Optimal Satellite Gateway Placement in Space-Ground Integrated Networks

Yurui Cao, Hongzhi Guo, Jiajia Liu, and Nei Kato

Abstract

The space-ground integrated network appears to be a promising solution for providing global coverage and broadband communications. Over the past several years, many pioneering research works toward space-ground integrated networks have emerged. However, it has been noticed that most existing research works have neglected the impact of satellite gateway placement on network reliability, in particular, not considering the practical capacity constraint on satellite links. In light of this, we study in this article the gateway placement problem with capacity constraint in the space-ground integrated network, and propose an enumeration scheme and a heuristic greedy scheme as our solutions. Extensive numerical results validate the efficacy of our proposed strategies.

Introduction

It has been noticed that there are many deficiencies in traditional terrestrial networks, and integrating satellite communication toward an integrated network has become a tendency in recent years. In particular, with the rapidly increasing number of customers, the load of the network is unprecedented, and network congestion occurs when the traffic amount exceeds the capacity of terrestrial links. The network infrastructure is especially vulnerable to natural disasters [1]. Furthermore, some rural and environmentally harsh areas are difficult to be covered by networks. Integrating satellite communication into terrestrial networks can solve most of these problems since the integrated network can provide wireless data access service with the benefit of providing global coverage [2] and enhancing the network performance. Moreover, satellite links with high throughput can offload the terrestrial traffic efficiently [3].

Over the past several years, many pioneering research works toward space-ground integrated networks have emerged. We have noticed that most works have mainly focused on the network performance analysis [4, 5] and promotion specifically considering different interferences [6], network traffic distribution resource management [7, 8], and secure transmission [9]. Specifically, in [6] Ruan *et al.* studied the network outage performance while undergoing hybrid co-channel interference. Vassaki *et al.* [8] proposed an efficient resource management mechanism and presented a new power allocation algorithm to optimize the effective terrestrial link capacity for given quality of service (QoS) requirements while guaranteeing a specified outage probability for the satellite link. Furthermore, to enhance secure transmission in the satellite network, An *et al.* [9] studied the physical layer security of a satellite network and adopted two beamforming schemes.

Existing works in space-ground integrated networks, although providing precious insights into satellite gateway placement optimization [10, 11], have one common limitation: most of them neglected the impact of the practical capacity constraint on satellite links on satellite gateway placement. In [10], although the authors solved the gateway placement problem to optimize the propagation latency, they only considered the terrestrial links in the network. In [11], the authors proposed two solutions to optimize the gateway placement for minimizing the network latency with the reliability constraint. Since the rapidly increasing number of users may cause network congestion and then influence network reliability, it is of great important to take the capacity of satellite links into account. To the best of our knowledge, we are the first to study how to deploy satellite gateways in the space-ground integrated network to maximize the whole network's reliability while satisfying the satellite link capacity limit.

The remainder of this article is organized as follows. We present the general architecture of a space-ground integrated network and analyze the capacitated gateway placement in the following section. Then we define the problem of satellite gateway placement with link capacity constraint and propose an enumeration scheme and a heuristic greedy scheme as our solutions. Moreover, we give extensive numerical results. The final section concludes the whole article.

Gateway Placement in Space-Ground Integrated Networks

Space-Ground Integrated Networks

As illustrated in Fig. 1, the space-ground integrated network is generally composed of two parts: the space network and the ground network. The space network mainly consists of high-throughput satellites, which may be equipped with digital channelizers and able to adjust the frequency bandwidth flexibly. Satellites use inter-satellite links (ISLs) to communicate with their neighbor satellites [10]. The space network connects with the ground network through satellite links. The mobility of satellites and inter-satellite links are not considered in this article.

