Ground Station Site Selection with Real Cloud Data for Satellite-Ground Optical Networking

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Abstract. Optical communication is an important technology for future space networks. However, compared with inter-satellite optical communication, satellite-ground optical communication is more challenging because of weather, which are mostly cloud factors. To deal with this problem, an effective strategy is to achieve ground station site diversity. In this paper, we propose a method to determine the range of clouds that affects satellite-ground optical links for a certain ground station. Given the number of candidate ground stations, through processing the cloud products of the Himawari-8 GEO satellite, we obtained the cloud coverage data corresponding to each ground station. Then, by calculating the availability probability of possible combinations of ground stations, the network with the highest availability is chosen as the optimal optical ground station network. By calculating the availability probability with real cloud data, the results of ground station site selection in mainland China are obtained.

Keywords: Satellite-ground optical networking · Ground station site selection · Network availability

1 Introduction

Optical communication is one of the most promising communication technologies for the future space networks. Compared with the traditional RF communication technology, optical communication uses optical beams as the carrier, which can not only realize high transmission rate, but also achieve higher anti-interference performance. These characteristics of optical communication allow it to be applied to downlink earth observation data form LEO satellites, or to transmit data to GEO satellites as feeder links, etc. [3]. However, compared with inter-satellite optical links, satellite-ground optical links are subject to weather conditions such as cloud coverage condition, which will seriously attenuate the optical signal and even directly interrupt the optical links.

Q. Wu et al. (Eds.): WiSATS 2020, LNICST 357, pp. 352–361, 2021.
https://doi.org/10.1007/978-3-030-69069-4_29

An effective strategy to solve this problem is to use multiple ground stations to form an optical ground station (OGS) network [2–8]. When some ground stations are covered by clouds and can't communication, site diversity guarantees one or more ground stations with cloud free line of sight to maintain the optical communication and avoid communication disruption. Therefore, the selection of ground stations for an optical ground station network is particularly important for improving the availability of satellite-ground optical networking (Fig. 1).

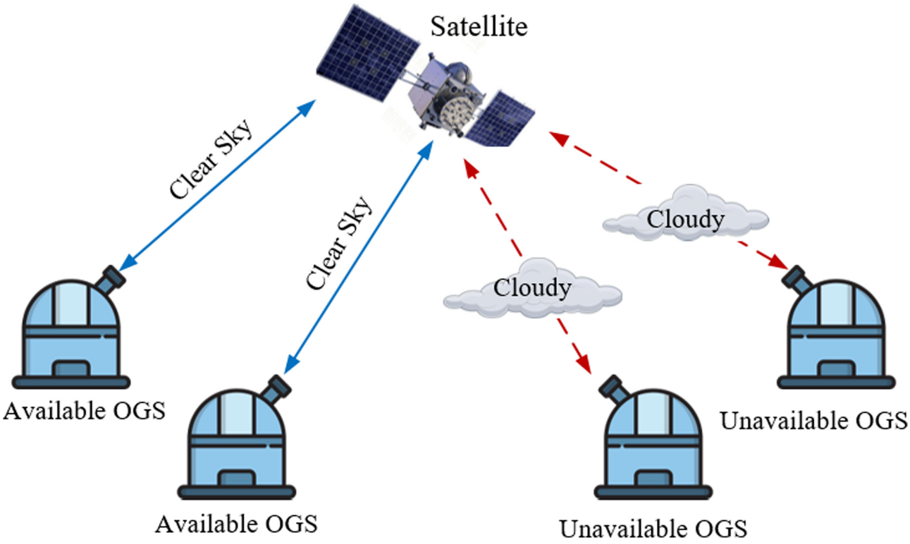

Fig. 1. OGS network of multiple ground stations

In [1], a ground station selection scheme is proposed based on the consideration of geographical and climatic characteristics in mainland China. The effects of atmospheric scattering and atmospheric turbulence on satellite-ground links were simulated. And the satellite tool kit (STK) software was used to analyze the link characteristics between the GEO satellite and five ground stations. However, this work mainly considered the effect of atmospheric environment such as atmospheric turbulence, the effect of cloud coverage was not discussed in depth. Three approximation methods including Monte Carlo sampling, the Lyapunov central limit theorem and Chernoff bound are adopted in [2] to estimate the probability of having a certain number of satellite-ground links fail due to cloud coverage.

