Topology Analysis of Inter-Layer Links for LEO/MEO Double-Layered Satellite Networks

Hongcheng Yan(✉), Jian Guo, Xianghui Wang, Yahang Zhang, and Yong Sun

Institute of Spacecraft System Engineering,
China Academy of Space Technology, Beijing 100094, China
hongcheng.yan@gmail.com

Abstract. Due to the relative orbiting of Low Earth Orbit (LEO) satellite and Medium Earth Orbit (MEO) satellite, the inter-layer links (IIL) of LEO/MEO Double-Layered Satellite Networks (DLSN) have to switch dynamically, resulting in dynamic changes of satellite network topology, which has an impact on the data transmission performance of DLSN. In this paper, the IIL topology of LEO/MEO DLSN is analyzed and simulated. Firstly, the visibility calculation method and establishment strategy of IIL between LEO and MEO satellite as well as the calculation and optimization of system snapshots is analyzed. Then, simulation analysis regarding the number and duration of system snapshots, IIL switching time for LEO, the number of switching IIL in each system snapshot, the number of IILs that each MEO needs to establish are presented. Finally, the future research trends of DLSN IIL topology are discussed, such as how to reduce the maximum IIL number for MEO and so on.

Keywords: Double-Layered Satellite Networks · Inter-layer link
Snapshot optimization · Simulation analysis

1 Introduction

In non-geostationary orbit satellites, Low Earth Orbit (LEO) satellites have a lower transmission latency, lower link loss and thus low requirements to user terminals due to its low altitude. However, the coverage of a single LEO satellite is limited and usually need a larger constellation to achieve global coverage thus having a big system investment. Meanwhile, Medium Earth Orbit (MEO) satellites have a higher altitude, higher transmission latency and higher link loss, thus have higher requirements to user terminals. However, due to the higher altitude and wide coverage of MEO satellites, global coverage only needs a dozen MEO satellites and thus having a low system investment. Moreover, the long distance transmission latency of MEO constellation is better than LEO constellation. Therefore, LEO/MEO Double-Layered Satellite Networks (DLSN), which can combine the advantages of both LEO and MEO satellites, has become a research focus in satellite communication network field [1].

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In LEO/MEO DLSN, LEO satellites have to establish Inter-Layer Link (IIL) with MEO satellite in addition to establishing Inter-Satellite Links (ISL) with intra-orbit LEO satellites and inter-orbit LEO satellites. MEO satellites also have to establish IILs with LEO satellites in addition to establishing ISLs with intra-orbit and inter-orbit MEO satellites [2]. Because MEO satellites cannot always be visible to LEO satellites, the IILs have the characteristics of dynamic switching. Meanwhile, the ISLs in LEO constellation and MEO constellation can generally be fixed by choosing a reasonable constellation configuration [3]. Therefore, it can be concluded that the topological dynamics of LEO/MEO DLSN are mainly due to the dynamic change of the IIL.

At present, the academia mainly focuses on the satellite network routing algorithm [4, 5], and the research on the dynamic of satellite network topology is relatively little [3, 6–11]. Markus et al. [3] proposed that choosing an inclined walker constellation can achieve fixed laser ISLs for broadband LEO satellite networks. Wang et al. [6] presented an analysis on how to reduce the dynamics of LEO satellite network topology by choosing a reasonable constellation configuration. Wang et al. [7] proposed an equal-duration snapshot optimization method for LEO satellite networks. The above researches are mainly focus on topology analysis and optimization for single layer satellite networks. Wang et al. [8] argued that the LEO constellation selection has an impact on the topology dynamics of multilayered satellite network. Wu and Wu [9] proposed a centralized IIL establishment strategy for LEO/MEO DLSN and made a performance evaluation. Zhou et al. [10] and Long et al. [11] proposed a snapshot optimization method based on snapshot merging and achieved a remarkable improvement.