The ground network is mainly composed of switches, satellite gateways, eNBs, and eNBs with

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satellite terminals. Although a traditional terrestrial network is able to provide high data rate to users, the network coverage is limited in rural and remote areas. After being integrated with satellites, traffic, if necessary, can be delivered to the satellite via gateways and eNBs with satellite terminals in areas of limited network coverage. Switches and satellite gateways mainly use fiber to establish connections among each other.

Digital Channelizer

In the process of data transmission, there are two types of satellite communication. In the first type, all traffic needs to go through satellite gateways, and the link between satellite and gateway is called the feeder link. In another type, traffic is delivered to the destination only through the satellite, using a link called the user link. In the satellite communication system, a satellite equipped with a digital channelizer can change the frequency bandwidth allocation dynamically according to the amount of communication demand. It will reduce waste of communication resource, which is strictly limited at present since the bent-pipe satellite system can only provide fixed communication resource allocation [12]. For some situations such as disaster relief, which need large-capacity communication, the satellite with digital channelizer can accordingly allocate more frequency bandwidth to the disaster area. On the contrary, in some remote and rural areas with no need for large frequency bandwidth, the channelizer will reduce the frequency bandwidth allocation. It is obvious that the satellite equipped with a digital channelizer can improve the efficiency of frequency utilization in the satellite communication system.

The digital channelizer technology is realized using frequency-division multiple access (FDMA) or multi-frequency time-division multiple access (MF-TDMA). In the satellite communication system, the uplink channel comprises a diversity of sub-signals. The digital channelizer reforms a sub-signal through separation, exchange, and combination, and sends the signal to the downlink channel. In the first type of satellite communication, the digital channelizer can multiplex the traffic data delivered from the uplink to avoid generating vacant channels and then transmit the data through downlink. Since a bent-pipe satellite has static frequency bandwidth allocation, if the amount of generated traffic is small, the downlink will have many vacant channels. In the second type of satellite communication, the satellite equipped with digital channelizer can allocate frequency bandwidth for each user link according to the traffic demands of the destination beam. Therefore, the satellite with digital channelizer has the potential to optimally allocate frequency resources to different spot beams according to the communication requests.

Capacitated Gateway Placement

In the space-ground integrated network, satellite gateways play an important role in the process of traffic delivery from ground network to space network. It is noticed that different placement of satellite gateways would produce varying network performance. Many factors like geographical locations and poor meteorological conditions can

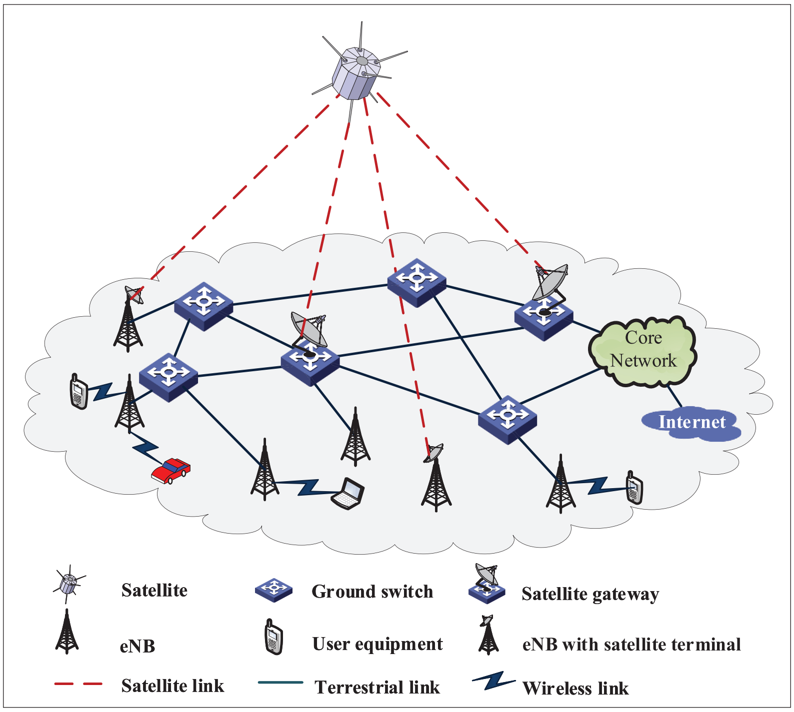

FIGURE 1. Illustration of architecture for space-ground integrated network.