An efficient algorithm is proposed in [3] to calculate the availability of an optical ground station network, and used five years of cloud data to simulate the behavior of three networks with different topologies including German, European and intercontinental. In [4], a method is presented to estimate the cloud-free line-of-sight probability of both a single optical ground station and a network of optical ground stations for medium earth orbit (MEO) constellation satellite communication systems. In [5], a mixed integer linear program model and a hierarchical method are presented based on an exhaustive enumeration of the sets of stations and on a dynamic programming algorithm. And a model is presented in [6] to optimally determine the location of optical ground stations to serve LEO missions, considering the trade-offs between minimal cloud probability, minimal latency and proximity to support infrastructure. In [7], the authors investigated the monthly variation of cloud coverage statistics and used them for the optimum selection of network with minimum number of ground stations, which satisfied the monthly availability requirements. In [8], a new algorithm is proposed based on gradient projection method after performing smoothing and relaxation on the original problem.

In order to make the OGS site selection more accurate, besides improving the way to calculate availability probability, the improvement in the method of processing and using cloud products is also important. This paper proposes a method to process cloud data more effectively, which can determine the range of clouds that affects satellite-ground optical links for a certain ground station. Through processing the cloud products of the Himawari-8 GEO satellite, the cloud coverage data corresponding to each ground station can be obtained. By calculating the availability probability with these cloud data, we finally obtained the results of ground station site selection in mainland China.

The structure of this paper is as follows: Sect. 2 describes how to process and utilize the real cloud data, which is necessary for the optical ground station site selection. Section 3 describes a method to calculate availability for a given optical ground station network. Section 4 presents the site selection results. The conclusions are drawn in Sect. 5.

2 Processing and Utilization of Real Cloud Data

At first, in order to achieve OGS site selection, it is necessary to get the cloud coverage data over each candidate ground station. Considering the location of candidate ground stations, we selected the Himawari-8 GEO satellite to get real cloud data. Figure 2 shows the observation range of the Himawari-8 GEO satellite. The resolution of cloud mask products is 5500×2200 pixels, while the spatial resolution 2 km and the temporal resolution is 30 min.

All the data we obtained is the cloud coverage information of every pixel from January 1, 2017 to December 31, 2017 every 30 min. In addition, the data is divided into four values of 0, 1, 2, and 3 according to the cloud coverage, which respectively represent clear, probably clear, probably cloudy and cloudy. The latitude and longitude information of a ground station can be used to find which pixel corresponds to this ground station, and then we can finally obtain the cloud coverage data over this ground station.

However, satellites are rarely directly above ground stations. The more common case is that the optical link between a satellite and a ground station maintains an inclination with the normal direction of ground. Therefore, the factor

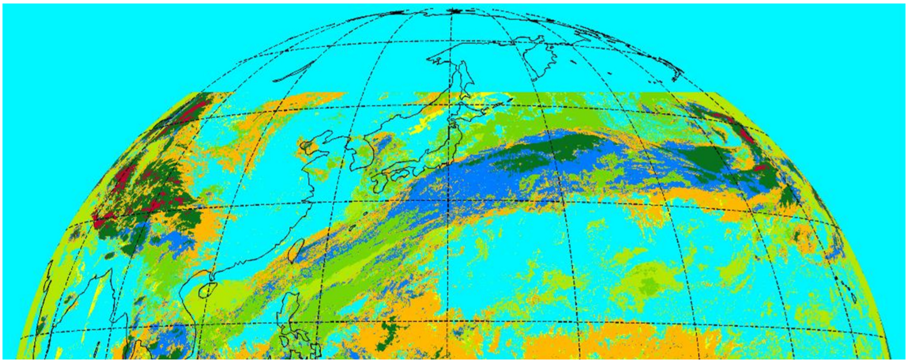

Fig. 2. The observation range of the Himawari-8 GEO satellite

that really affects optical links is not the cloud directly above a ground station, but the cloud at the intersections of cloud layer and optical links. Furthermore, a ground station usually communicates with multiple satellites, thus a ground station can have more than one optical link. Therefore, the cloud area that affects optical links of satellite-ground communication is a range rather than a point. In this case, all the cloud data in this range must be considered.

