A Time Window Intersection (TWI) Based Snapshot Configuration Scheme in Terrestrial-Satellite Optical Networks

Daixuan Li
School of Electronic Engineering
Beijing University of Posts and Telecommunications
Beijing, China
lidaixuan@bupt.edu.cn

Xin Li
School of Electronic Engineering
Beijing University of Posts and Telecommunications
Beijing, China
xinli@bupt.edu.cn

Yu Liu
School of Electronic Engineering
Beijing University of Posts and Telecommunications
Beijing, China
liuyu0411@bupt.edu.cn

Lu Zhang
School of Electronic Engineering
Beijing University of Posts and Telecommunications
Beijing, China
luzhang@bupt.edu.cn

Chenyu Zhao
School of Electronic Engineering
Beijing University of Posts and Telecommunications
Beijing, China
chenyuzhao@bupt.edu.cn

Shanguo Huang
School of Electronic Engineering
Beijing University of Posts and Telecommunications
Beijing, China
shghuang@bupt.edu.cn

***Abstract*—We propose a time window intersection (TWI) based snapshot configuration scheme from the perspective of multiple GSs cooperation in TSON. Over 80% of snapshots and 20% of end-to-end shortest routing changes can be reduced.**

Keywords—SGL handover scheme, topology snapshot, route stability, terrestrial-satellite optical network (TSON)

I. INTRODUCTION

As a supplement to the traditional terrestrial optical network (TON), the satellite optical network (SON) has recently received significant attention. Several low-earth orbit (LEO) satellite constellations, such as Starlink and Telesat, have been successfully deployed. The optical inter-satellite links (OISL), which have high capacity and low delay advantages, have been adopted for inter-satellite connection of the constellations [1]. The LEO satellites in orbit between 500 and 2,000 km from the earth provide lower latency than GEO and MEO satellites.

The high-speed movement of LEO constellations leads to frequent satellite-to-ground links (SGLs) handovers. Rapid change in the terrestrial-satellite optical network (TSON) topology is the most significant difference from TON. Referring to the Starlink phase I constellation, the orbital period is 90 to 100 minutes. The high relative velocity between the satellites and the ground frequently varies the visibility between the satellites and the ground stations (GSs). Snapshots describe the visible relationships between satellites and GSs in time order to deal with the continuous TSON topology changes.

Satellites store topology and routing information onboard for every snapshot [2]. The storage resources on the satellite are limited, and various radiation in the universe also damages the hard disk, further reducing the storage resources [3]. With the increase in the number of satellites and satellite deployment layers of constellations, the period of the SON is significantly increased, which will cause the number of topology snapshots to grow and waste lots of onboard storage resources [4]. Even for GNSS constellations with a relatively shorter constellation cycle, more than 10,000 routing tables need to be stored within a system cycle [5]. The problem that too many snapshots take up too much satellite storage space was also pointed out by [6]. Large quantities of visibility snapshots should be merged into a small number of snapshots [5].

The constantly changing topology of TSON also complicates the problem of link allocation [7]. The topology during each snapshot is considered stable so that routes can be pre-calculated based on each snapshot [8]. As a result, the rising snapshot quantity directly leads to frequent end-to-end route switching, which weakens the stability of SONs [5], especially for long-time transmission duration services. The disconnections of the original SGLs result in some of the transmitted data packets not reaching the destination and getting lost [9]. More handovers mean more path changes in the routing, which is inconducive to the stability of end-to-end delay and the implementation of routing protocols [3, 6].

Reducing the number of terrestrial-satellite network snapshots has attracted much attention, and several solutions have been proposed. According to [10], a graph-based satellite handover framework was proposed. The minimum handover counts of each GS can be found by calculating the shortest path in the directed graph, which is structured by the visible relationship between satellites and GSs. The continuous, seamless coverage under satellite movement was analyzed in [11], the lower bound of the number of SGL handovers was proposed, and the limiting factors were analyzed. Another handover scheme to reduce handover frequency was provided in [12] by considering the remaining service time of satellites. These strategies for lowering the snapshot count were analyzed from the perspective of each single GS. For any end-to-end service, at least two GSs are involved, the attention should be put on multiple GSs. Merging SGLs handover of different GSs in TSON should be considered to further reduce snapshot quantities and route changes.