The establishment strategy of IIL in LEO/MEO DLSN is generally based on satellite grouping and routing protocol [1], that is, LEO satellite will choose MEO satellite with the longest predicted coverage time to establish IIL. Each time the IIL changes, one new snapshot will be generated. Since the strategy did not initially take into account the snapshot optimization problem, the number of snapshots generated was high and the duration of the snapshot was short. Large number of snapshots makes the satellite network topology more dynamic and requires more storage space of the satellite; short duration of snapshots makes a higher demand for the convergence speed of the satellite routing algorithm. The snapshot optimization method based on snapshot merging proposed by Zhou-Long can greatly reduce the number of snapshots while increasing the duration of snapshots.

Since the IIL topology of LEO/MEO DLSN has not been thoroughly analyzed and simulated in the literature, therefore this paper will try to fill the gap and point out the future research direction. Firstly, the visibility calculation method and establishment strategy of IIL are presented. Secondly, the calculation and optimization of system snapshots proposed by Zhou-Long is analyzed. Thirdly, simulation analysis regarding the number and duration of system snapshots, IIL switching time for LEO, the number of switching IIL in each system snapshot, the number of IILs that each MEO needs to establish are presented. Finally, the future research trends are discussed.

2 The Establishment Strategy of IIL

The architecture of LEO/MEO DLSN is shown in Fig. 1. LEO constellation generally needs a larger number of satellites to achieve global coverage due to its low orbit altitude while MEO constellation only need a dozen or more satellites to achieve global coverage due to its high altitude. Each LEO satellite generally establishes ISLs with two intra-orbit satellites and two inter-orbit satellites while each MEO establishes ISLs with MEO satellites according to the same strategy. Meanwhile, each LEO satellite will also choose an MEO satellite to establish IIL. Since the ISLs in LEO layer and in MEO layer can be fixed by choosing reasonable constellation configuration, the topology of LEO constellation and MEO constellation can be regarded as static. However, due to the relative orbiting of LEO and MEO satellites, the IILs are characterized by dynamic switching. Then, it can be concluded that the topological dynamics of LEO/MEO DLSN are mainly due to the dynamic change of the IIL.

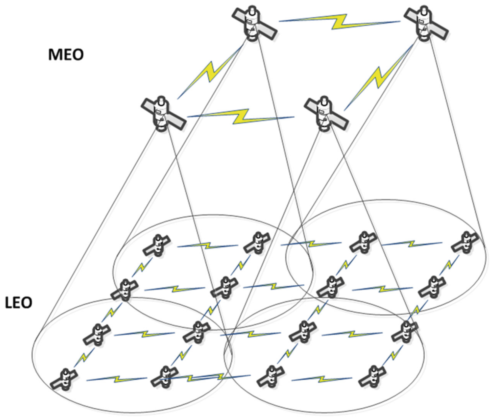


Fig. 1. Architecture of LEO/MEO DLSN

At present, the establishment strategy of IIL is generally based the longest coverage time strategy proposed in satellite grouping and routing protocol [1], that is, the LEO satellite will choose the MEO satellite with the longest predictable coverage time in all visible MEO satellites to establish IIL until the MEO satellite can no longer cover itself. Then, the LEO satellite will use the same longest coverage time strategy to select the next MEO satellite to establish IIL. Each time the IIL changes, one new snapshot will be generated.

Since LEO satellite and MEO satellite must be visible to each other to establish IIL between them, we first formulate the LEO-MEO visibility condition which is shown in Fig. 2 [1]. O is the earth center and A is an MEO satellite while B is the LEO satellite. A’ is the crossing point of line OA and the sphere with the radius ($R + h_L$) where R is the radius of the earth and h_L is the radius of LEO constellation.