cause the network nodes and links to fail. Thus, selecting the appropriate placement of gateways can enhance the network reliability [11]. Furthermore, when the traffic exceeds the capacity of a satellite link, it will result in network congestion and high delay. If the traffic is real time, the traffic will drop in the network because of the stringent delay requirement [13]. According to the above reasons, how to place the satellite gateways so as to maximize the network reliability while the upstream terrestrial traffic does not exceed the capacity limit of satellite links is worth further study. Generally, when deciding how to place the satellite gateways, we need to take into account not only geographical locations, but also the terrestrial topologies as well as the overall traffic distributions.

Capacitated Gateway Placement for Reliability Maximization

In this section, we first define the problem of gateway placement with link capacity constraint in the space-ground integrated network, and then propose two algorithms as our solutions.

Problem Definition

As illustrated in Fig. 1, we consider a scenario in the space-ground integrated network, where the traffic is transmitted to the satellite via gateways, and each satellite link has the same link capacity. Without loss of generality, only the scenario with one satellite in the network is considered in this article. We assume that there are no constraints on the bandwidth of each terrestrial link, and the communication traffic originated from each terrestrial node is randomly generated from a certain closed interval. Moreover, the traffic originated from each terrestrial node is assumed to be under each satellite link capacity constraint, and it cannot be shunted in the data transmission process.

Input: network topology and data traffic, network component failure probability, the number of satellite gateways, satellite link capacity
Output: the optimal gateway placement within given capacity constraint and the average weighted maximum network reliability; otherwise, NIL

enumerate all possible combinations of gateway placement and the traffic transmission route, and calculate the total traffic of each satellite link
discard those traffic transmission routes in the network cannot meet given link capacity constraint and calculate the average weighted network reliability
find the optimal satellite gateway placement which can achieve the maximum average weighted network reliability; otherwise, output NIL

ALGORITHM 1. An optimal enumeration placement algorithm (OEPA).

Input: $G(V, E)$, k, GP, n
Output: $\bar{r}$

Initialize $D = \emptyset$, $I = \emptyset$
sort the traffic of each terrestrial nodes in a descending order and record each associated node into D
for each switch node in D **do**
    for each gateway g **do**
        calculate the reliability from switch node to satellite via gateway g
        calculate the *ratio*
    end for
    sort *ratio* in a descending order and record each associated gateway into I
    for each gateway g in I **do**
        if traffic within the remaining link capacity **then**
            calculate the reliability from switch node to satellite via gateway g
            calculate the remaining link capacity after transferring data via g
            break
        end if
        if traffic transferred via no gateways within the remaining link capacity **then**
            abandon GP
        end if
    end for
end for
calculate the average weighted network reliability $\bar{r}$
return $\bar{r}$

PROCEDURE 1. A greedy procedure.

The number of satellite gateways to be deployed in the network only depends on the network traffic and satellite link capacity.

The number of gateways can be obtained by calculating the ratio of the total network traffic to the satellite link capacity and then rounding it up to the nearest integer. The nodes in the network comprise terrestrial nodes and a satellite node. The data originated from each terrestrial node is transmitted to the satellite via one satellite gateway. For each satellite gateway, the total traffic transported through it should satisfy the satellite link capacity.

Note that since the failure of each network component will influence the reliability of the whole network, we assume that each terrestrial node and link has its own failure probability. Thus, the reliability of each network component can be given as $r_i = 1 - f_i$, where f_i is the error rate of network component i. We only take the reliability of the path from the switch to the satellite with the minimum hops into account, since more hops will increase the failure probability of the path. For each data transmission path, we suppose that no failure resulting from the error of the original point and the destination occurs. Then the reliability of the path from each switch to the satellite via one gateway can be given by the product of r_i, where network component i is in the set of both the links and the nodes on the path except the original node and satellite.

