Inter-layer Link Design for Resource-Constrained Double-Layered Satellite Network

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Abstract. Due to the relative motion of low-orbit satellites and high-orbit satellites, the inter-layer links (ILL) of double-layered satellite networks (DLSN) need to be dynamically switched, thus causing the satellite network topology changing dynamically. Traditional inter-layer link establishment strategy is low-orbit-centric which assumes that the number of ILLs equipped on high-orbit satellite is not limited. However, actual DLSNs are generally resource-constrained, such as weight and power. Thus the number of ILLs can be equipped on one satellite is limited. Therefore, traditional ILL establishment strategy is hard to apply in practice. In this paper, we first propose an ILL establishment strategy which is high-orbit-centric. We assume that high-orbit satellites have only one ILL and use this as a precondition to establish ILL. Then, the system snapshot performances of two ILL establishment strategies under two typical DLSNs constellation configurations, which are LEO/MEO and IGSO/MEO, are simulated and analyzed. Finally, since ILL establishment strategy which is high-orbit-centric can make the ILLs of some low-orbit satellites idle for some time, we point out that further research should be carried out about how to effectively use low-orbit satellite ILLs.

Keywords: Inter-layer link design · Double-layered satellite networks · Higher-orbit-centric · Simulation analysis

1 Introduction

Since double-layered satellite networks (DLSN) can integrate the strong points of both low-orbit satellites and high-orbit satellites, it has attracted much attention in the research field [1]. Due to the relative motion of low-orbit satellites and high-orbit satellites in the DLSN, they cannot be always visible. Therefore, the inter-layer links (ILL) of the DLSN need to be dynamically switched, thus causing satellite network topology changing dynamically. Since the inter-satellite link within a layer can generally be fixed by selecting an appropriate constellation configuration [2], the dynamical topology of DLSN is mainly attributed to the continuous switching of the ILLs.

S. Sun et al. (Eds.): ICSINC 2018, LNEE 550, pp. 91–99, 2019.
https://doi.org/10.1007/978-981-13-7123-3_11

Currently, the academic community has carried out some research work on the inter-layer topological dynamics of DLSN, and mainly uses some optimal strategies to establish ILL, such as the shortest distance, the longest connection time, and the maximum resource utilization. Currently, the most popular ILL establishment strategy is based on the longest connection time strategy, that is, low-orbit satellites will choose a high-orbit satellite which has the longest predictable connection time to establish ILL [3]. Each time the ILL changes, a new topology snapshot will be generated. Since this strategy does not consider snapshot optimization issues, it will generate a large amount of snapshots and the durations of snapshots are mostly short. Zhou et al. [4] and Long et al. [5] proposed a snapshot optimization method based on snapshots merging, which can greatly reduce the snapshots amount, while at the same time, increase the snapshots duration.

Wu et al. [6] propose a concentrated link establishment strategy for ILLs of LEO/MEO satellite networks. The authors force the ILLs to be reestablished at the same time to reduce the topological dynamics. For example, for concentrated time strategy, each LEO satellite will independently find the MEO satellite that can provide the longest coverage time to establish ILL, and the next actual reconstruction time of all LEO ILLs is the minimum of all LEO theoretical reconstruction time. Because the reconstruction of the laser inter-satellite link takes a long time, the centralized ILL reconstruction strategy of DLSN will cause the MEO layer and the LEO layer to be isolated during the link reconstruction. Therefore, Li et al. [7] proposed a two-step synchronous handover scheme for laser ILLs. The authors divide the ILLs into two groups which perform ILL switching alternately. On the basis of ensuring the connectivity of satellites in two layers, the topological dynamics of the inter-layer can be reduced. Shi et al. [8] propose a traffic aware ILL selection method by considering both the flow situation of the associated nodes and the connection time of the associated nodes and obtain balanced flow distribution among high-orbit satellites.

The above ILL establishment strategy is low-orbit-centric and assumes that the number of ILLs of high-orbit satellite is not limited. However, actual DLSNs are generally resource-constrained, such as weight and power. Thus the number of ILLs can be equipped on one satellite is limited. Therefore, traditional ILL establishment strategy is hard to apply in practice [9].

In this paper, we first propose an ILL establishment strategy which is high-orbit-centric. We assume that high-orbit satellites have only one ILL and use this as a precondition to establish ILLs. Then, the system snapshot performances of two ILL establishment strategies under two typical DLSNs constellation configurations are simulated and analyzed. Finally, further research trends are pointed out.