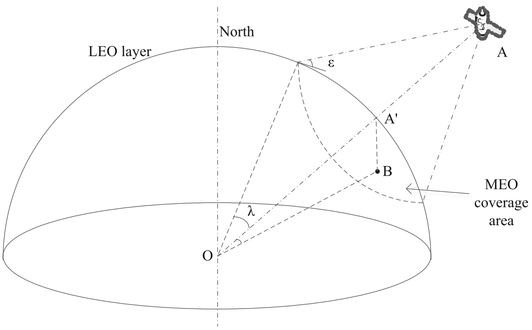


Fig. 2. Visibility condition between LEO and MEO satellite

Assume the radius of the MEO constellation is h_M and ε is the minimum elevation angle between LEO and MEO satellite, the half-sided center angle of the MEO coverage area on the LEO layer λ is calculated as:

$$\lambda = 90 - \varepsilon - \arcsin\left(\frac{R + h_L}{R + h_M}\sin(90 + \varepsilon)\right)$$

Then, LEO-MEO visibility condition is as follows:

$$\angle A'OB = 2\arcsin\frac{|A'B|/2}{R + h_L} \leq \lambda$$

According to the visibility conditions of LEO and MEO, the visible period of a LEO for all MEOs can be obtained. According to these visible periods, we can get MEO satellites that LEO will choose to establish IILs and the switching time of IILs. For all LEO satellites to perform the above operations, we will be able to get all IIL switching time of all LEO. All IIL switching time of all LEOs together constitute the division time of the system snapshot.

Since the satellite grouping and routing protocol does not take into account the optimization of the snapshot at first, the number of snapshots generated by the above method is large which makes the topology of DLSN highly dynamic. At the same time, the resulting snapshots have a short duration which makes a higher demand for the convergence speed of the satellite routing algorithm. In order to solve the above problems, Zhou-Long proposed a snapshot optimization method which can greatly reduce the number of snapshots while increasing the duration of the snapshots. The snapshot optimization method will be introduced in the following section.

3 Snapshot Optimization Method

Assume t_i is one division time of the system snapshots. At t_i one LEO satellite will switch IIL from one MEO satellite to another MEO satellite with longest predictable coverage time. Assume tip1 is another division time of the system snapshots. At t_{i+1} one LEO satellite L_i will no longer be visible to one MEO satellite M_i. Therefore, the IIL between L_i and M_i will be disconnected and L_i will select another MEO satellite M_{i+1} according to longest coverage time strategy. This situation is shown in Fig. 3 [11].

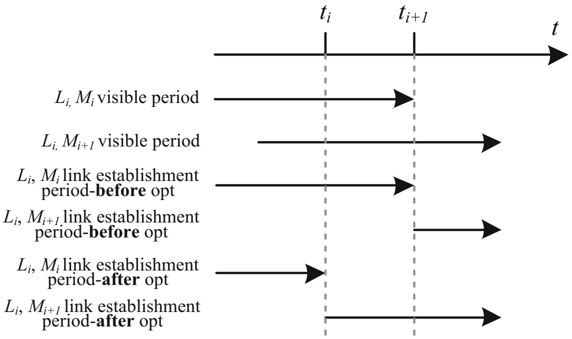


Fig. 3. Snapshot optimization method

Since L_i disconnects IIL with M_i and establishes a new IIL with M_{i+1} at t_{i+1}, a new division time t_{i+1} of the system snapshots is generated, resulting in a new snapshot. Because L_i is visible to both M_i and M_{i+1} at time t_i, Zhou-Long tried to advance the IIL switching time of L_i with M_i and M_{i+1} from t_{i+1} to t_i, thereby reducing a system snapshot.

As regarding to implementation of the snapshot optimization method, it is possible to traverse the division time of the system snapshots which are sorted by time, and for each division time t_i, search for division time t_{i+1} that can be merged with t_i. Whether t_i and t_{i+1} can be merged is based on two conditions: the first one is that the start time of the visible period of L_i and M_{i+1} is earlier than t_i; the second one is that the end time of the visible period of L_i and M_i is later than t_i (Since t_{i+1} is greater than t_i, therefore the second condition must be satisfied).