As discussed in [9], considering the characteristics of optical links, an optical ground station is available for communication only if it has an optical link with an elevation angle to the satellite of more than 20° and the satellite-ground optical link is not blocked by clouds.

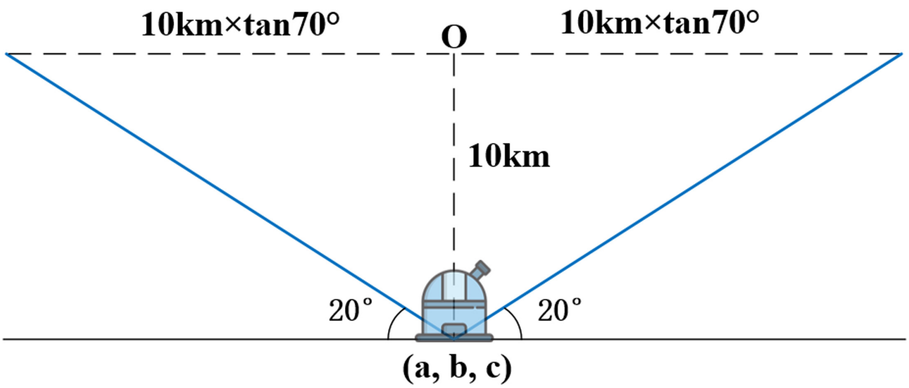

Fig. 3. The range of clouds that needs to be considered

As shown in the Fig. 3, the coordinates of the ground station in the Cartesian coordinate system are (a, b, c), and the height of cloud layer is assumed to be 10 km. Therefore, the range of cloud data that we need to consider for this ground station is a circular area with a radius of $10\,\text{km} \times \tan 70^\circ = 27.47\,\text{km}$, which needs to satisfy the following inequality:

$$\sqrt{(x-a)^2 + (y-b)^2 + (z-c)^2} \leq 27.47\,\text{km} \tag{1}$$

Then, we average all cloud data of the points in this circular area. And a binary process also be done after averaging. If the averaged data is greater than 1.5 and less than 3, we set it to 1, otherwise set it to 0. Finally, the processed data is regarded as the cloud data corresponding to this ground station.

3 Network Availability of Optical Ground Networks

In this section, we introduce an effective method to achieve the optimal OGS network based on the calculation of network availability [3].

As described in Sect. 2, through the processing and utilization of real cloud data, we can get the cloud coverage data of each candidate ground station. To facilitate calculation, for each candidate ground station, a cloud data vector C_i is constructed:

$$C_i = [C_1, C_2, ...C_j, ...C_{N_{Sample}}] \tag{2}$$

There are N_{Sample} elements in this vector, which represents that the number of sample data points is N_{Sample}. The data we obtained is sampled by Himawari-8 GEO satellites every 30 min, and we use the data of one year to calculate the availability probability, so the number of elements N_{Sample} of each cloud data vector is 17520.

It should be noted that C_i is obtained by averaging the original data within a range, which is determined by the method in Sect. 2. The original data contains 4 states, which are 0, 1, 2 and 3, so the averaged data will be a double type. To facilitate calculation, we binarize it. We set the data greater than 1.5 and less than 3 to one, others are set to zero.

