > \lambda_T$. The pseudo-code is given in Appendix A.

Performance analysis. The simulation is implemented by MATLAB and STK. The factor p balances network cost and requirement to offer different networking schemes and compare their performances. In particular, $p = 0$ represents a maximum demand scheme; $p = 1$ represents a minimum cost scheme; and $p = 0.5$ represents a heuristic networking scheme. The simulation results are depicted as Figure 1. Figures 1(b) and (c) show that when the number of optimized links reaches 9 or 10, the link utilization of the network reaches the optimum state, and the heuristic networking scheme performs better than others. Furthermore, the stabilities of the three schemes are almost the same, as depicted in Figure 1(d).

Conclusion. We propose a MOP algorithm based on Multi-QoS in MLSN. This optimization algorithm combined the network topology and the routing scheme, and it improves the performance of the network average delay. The heuristic networking scheme has better performance than the minimum cost scheme and the maximum demand scheme. Moreover, the heuristic networking scheme can meet the needs of different network designs and provide new ideas for satellite communication research.

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Supporting information Appendix A. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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