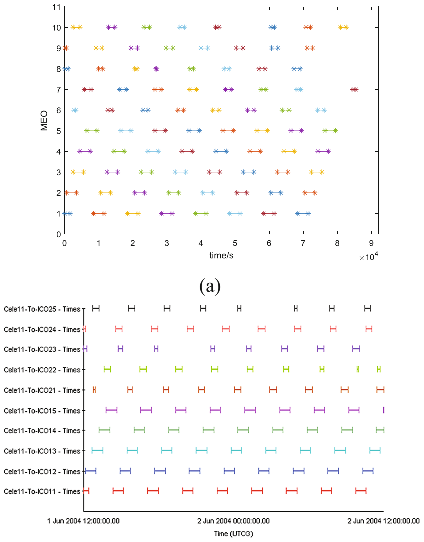
4 Simulation Analysis of IIL Topology

In this section, the IIL topology is analyzed by simulation. The simulation time is one solar day and the simulation step is 1 s. In the simulated LEO/MEO DLSN, LEO layer uses a Celestri constellation and MEO layer uses an ICO constellation [12]. The constellation parameters of LEO and MEO are shown in Table 1. Celestri constellation is an inclined walker constellation, so ISLs within LEO layer can be fixed.

Table 1. Constellation parameters of LEO/MEO DLSN

Constellation parameter	LEO	MEO
Inclination (°)	48	45
Altitude (km)	1400	10390
Number of planes	7	2
Number of satellites per plane	9	5
Inter-spacing of planes (°)	51.43	180
Inter-spacing of satellites in one planes (°)	40	72
Phase factor	5	0

Firstly, the visible period of LEO and MEO are simulated and Fig. 4(a) shows the visible periods between LEO1 and all 10 MEO satellites while Fig. 4(b) is the simulation result of STK (Systems Tool Kit) which is consistent with our simulation result.

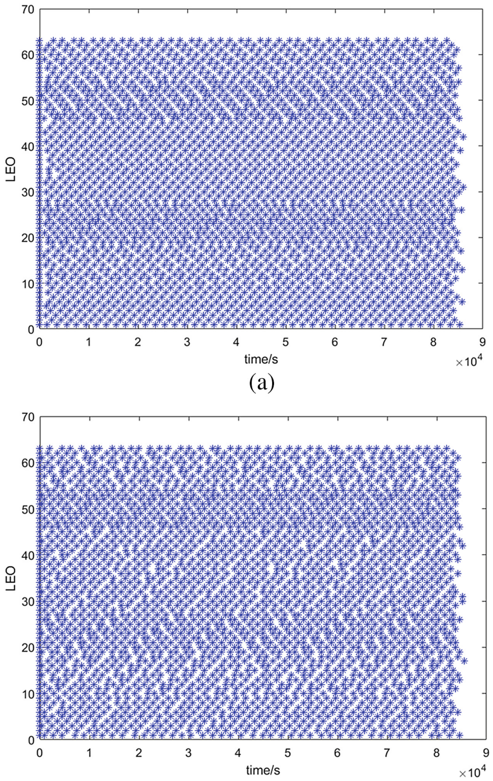


(a)

(b)

Fig. 4. Visible periods between LEO1 and all 10 MEO satellites. (a) Our simulation results; (b) STK simulation results.

For each LEO satellite, based on the longest predictable coverage time strategy to select an MEO satellite to establish IIL, we can obtain the IIL switching time of each LEO as shown in Fig. 5. Figure 5(a) is the IIL switching time of each LEO before snapshot optimization while Fig. 5(b) is the IIL switching time of each LEO after snapshot optimization. In Fig. 5 the horizontal coordinate is time while the vertical coordinate is LEO satellite.