This study proposes a time window intersection (TWI) based snapshot configuration scheme from the perspective of multiple GSs in TSON instead of a single GS. The reduction of TSON snapshots is considered on the premise of minimizing the handover times of each single GS. Following this scheme, the number of snapshots can be effectively reduced, and the frequency of end-to-end shortest route changes caused by SGL handover can be decreased. The rest of this paper is organized as follows. Section II analyzes the satellite-to-ground visibility. Section III introduces the TWI based snapshot configuration scheme. Section IV describes a heuristic algorithm to implement the scheme. In Section V, the simulation results and performance analysis are presented. Section VI gives the conclusion.

II. PROBLEM STATEMENT

To further study the reduction of snapshot quantities, the structure of the satellite constellation should be analyzed. The Walker-delta constellation is the structure that Starlink, OneWeb, and other typical constellations adopt. The orbits of the constellations and the satellites in orbit are distributed at equal intervals. When phase factor F=0, the number of satellites in the same latitude remains constant, resulting in satellites being clustered near the poles and scattered near the equator, as shown in Fig. 1. The distribution density of visible satellites in the low-latitude region (coverage range *A*) is lower than that in the high-latitude area (coverage range *C*) simultaneously, which means the GSs in the low-latitude region have fewer available access satellites.

The general method to reduce the SGL handover times is selecting the satellite access with a long remaining visible time. Under the same minimum elevation of GS, the closer the satellite orbit is to the directly above GS, the longer the visible time window between the satellite and the GS, and the more likely it is to provide the scheme of the minimum number of SGL handover. Meanwhile, the more the visible satellites are simultaneous, the greater the probability that satellites pass over directly above or near the head of GSs. This leads to more accessible satellites with long visible windows for GSs. Therefore, high-latitude GSs with dense satellite coverage have a more extensive set of handover scheme choices, tending to have fewer handover times than low-latitude GSs.

Another factor that limits the number of handovers is the time window intersection, which is defined as the period during which two satellites are simultaneously visible to the GS, as exhibited in Fig. 2. For the two satellites with long visible windows next to each other in time, the length of the window intersection restricts the handover efficiency, which should be selected as short as possible. The window intersection also limits the moment that SGL can be switched.

For each GS, there is more than one scheme with the least handover number. These schemes have the least snapshots for each GS, but the snapshots for the entire TSON topology with multiple GSs may not be the least. Combining multiple SGL handover schemes can reduce the number of snapshots.

III. TIME WINDOW INTERSECTION MODEL

Traditional methods only concerned one pair of satellite-to-GS relations to get the handover strategy with the least snapshot number. However, the long-distance communication through SGL and SON must pass through the source and the destination GSs, and the route switching is affected by the effect of the two stations' handover. It is inadequate that it only minimizes a single GS snapshot quantity. The time window intersection (TWI) based snapshot configuration scheme is provided for the cooperation of multiple GSs, which can reduce the number of topology snapshots of TSON.

Figure. 3 illustrates the SGL handover of the three GSs corresponding to Fig. 1. As shown in Fig. 3(a), the traditional handover scheme only considers a single GS and often handover to the next satellite with a longer remaining service

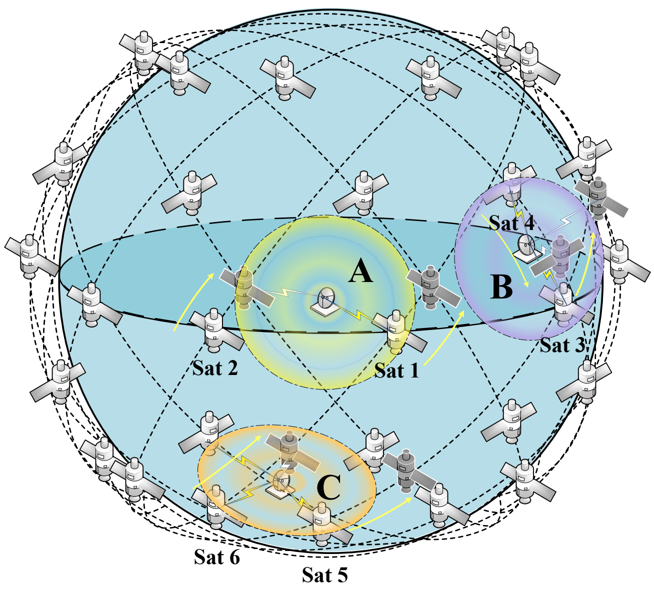

Fig. 1. Distribution of satellites and GSs in the Walker-delta constellation.