Obviously, the total data transmitted to the satellite via the satellite gateway can affect the entire network's reliability. To quantify the impact of the traffic on network reliability, we calculate the weighted average network reliability, and let the weight denote the amount of traffic. In this article, our aim is to find an optimal set of gateway placement from the terrestrial nodes in the integrated network that maximizes the weighted average network reliability while satisfying a predefined satellite link capacity constraint. Specifically, this problem can be defined as follows.

Gateway Placement with Capacitated Constraint (GPCC): Given the initial space-ground integrated network information, such as the network topology, including component failure probability and the traffic originated from each terrestrial node as well as the capacity of the satellite link, the problem of GPCC is to find an optimal set of satellite gateways from the terrestrial nodes that maximizes the weighted average network reliability while the traffic delivered to the satellite via the satellite gateways satisfies the given capacity constraint of the satellite link.

Unfortunately, the problem of GPCC is NP-hard since it can be converted to the Knapsack problem easily. In the following, we present two algorithms to solve the GPCC problem.

Solutions

In this subsection, we present two solutions to solve the GPCC problem. To simplify our algorithm presentation, we predefine some notations as follows. Let $G(V, E)$ denote the topology of the integrated network, and V and E denote the set of network nodes and links, respectively. Let b denote the satellite link capacity, and k is the number of gateways. Let GP denote the set of satellite gateway placement.

An Optimal Enumeration Placement Algorithm: In order to address the GPCC problem, a simple solution is to enumerate all possible gateway placements and combinations of traffic transmission routes, and then to choose an optimal gateway placement that achieves the maximum network reliability within a given satellite link capacity. The details of the optimal enumeration placement algorithm are briefly described in Algorithm 1.

Obviously, in order to find an optimal solution to the GPCC problem, OEPA in Algorithm 1 has to run for a very long time due to its exponential computational complexity. As described in Algorithm 1, the time complexity of OEPA is $O(C_n^k \cdot S_2(n, k))$, where S_2 is the second Stirling number [14], and n and k denote the number of terrestrial nodes and gateways, respectively.

A Heuristic Greedy Placement Algorithm: Since the computational complexity of OEPA is so high, we further develop another heuristic greedy approximation algorithm, HGPA, which can obtain a near optimal solution to the GPCC problem. At first the algorithm generates an initial set of gateway placements GP_{opt}. Then we calculate the weighted average network reliability $\bar{r}_{max}$ in Procedure 1. We define the ratio of the reliability of the transmission path to the traffic of one switch node as *ratio* to evaluate the impact of the traffic delivered via one gateway on network reliability. Since different traffic may influence network reliability, we compute the *ratio* of each node to each gateway in order of traffic. For one switch node, larger value of *ratio* indicates that the traffic delivered via one gateway can achieve higher reliability when occupying the same capacity. Therefore, for switch node v, we select the gateway that achieves the largest *ratio* to deliver the traffic from v to the satellite. If no gateway transports the traffic from v within link capacity, this placement strategy will be abandoned.

During each iteration, we replace the placement of some gateways randomly to generate a new solution, GP_{new}. If the new solution can achieve higher network reliability, it will be accepted, and both GP_{opt} and $\bar{r}_{max}$ will be updated. To avoid running into a locally optimal solution, the new solution will be accepted with a certain probability if it obtains lower network reliability. The details of the heuristic greedy placement algorithm are shown in Algorithm 2.