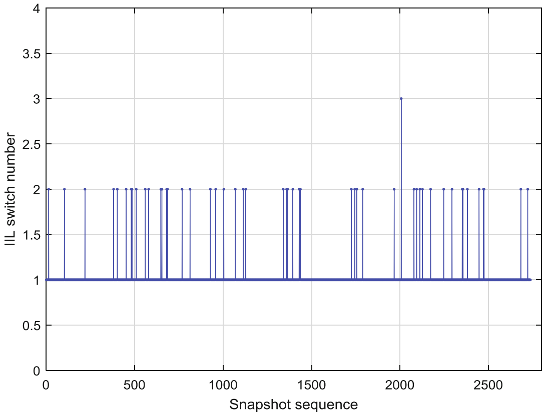


(a)

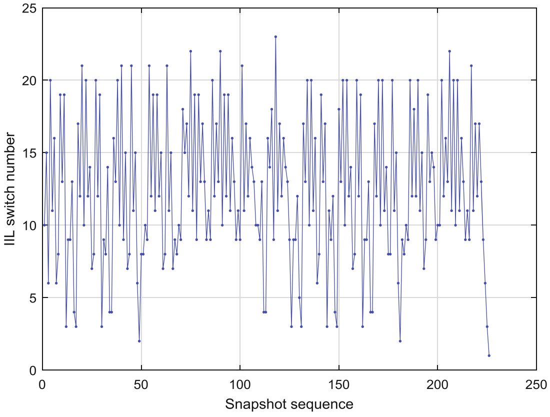
(b)

Fig. 5. IIL switching time for each LEO. (a) Before optimization; (b) After optimization.

Since the IIL switching time is plotted densely (one LEO has to switch IILs 42 times at least while 52 times at most), it is difficult to find the IIL switching time improvement after snapshot optimization from Fig. 5. So the number of IIL switching



(a)



(b)

Fig. 6. The number of IIL switching at each division time of system snapshots before and after snapshot optimization. (a) Before optimization; (b) After optimization.

at each division time of system snapshots before and after snapshot optimization are collected and shown in Fig. 6. As we mentioned earlier, all IIL switching time of all LEOs together constitute the division time of the system snapshot. Therefore, Fig. 6 is the combination of IIL switching time of all LEO in Fig. 5. Before snapshot optimization, the number of IIL switching at each division time of system snapshots is only 1 or 2 or 3 at most. While after snapshot optimization, the number of IIL switching at each division time of system snapshots is 12 in average and 23 at most. In another word, the snapshot optimization makes many IILs that have been switched in difference times to switch at the same time, thereby reducing the number of system snapshots.

Figure 7 shows the distribution of the number of IIL switching at each division time before and after optimization. From Fig. 7(a) we can see that before snapshot optimization, the number of IIL switching at each division time is mostly 1. While after snapshot optimization, the number of IIL switching at each division time increases dramatically.

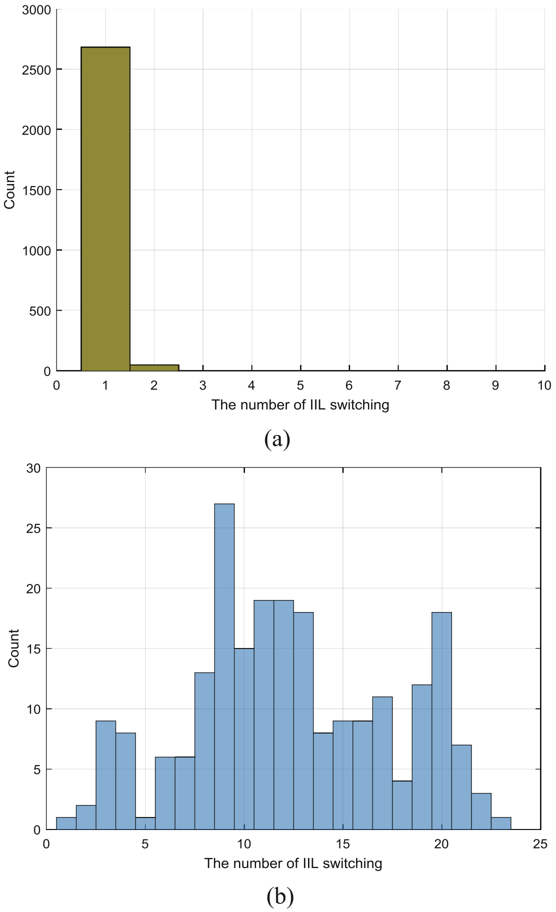
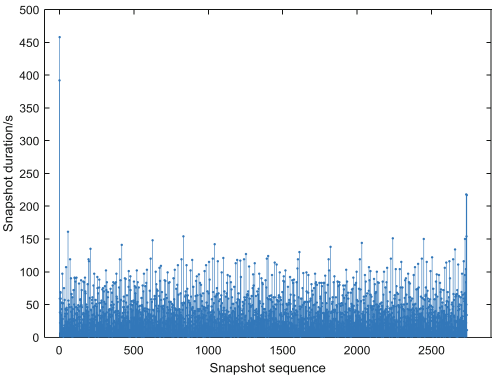
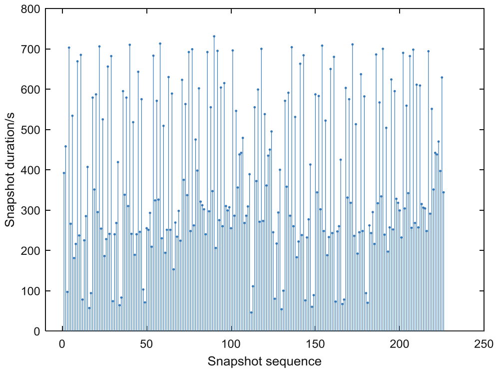