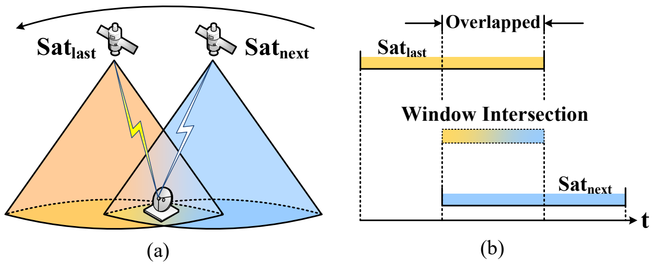

Fig. 2. SGL handover (a)Overlapping satellite coverage (b)Definition of the time window intersection.

time based on the moment the last satellite leaves the visible range. Considering multiple GSs, as shown in Fig. 3(b), the SGLs can be switched simultaneously when multiple GSs visibility window intersections overlap. From the example in Fig. 3, the number of snapshots is reduced from four to two. The TSON topology can get fewer snapshots in this scheme than in the traditional handover scheme.

For multiple GSs in the same TSON, based on the least handover number scheme of each SGL, calculate the time range of the two satellites when they are simultaneously visible to the same GS before and after the handover (each time window intersection), and arrange them in order. Figure. 4 is an example of a real situation for further illustration. It presents all the time window intersections in 20 minutes of the 14 GSs in TSON comprised of NSFNET and Starlink stage I. Each row corresponds to a GS, with a minimum visible elevation of 35 degrees. Suppose n intersection of GSs time windows overlapped simultaneously. In that case, n SGLs can be switched together, and the number of TSON topology snapshots is reduced $(n-1)$. This TWI based snapshot configuration scheme is carried out based on the least snapshot number of single GSs, ensuring good handover robustness of each GS.

Due to the large scale of the constellation and numerous satellites, each GS can choose more than one scheme for the minimum number of handover times. For a vast TSON composed of multiple GSs, the time window intersection matching problem among these schemes should be solved to reduce the number of snapshots.

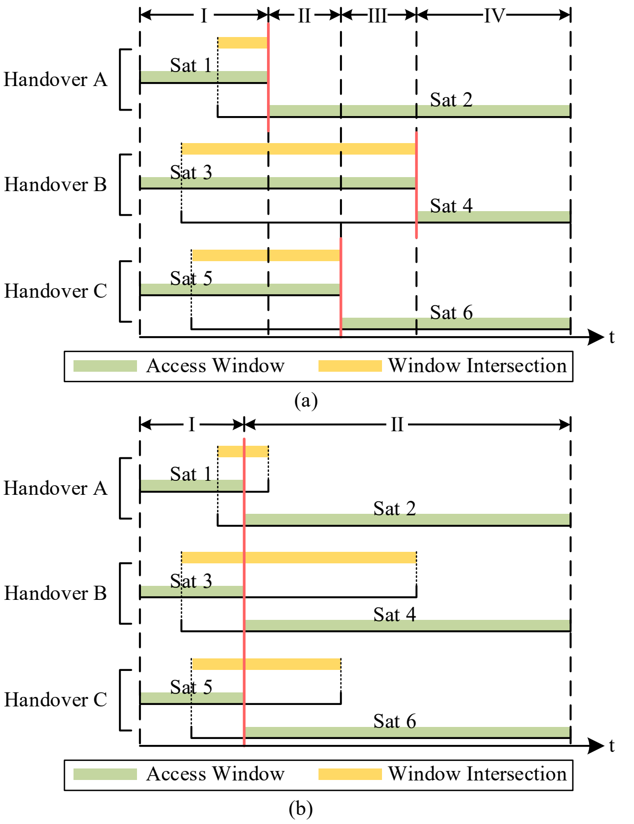

Fig. 3. Handover scheme comparison (a)Traditional handover scheme (b)Time window intersection-based handover scheme.