Input: $G(V, E)$, b, k
Output: GP_{opt}, $\bar{r}_{max}$
1: Initialize n-the number of terrestrial nodes, $\bar{r}_{max} = 0$, Γ and Γ_{final}-parameters to control the terminal of the iteration, α-decline coefficient
2: select k terrestrial nodes as the initial gateway placement GP_{opt}
3: execute the greedy procedure in Procedure 1 to calculate network reliability $\bar{r}_{max}$
4: **while** $\Gamma > \Gamma_{final}$ **do**
5: $GP_{new} = GP_{opt}$
6: replace a certain number of gateway placement randomly to generate new set GP_{new}
7: execute the greedy procedure in Procedure 1 to calculate network reliability $\bar{r}_{new}$
8: $\Delta = \bar{r}_{new} - \bar{r}_{max}$
9: **If** $\Delta \le 0$ **OR** $e^{-\Delta/\Gamma} > Rand(0, 1)$ **then**
10: $GP_{opt} = GP_{new}$
11: $\bar{r}_{max} = \bar{r}_{new}$
12: **end if**
13: $\Gamma = \Gamma * \alpha$
14: **end while**
15: **return** GP_{opt}, $\bar{r}_{max}$

ALGORITHM 2. A heuristic greedy placement algorithm (HGPA).

Discussions

Since Algorithm 1 traverses the whole solution space, it is obvious that if there are optimal solutions to the GPCC problem, OEPA can find one of them. But the computational complexity of OEPA is very high, so it is impractical in a large-scale network.

For Algorithm 2, the running time of step 2 is $O(k)$. For step 3, which uses Procedure 1 to calculate the network reliability, its running time is $O(n\log n)$. Regarding the while loop of steps 4–14, the outer loop runs at most m times, where m denotes the number of iterations. Steps 5–6 run for an $O(1)$ time. Step 7, which calls Procedure 1, runs at most $n\log n$ times. Steps 8–13 run for an $O(1)$ time. Thus, the running time of steps 4–14 is $O(m \cdot n\log n)$. Finally, the time complexity of HGPA can be calculated by adding them up, that is, $O(m \cdot n\log n)$.

Compared to OEPA, HGPA in Algorithm 2 is a little more complex and can only give a near optimal solution to the GPCC problem, but it has much higher computational efficiency than OEPA. Therefore, OEPA is just presented as a baseline for HGPA.

Numerical Results and Discussions

Parameter Settings

Without loss of generality, we took actual online topologies from the Topology Zoo [15]. Three network topologies were adopted in our experiment: Arpanet (9 nodes, 10 links), Nsfnet (13 nodes, 15 links), and Agis (25 nodes, 30 links). The failure probability of each network component was generated randomly from the interval [0.02, 0.04]. For each terrestrial node, the traffic data was generated varying from 10 Mb/s to 305 Mb/s, and the capacity of each satellite link b was set as 300 Mb/s in Figs. 2 and 3. Note that only the case in which total traffic was less than the sum of all satellite links capacity was accepted during our experiment. To get stable performance of our algorithms, we repeated each experiment 50 times and took the average value. All experiments were performed in Matlab R2017a running on a PC with double 3.30 GHz CPUs, 8.00 GB RAM, and Windows 7 OS.

Reliability

Figure 2a illustrates the comparison results of the network reliability between OEPA and HGPA, where the X axis denotes the number of satellite gateways and the Y axis denotes the overall network reliability with satellite link