Fig. 7. The distribution of the number of IIL switching at each division time before and after optimization. (a) Before optimization; (b) After optimization.

The number and duration of system snapshots before and after optimization is shown in Fig. 8.



(a)



(b)

Fig. 8. The number and duration of system snapshots before and after optimization. (a) Before optimization; (b) After optimization.

Table 2 shows the statistical characteristics comparison of system snapshots before and after optimization. The total number of system snapshots reduced from 2737 to 226, i.e. reduced to the 8.26%. The shortest duration of system snapshots increase from 1 s to 46 s. The longest duration of system snapshots increase from 458 s to 731 s. The average duration of system snapshots increase from 31.4370 s to 378.6593 s. The reduction of the number of system snapshots can reduce the topology dynamics of DLSN while the increase of snapshot duration can make the routing algorithm have enough time in each snapshot to converge, which is of great importance to improve the data transmission performance of DLSN.

Table 2. Statistical characteristics comparison of system snapshots

Statistical characteristics	Before optimization	After optimization	Improvement
Total number	2737	226	Reduced to 8.26%
Shortest duration/s	1	46	46 times
Longest duration/s	458	731	1.6 times
Average duration/s	31.4370	378.6593	12 times

Figure 9 shows the distribution of system snapshot duration before and after optimization and it can be seen more clearly that the snapshot optimization has reduced the number of snapshots and increased the duration of snapshots.

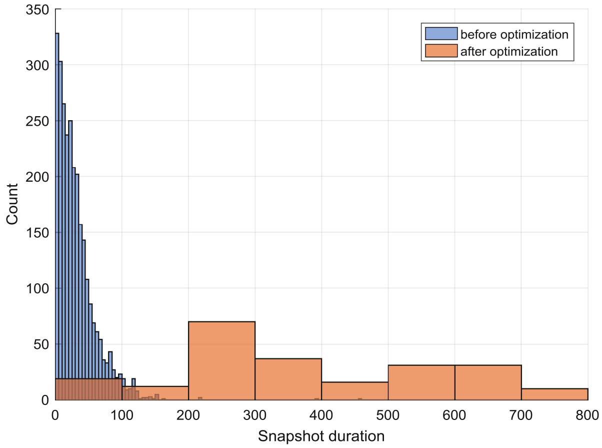
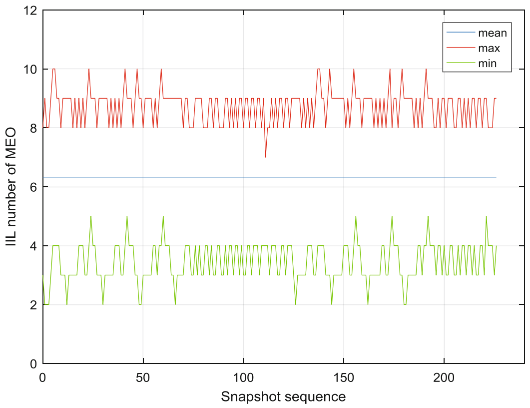
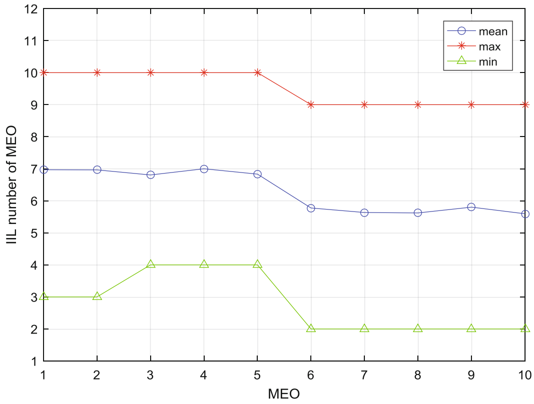