2 ILL Establishment Strategy Which Is High-Orbit-Centric

The typical architecture of DLSN is shown in Fig. 1. Since the inter-satellite links (ISL) in the same layer can be fixed by choosing an appropriate constellation configuration [2], the topology of low-orbit satellite constellation or high-orbit satellite constellation alone can be regarded as constant. However, due to the relative motion of high-orbit satellites and low-orbit satellites, the ILLs have to be dynamically switched.

Then, it can be summarized that the topological dynamics of DLSN are mainly attributed to the dynamic switching of the ILLs.

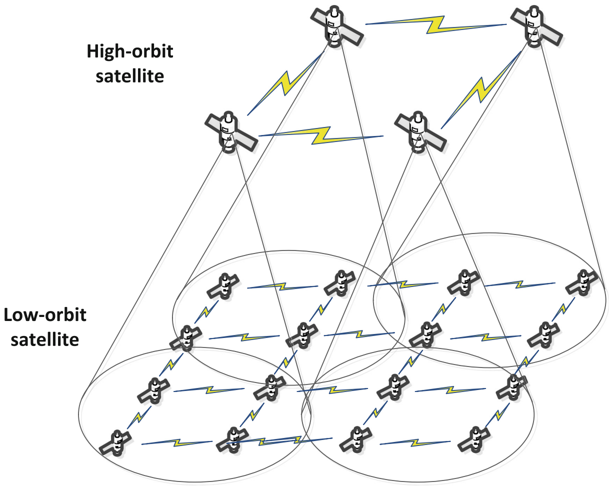


Fig. 1. Architecture of double-layered satellite networks (DLSN)

The traditional ILL establishment strategy is generally based on the longest coverage time strategy [3], where, the low-orbit satellite will choose a high-orbit satellite with longest predicted connection time in all visible high-orbit satellites until the high-orbit satellite can no longer be visible. Then, the low-orbit satellite will continue to use the same longest coverage time strategy to select the next high-orbit satellite to establish ILL.

The traditional ILL establishment strategy is low-orbit-centric, that is, all low-orbit satellites can establish ILLs with high-orbit satellites. Since the high-orbit satellites is generally less than low-orbit satellites, high-orbit satellites generally need to establish multiple ILLs. Taking the LEO/MEO constellation selected in [9] for example, the MEO needs to establish 10 ILLs at most, 2 ILLs at least, 6 ILLs on average. This poses very high requirements for the MEO satellite platform, since it should be equipped with many ILLs. Therefore, traditional ILL establishment strategy is hard to apply in practice.

We propose an ILL establishment strategy which is high-orbit-centric based on the premise that each high-orbit satellite can only establish one ILL. The ILL establishment strategy which is high-orbit-centric is described as follows: the high-orbit satellite will choose a low-orbit satellite with longest predicted visible time in all visible low-orbit satellites until the low-orbit satellite can no longer cover itself. Then, the high-orbit satellite will continue to use the same longest visible time strategy to select the next low-orbit satellite to set up ILL.

The ILL establishment strategy which is high-orbit-centric can guarantee that each high-orbit satellite only establishes one ILL, and because there are generally fewer high-orbit satellites than low-orbit satellites, it cannot guarantee that all low-orbit satellites can establish ILL.

3 Simulation Analysis

This section analyzes the ILL topology through simulation. The simulation time is 24 h and we choose the simulation step as 1 s. The simulation analysis is focusing on two typical DLSNs, one is LEO/MEO and the other is IGSO/MEO. For each type of DLSNs, traditional ILL establishment strategy which is low-orbit-centric and the proposed ILL establishment strategy which is high-orbit-centric are used to establish ILL. The snapshots are all merged using the method proposed by Zhou-Long.

3.1 LEO/MEO

The constellation configuration of the LEO/MEO DLSN selected is shown in Table 1, in which LEO adopts the Celesti constellation and MEO adopts the ICO constellation.