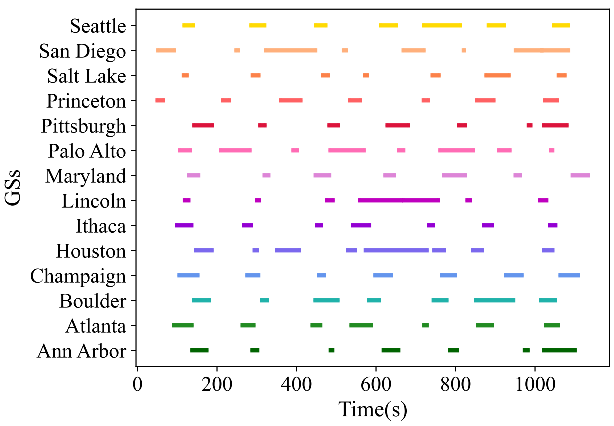

Fig. 4. All the time window intersections of NSFNET and Starlink network in 20 minutes.

IV. Window Intersection Cooperative Algorithm

The window intersection cooperative algorithm (WIC) is proposed to solve the time window intersection matching problem. The set of all snapshots is pre-calculated as SGV. From the SGV, the minimum SGL handover number scheme based on each single GS can be obtained by the auxiliary topology method [10]. Each satellite in the visible range is regarded as a topological node. The satellites under the same snapshot, which can be switched between each other, are connected directly in the topology. Virtual nodes are added at the beginning and end moments to select and connect to the visible satellites of the first and last snapshots. The Dijkstra algorithm is used to obtain all the schemes of the minimum handover times of k GSs respectively, get the strategy set St_g, where g is the index of GSs. Each St_g set contains many strategies $St_{g,x}$ of the same minimum handover times, x is the index of the strategy itself. For all the satellites involved in the scheme, find the moments $t_{i,g}^e$ and $t_{i,g}^l$ when they enter and leave the corresponding GS visible range, i is the satellite ID.

The large solution domain leads to a poor convergence effect of the genetic algorithm (GA). The elitist preservation strategy is adopted to maintain the best solution found over time before selection. Each chromosome is a handover scheme combination $\{St_{1,x}, St_{2,x}, \dots, St_{k,x}\}$ for all GSs, and each St_g presents a gene. The fitness is calculated according to the sum of snapshot quantities in the topological network composed of multiple GSs. The intersections of all time windows are calculated and arranged in ascending order according to the start time. The satellite relations that can be switched simultaneously are included in the same set in H_{to} successively, and the optimized snapshot quantity n_{tot} and handover strategy St_{tot} are obtained. Algorithm 1 shows the WIC algorithm, and Algorithm 2 describes the fitness calculation part of GA in Algorithm 1.

Algorithm 1: WIC

Input: SGV; **Output:** n_{tot}, St_{tot}

for g in GSs **do**
 Generate auxiliary topology from SGV_g, each satellite is a node, all visible satellites in the same snapshot are directly connected;
 Add virtual nodes at both ends, use the Dijkstra algorithm to find all the shortest paths, get all schemes for the minimum number of snapshots;
end for
for each St_g **do**
 Find all the participating satellites in St_g;
 Record the moment all participating satellites enter and leave the visible range as $t_{i,g}^e$ and $t_{i,g}^l$;
end for
Generate the initial chromosome population Ch randomly, each chromosome $\{St_{1,x}, St_{2,x}, \dots, St_{k,x}\}$, calculate the fitness;
for generations **do**
 Each $St_{g,x}$ is a gene, do selection and reproduction based on fitness, update a new chromosome population to Ch;
 Crossover, mutation, and fitness calculation;
end for
return n_{tot}, St_{tot}

Algorithm 2: Fitness calculation in GA

Input: Ch, $t_{i,g}^e$, $t_{i,g}^l$; **Output:** n_{tot_temp}, St_{tot_temp}

For each chromosome handover scheme in Ch, calculate the time window intersection of each handover according to $t_{i,g}^e$ and $t_{i,g}^l$;
Record the moments of all window intersections when they start and end as $wit_{i,g}^s$ and $wit_{i,g}^e$;
Arrange $wit_{i,g}^s$ to wi_j^s in ascending order, arrange $wit_{i,g}^e$ to wi_j^e in the corresponding order of wi_j^s;
$t_s = wi_1^s$, $t_e = wi_1^e$;
for wi_j^s without wi_1^s **do**
 $t_{s\_new} = wi_j^s$, $t_{e\_new} = wi_j^e$;

```
    if t_{s_new} < t_e do
        Add SGL: (i-g) to the set in H_{to};
        t_e = min (t_e, t_{e_new});
    else do
        t_s = t_{s_new}, t_e = t_{e_new};
        Add a new set to H_{to};
    end if
end for
return n_{tot_temp}, St_{tot_temp}
```