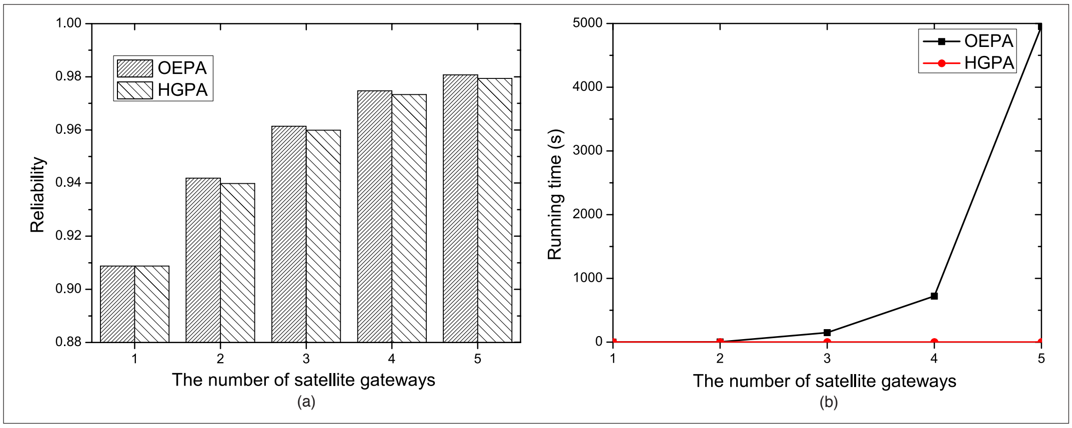

FIGURE 2. Illustration of experimental results of the network reliability and running time in the Arpanet network: a) comparisons of overall network reliability; b) comparisons of the overall running time.

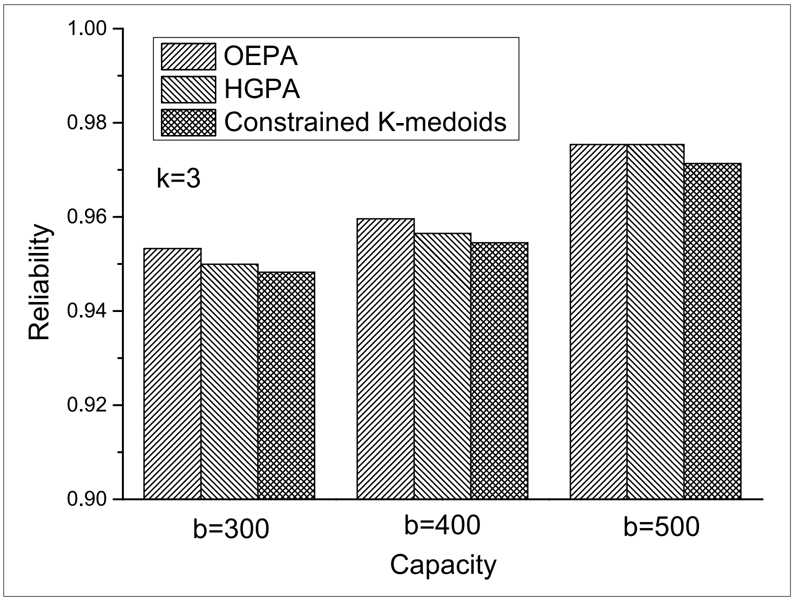

FIGURE 3. Illustration of the comparison results with different satellite link capacity constraints in the Arpanet network.

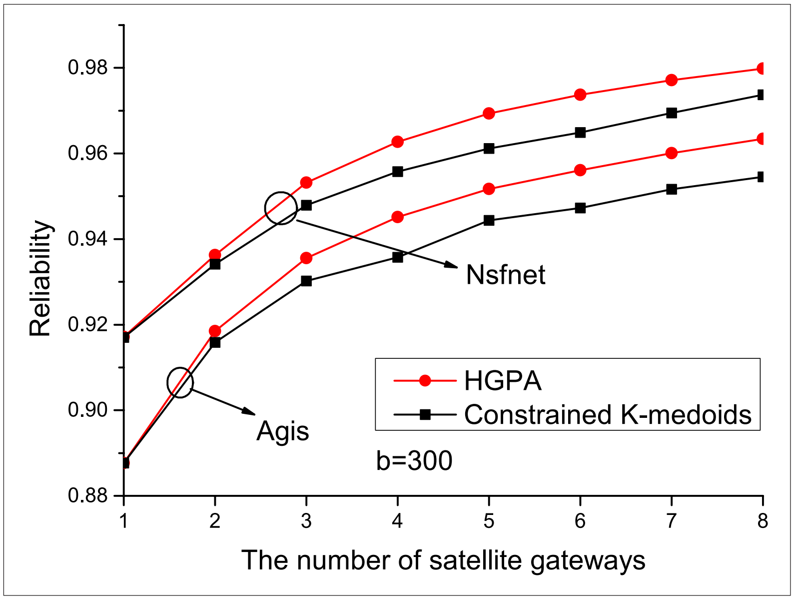

FIGURE 4. Illustration of the comparison results in different network topology settings.