Therefore, each of these elements C_i is binary. If it is zero, it means there is no cloud over the sky and this station is available. Otherwise, it means there is cloudy over the OGS, and this station is unavailable. Suppose the number of ground stations in the OGS network is N, and there will be N cloud data vectors. Then, we use each of these vectors as a row to form a matrix, so we can get the cloud data matrix C, whose size is $N \times N_{Sample}$. The i-th row of the matrix C represents the cloud data of the i-th ground station during the period of N_{Sample} time points, and the j-th column of the matrix represents the cloud data of all stations at time sample j. Therefore, for a given network S, which including N OGS, the number of available ground stations at time sample j can be calculated as:

$$a_j = N - \sum_{i \in S} C_{i,j} \tag{3}$$

In order to calculate the availability, in addition to defining the parameter N which represents the number of ground stations included in the network, we also need to define the parameter M, which represents the number of required OGS. That is, the network is available when at least M stations are available. Then, if a_j is greater than or equal to M, set the redefined $a_j{}^*$ to one, otherwise set it to zero. Following [3], the availability of OGS network can be calculated as:

$$A = \frac{1}{N_S} \sum_{j=1}^{N_S} a_j^* \tag{4}$$

In the case that we have a certain number of candidate ground stations, we only need to calculate the network's availability for each possible combination of ground stations. The combination with the highest availability probability can be regarded as the optimal OGS network, that is, the ground station site selection results under the parameters of N and M.

4 Results

First, we selected 15 candidate ground stations as shown in Table 1:

Table 1. Candidate ground stations

Number	Name	Latitude	Longitude
1	Beijing	39.91N	116.39E
2	Xian	34.27N	108.94E
3	Taiyuan	38.50N	111.36E
4	Qingdao	36.07N	120.38E
5	Changchun	43.81N	125.33E
6	Xiamen	24.48N	118.09E
7	Nanning	22.82N	108.35E
8	Jiuquan	40.58N	100.18E
9	Xichang	27.88N	102.21E
10	Kashi	39.48N	75.93E
11	Wenchang	19.61N	110.73E
12	Sanya	18.24N	109.54E
13	Kunming	24.88N	102.83E
14	Urumqi	43.82N	87.53E
15	Ali	31.59N	81.84E

Secondly, calculating the range of clouds that affects satellite-ground optical communications for these candidate ground stations by the method in Sect. 2.

Table 2. OGS site selection results when M is 1

N	Maximum network availability	Selection results
1	61.71%	5
2	83.25%	3, 5
3	91.28%	3, 5, 15
4	95.12%	3, 5, 9, 14
5	97.20%	3, 5, 6, 13, 14
6	98.38%	3, 4, 5, 6, 13, 14
7	99.05%	3, 4, 5, 6, 8, 13, 14
8	99.39%	2, 3, 4, 5, 6, 8, 13, 14
9	99.59%	2, 3, 4, 5, 6, 8, 11, 13, 14
10	99.72%	1, 2, 3, 4, 5, 6, 8, 9, 13, 14
11	99.80%	1, 2, 3, 4, 5, 6, 8, 9, 11, 13, 14
12	99.83%	1, 2, 3, 4, 5, 6, 8, 9, 11, 13, 14, 15
13	99.85%	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 13, 14, 15
14	99.86%	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 14, 15

Table 3. OGS site selection results when M is 2

N	Maximum network availability	Selection results
1	0%	/
2	45.55%	1, 3
3	63.27%	1, 3, 5
4	75.18%	1, 3, 5, 15
5	83.83%	1, 3, 5, 14, 15
6	89.65%	1, 3, 5, 6, 14, 15
7	93.18%	1, 3, 5, 6, 13, 14, 15
8	95.20%	1, 2, 3, 5, 6, 13, 14, 15
9	96.57%	1, 2, 3, 4, 5, 6, 9, 14, 15
10	97.68%	1, 2, 3, 4, 5, 6, 9, 12, 14, 15
11	98.40%	1, 2, 3, 4, 5, 6, 8, 9, 13, 14, 15
12	98.81%	1, 2, 3, 4, 5, 6, 8, 9, 12, 13, 14, 15
13	99.06%	1, 2, 3, 4, 5, 6, 8, 9, 10, 12, 13, 14, 15
14	99.20%	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15

After that, by processing all the cloud data in this range, as described in Sect. 2, we can obtain the cloud data vector of each candidate ground station, and then the cloud data matrix C can be constructed.