V. Simulation Results

The algorithm is verified by Starlink phase I, which has 72 orbits with 22 satellites on each orbit, phase factor F=0, and an orbital altitude of 550km. NSFNET with 14 GSs and China's future network with 40 nodes are selected as the TON. Each GS works as a gateway, connecting TON and SON. The minimum elevations of GSs are set to 15°, 25°, and 35°, respectively. For GA parameter settings, population size is set to 100, generations equal to 500, crossover rate is 0.6, and mutation rate is 0.01.

For the TSON composed of Starlink and NSFNET, the comparison of the number of snapshots using the traditional handover scheme and the time window intersection handover scheme is shown in Fig. 5. With the increase of the minimum elevation angle of GS, the average coverage time of the satellite decreases, the number of handover times increases, and the number of snapshots increases. It can be seen that the number of snapshots obtained by the WIC algorithm in this paper is reduced by 80% on average compared with the traditional strategy.

For China's future network, a more extensive topology with 40 GSs, works with Starlink to build TSON. The number of snapshots obtained by the two handover strategies is compared, as shown in Fig. 6. As the number of GS increases, the maximum number of snapshots that can be merged increases. The average number of snapshots reduced by the WIC algorithm is increased to 86%, which helps save the onboard storage resources.

To verify the influence of the WIC algorithm on the end-to-end shortest path change, Fig. 7 compares the number of Dijkstra-based end-to-end shortest route changes in TSON networks (Starlink and NSFNET) in 20min and 30min. The shortest routes between GSs are pre-calculated based on the snapshot topology. The WIC algorithm reduces the average changes of 20% end-to-end shortest routes, decreasing service transmission changes, which helps to improve SON stability.

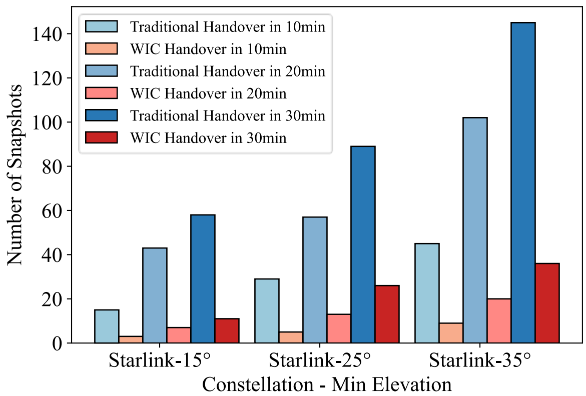

Fig. 5. Comparison of the number of snapshots in NSFNET and Starlink.

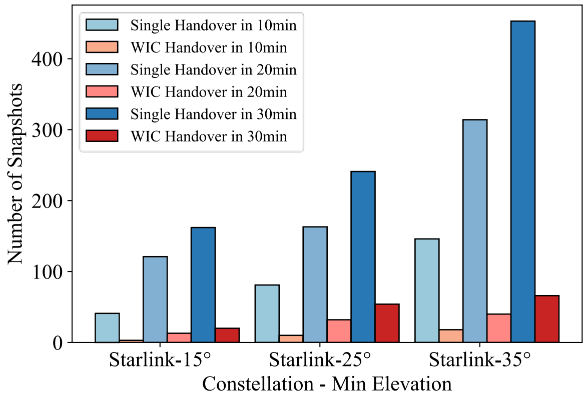

Fig. 6. Snapshots comparison in China's future network and Starlink.

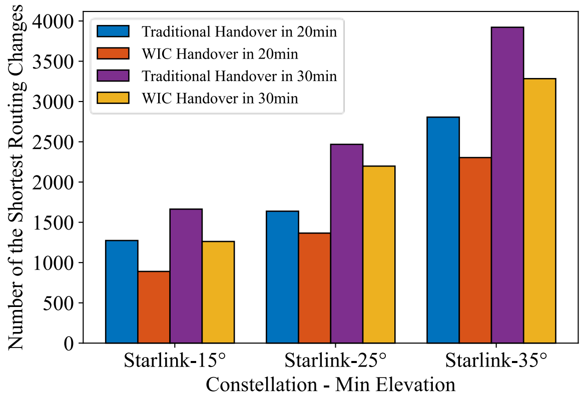

Fig. 7. The shortest routing changes comparison in NSFNET and Starlink.