capacity constraint. From the figure, one can easily observe that with the number of gateways increasing from 1 to 5, the gap between OEPA and HGPA is small, that is, HGPA can find a near-optimal solution to the GPCC problem. Moreover, we can also find that with the number of satellite gateways increasing, the reliability of the whole network grows since more gateways can reduce the hops for delivering traffic originated from each terrestrial node to the satellite.

Figure 2b illustrates the comparison results of the running time between OEPA and HGPA with different numbers of satellite gateways. From the figure, it can be observed that the running time of OEPA grows sharply, while that of HGPA increases smoothly. Obviously, HGPA can obtain a near-optimal solution with high computational efficiency. As discussed previously, the running time of the algorithm depends on the number of gateways and the scale of the network.

From the above experiments, we can see that although OEPA is simple and can give an optimal solution to the GPCC problem, it cannot be adopted in practice due to its high computational complexity. Compared to OEPA, although HGPA can only achieve a near-optimal solution, it has much higher computational efficiency than OEPA, and thus it provides a workable solution to the GPCC problem. We next evaluate the performance in different capacity and topology settings of our proposed HGPA, and compare it to a clustering algorithm with constraint (i.e., Constrained *K*-medoids).

To identify how the satellite link capacity constraint affects the maximum reliability of the space-ground integrated network, we compare the performance between OEPA, HGPA and Constrained K-medoids with different capacity settings. The number of satellite gateways k is set as 3. Since the gateway placement with optimal network reliability, which may exceed the stricter constraint, will be abandoned in the experiment, the optimal gateway placement may be different with different capacity settings.

Similar conclusion can be obtained from Fig. 3, that is, HGPA can achieve a near-optimal solution on solving the GPCC problem in integrated network compared to OEPA. Besides, we can also find that the network reliability grows when we broaden the satellite link capacity constraint. Figure 4 presents the performance of HGPA and Constrained *K*-medoids in different network topology settings. From Fig. 4, one can easily see that HGPA performs better than Constrained *K*-medoids in large-scale network settings. Furthermore, with the increasing number of network nodes and links, the network reliability decreases since more gateways can reduce the hops of the path from switch node to satellite.

Discussions

In this article, we have studied the GPCC problem in the space-ground integrated network. With link capacity constraint, we have discussed the influence of different gateway placements and capacity constraints of satellite links on the network reliability. Nevertheless, as our first step to study the GPCC problem in the space-ground integrated network, only the scenario where the terrestrial links have no capacity constraint and there is one satellite has been considered in this article. For future works, it should be meaningful to study the trade-off between the latency minimization and the reliability maximization in placing optimal satellite gateways in the space-ground integrated network, while taking more scenarios into account, including ones with more satellites and ones in which each terrestrial link also has its own capacity constraint.

Conclusions

In this article, we investigate the capacitated gateway placement problem in space-ground integrated networks. We define this problem as an optimization problem, which aims to maximize the weighted average network reliability with given capacity constraint. After that, we propose two algorithms as our solutions, OPEA and HGPA, where OPEA was adopted as a benchmark. OEPA provides an enumeration strategy to find an optimal gateway placement, and HGPA adopts an intelligently greedy optimization strategy for searching gateway placement. Numerical results corroborate that HGPA can not only give a near-optimal solution to our problem, but also can achieve much higher computational efficiency compared to our benchmark.

Acknowledgments

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Biography

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