Fig. 9. The distribution of system snapshot duration before and after optimization.

For the optimized system snapshots, the number of IIL that MEO needs to establish is analyzed. Figure 10(a) shows the statistical properties of the number of IIL for all MEOs in each system snapshot while Fig. 10(b) shows the statistical properties of the number of IIL in all snapshots for each MEO. It can be seen that MEO needs to establish 10 IILs at most and 2 IILs at least. The average IIL that MEO has to establish is 7 (The statistical result is 6.3).



(a)



(b)

Fig. 10. The statistical properties of the number of IIL MEO need to establish. (a) The number of IIL for all MEOs in each snapshot; (b) The number of IIL in all snapshots for each MEO.

5 Discussion and Future Research Trends

When constructing a DLSN, each LEO satellite will generally be equipped with one IIL while the number of IILs that MEO satellites needs to be equipped should be the maximum number of IIL established by all MEO satellites. Therefore, the simulated DLSN should equip 10 IIL for MEO satellites. However, due to the reason that some MEO satellites only needs to establish 2 IILs at some time, so 8 IILs will be idle. From the point of view of efficient use of resources, this will result in wasted IIL resources. Ideally, all MEO satellites equipped with 7 IILs should be the optimum configuration. Therefore, future research emphasis should be put on how to reduce the maximum number of IILs that MEO satellites needs to establish or to conduct multi-beam antenna research to achieve multiple IILs with one antenna.

In addition, since MEO satellites should be equipped with 6–10 IILs to connect with LEO satellites as well as 4 ISLs to connect with other MEO satellites, how to equip so many antennas on one MEO satellite platform is also a problem that needs further study.

If an MEO satellite platform can only be equipped with limited IILs (e.g., less than the average 7), then there will be some LEO satellites that cannot establish IIL with MEO satellites. Therefore, how to assign IILs among all LEO satellites to achieve optimum network topology is also a research problem.

6 Conclusions

In this paper, the IIL topology of LEO/MEO DLSN is analyzed and simulated. Firstly, the visibility calculation method and establishment strategy of IIL between LEO and MEO satellite as well as the calculation and optimization of system snapshots is analyzed. Then, simulation analysis regarding the number and duration of system snapshots, IIL switching time for LEO, the number of switching IIL in each system snapshot, the number of IILs that each MEO needs to establish are presented. Finally, future research trends are discussed.

It should be pointed out that although this paper is for LEO/MEO DLSN, but the analyzed method is also applicable to GEO/MEO, GEO/LEO and other DLSN. At the same time, multi-layer satellite networks such as GEO/MEO/LEO also is applicable. Unlike double-layer satellite networks, multi-layer satellite networks needs to perform snapshot optimization in each DLSN (GEO/MEO and MEO/LEO), and combines the two DLSN optimized snapshots into whole system snapshots.

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