Table 4. OGS site selection results when M is 3

N	Maximum network availability	Selection results
1	0%	/
2	0%	/
3	30.03%	1, 3, 4
4	48.07%	1, 3, 5, 8
5	61.35%	1, 3, 5, 8, 15
6	70.65%	1, 3, 5, 8, 14, 15
7	78.72%	1, 3, 5, 6, 9, 14, 15
8	84.32%	1, 3, 5, 6, 8, 9, 14, 15
9	87.96%	1, 3, 5, 6, 8, 9, 13, 14, 15
10	90.74%	1, 2, 3, 5, 6, 8, 9, 13, 14, 15
11	93.00%	1, 2, 3, 4, 5, 6, 8, 9, 12, 14, 15
12	94.47%	1, 2, 3, 4, 5, 6, 8, 9, 12, 13, 14, 15
13	95.44%	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 13, 14, 15
14	96.06%	1, 2, 3, 4, 5, 6, 8, 9, 10, 11, 12, 13, 14, 15

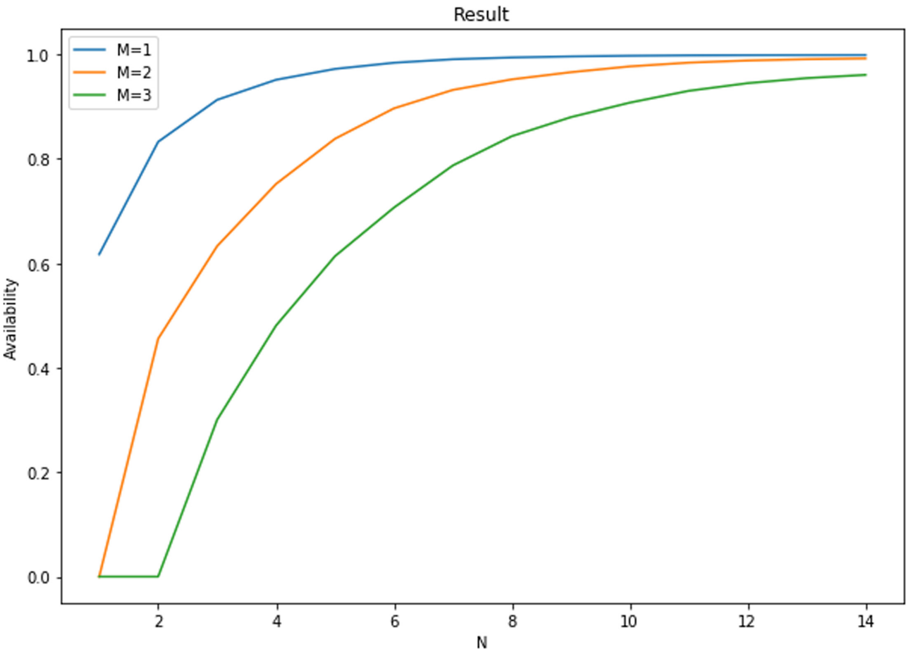

Fig. 4. Maximum availability of network under different N and M

Finally, this matrix is used as an input to the network availability calculation method. As mentioned above, the other two inputs are parameters N and M, where N is the number of all ground stations that make up the network, and M is the number of ground stations that required to be available. For different parameters N and M, by using the method in Sect. 3, we calculated the availability probability for each OGS network combination formed by these candidate ground stations. And the network with the highest availability is considered as the optimal OGS network, that is, the result of ground station network selection.

For the above-mentioned candidate ground stations, the ground station site selection results and the maximum network availability under different N and M are as follows, while the ground stations in the selection result is indicated by its number (Tables 2, 3 and 4).

The maximum availability of OGS network under different N and M is shown in Fig. 4.

5 Conclusion

As a key technology for future space network, satellite-ground optical networking can realize higher transmission rate than traditional RF technology. However, the optical links between satellites and ground stations are severely affected by cloud, which will seriously attenuate the optical signals.

In this paper, we proposed a method to determine the range of clouds which affect satellite-ground optical links for a certain ground station. By calculating the availability for all possible networks formed by fifteen candidate ground stations, the network with the highest availability is chosen as the optimal optical ground station network. Finally, we obtained the site selection results of optical ground station network for mainland China.

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