VI. Conclusion

Instead of the single GS-based handover strategy, a time window intersection based snapshot configuration scheme is proposed to reduce the number of snapshots in the perspective of multiple GSs in TSON. Based on the model, more than 80% storage of snapshots can be released, and about 20% of end-to-end shortest routing changes can be avoided.

Acknowledgment

This work was supported in part by the National Natural Science Foundation of China (62171050, 62125103), the Fund of State Key Laboratory of Computer Architecture (CARCH201906), and Open Fund of State Key Laboratory of Information Photonics and Optical Communications of BUPT (IPOC2021ZT15).

References

[1] A. U. Chaudhry and H. Yanikomeroglu, "Free Space Optics for Next-Generation Satellite Networks," *IEEE Consum. Electron. Mag.*, vol. 10, no. 6, pp. 21-31, Nov. 2021.

[2] J. Huang, Y. Su, L. Huang, W. Liu, and F. Wang, "An Optimized Snapshot Division Strategy for Satellite Network in GNSS," *IEEE Commun. Lett.*, vol. 20, no. 12, pp. 2406-2409, Dec. 2016.

[3] L. Zhao, C. Wang, K. Zhao, D. Tarchi, S. Wan, and N. Kumar, "INTERLINK: A Digital Twin-Assisted Storage Strategy for Satellite-Terrestrial Networks," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 58, no. 5, pp. 3746-3759, Oct. 2022.

[4] Y. Liu, Y. Zhao, W. Wang, and J. Zhang, "Adaptive Snapshot Routing Strategy for Software Defined Multi-domain Satellite Networks," 2020 IEEE Computing, Communications and IoT Applications (ComComAp), Beijing, China, 2020, pp. 1-6.

[5] Z. Ma, Y. Zhao, W. Wang, X. Xin, and J. Zhang, "Adaptive Snapshot Routing Based on Space Debris Risk Perception in Satellite Optical

Networks," 2021 International Conference on Optical Network Design and Modeling (ONDM), Gothenburg, Sweden, 2021, pp. 1-6.

[6] Y. Lu, F. Sun, and Y. Zhao, "Virtual Topology for LEO Satellite Networks Based on Earth-Fixed Footprint Mode," *IEEE Commun. Lett.*, vol. 17, no. 2, pp. 357-360, Feb. 2013.

[7] H. Chang, B. Kim, C. Lee, S. Min, Y. Choi, H. Yang, D. Kim, and C. Kim, "FSA-based link assignment and routing in low-earth orbit satellite networks," *IEEE Trans. Veh. Technol.*, vol. 47, no. 3, pp. 1037-1048, Aug. 1998.

[8] Z. Tang, Z. Feng, W. Han, W. Yu, B. Zhao, and C. Wu, "Improving the snapshot routing performance through reassigning the inter-satellite links," 2015 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), Hong Kong, China, 2015, pp. 97-98.

[9] J. Zhang, S. Zhu, H. Bai, and C. Li, "Optimization Strategy to Solve Transmission Interruption Caused by Satellite-Ground Link Switching," *IEEE Access*, vol. 8, pp. 32975-32988, 2020.

[10] Z. Wu, F. Jin, J. Luo, Y. Fu, J. Shan, and G. Hu, "A Graph-Based Satellite Handover Framework for LEO Satellite Communication Networks," *IEEE Commun. Lett.*, vol. 20, no. 8, pp. 1547-1550, Aug. 2016.

[11] Y. Seyedi and S. M. Safavi, "On the Analysis of Random Coverage Time in Mobile LEO Satellite Communications," *IEEE Commun. Lett.*, vol. 16, no. 5, pp. 612-615, May. 2012.

[12] J. Miao, P. Wang, H. Yin, N. Chen, and X. Wang, "A Multi-attribute Decision Handover Scheme for LEO Mobile Satellite Networks," 2019 IEEE 5th International Conference on Computer and Communications (ICCC), Chengdu, China, 2019, pp. 938-942.