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

Figure 2 shows the system snapshot sequence generated by two ILL establishment strategies. Figure 2(a) shows the simulation result of traditional ILL establishment strategy, and Fig. 2(b) shows the simulation result of proposed ILL establishment strategy. From Fig. 2, it can be seen that the system snapshot generated by the proposed

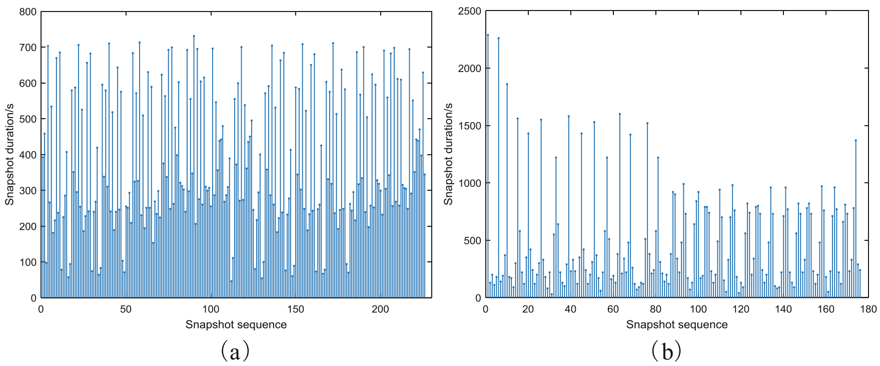


Fig. 2. System snapshot sequence generated by two ILL establishment strategies (a) low-orbit-centric, (b) high-orbit-centric

strategy is less than traditional strategy. The system snapshot duration generated by the proposed strategy is also larger than that of the traditional strategy. This is due to the reason that since there are fewer ILLs generated by the proposed strategy, the inter-layer topology may be less dynamic which is demonstrated by fewer number and larger duration of system snapshot.

Table 2. Statistical characteristics of system snapshots

Snapshots characteristics	Traditional strategy	Proposed strategy
Total number	226	176
Shortest duration/s	46	30
Longest duration/s	731	2289
Average duration/s	378.6593	485

The number and duration of system snapshots generated by two ILL establishment strategies are shown in Table 2. The system snapshot generated by the proposed strategy has a 22% reduction in number compared to the traditional strategy. In terms of time, the shortest snapshot duration is reduced, the longest snapshot duration is increased to 3.1 times and the average snapshot duration increased by 28%.

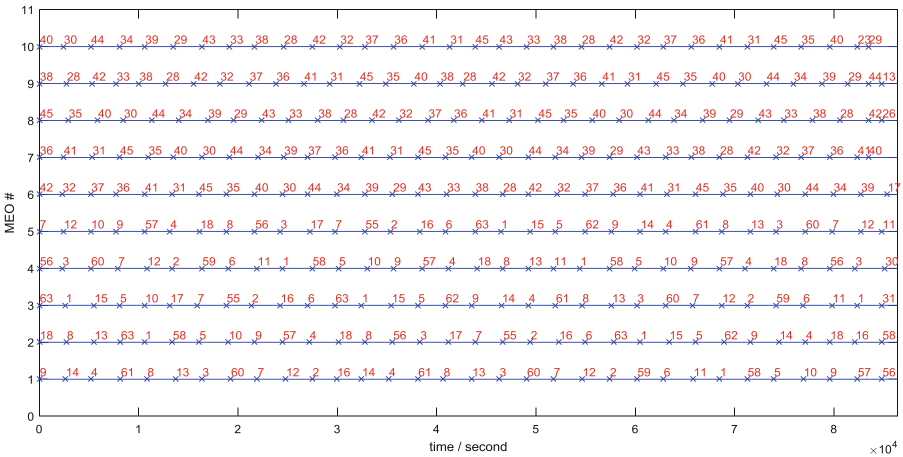


Fig. 3. The LEO satellites to which MEO satellite ILLs is connected

The visualization of inter-layer topology of LEO/MEO DLSN is shown in Fig. 3 which shows the LEO satellites to which MEO satellite ILLs is connected. The horizontal axis represents time and the vertical axis represents the MEO satellite number. The "x" symbol indicates that the MEO satellite has an ILL switch at that moment. The number in the upper right corner of the "x" symbol indicates the LEO satellite number to which the MEO satellite is switched at that moment.

The visualization from another perspective of inter-layer topology of LEO/MEO DLSN is shown in Fig. 4 which shows the MEO satellites to which LEO satellite ILLs is connected. The horizontal axis represents time and the vertical axis represents the LEO satellite numbers. The “x” symbol indicates that the LEO satellite had an ILL switch at that time. The number in the upper right corner of the “x” symbol indicates the MEO satellite number to which the LEO satellite is switched at that moment. If there is no number in the upper left corner of the “x” symbol, then the ILL of the LEO satellite will be idle after this time, i.e. no MEO satellite will establish an ILL with it. The solid line between the “x” symbols indicates that the LEO satellite established an ILL with a certain MEO satellite during that time period, and the dotted line indicates that the ILL of LEO satellite is idle during that time period.

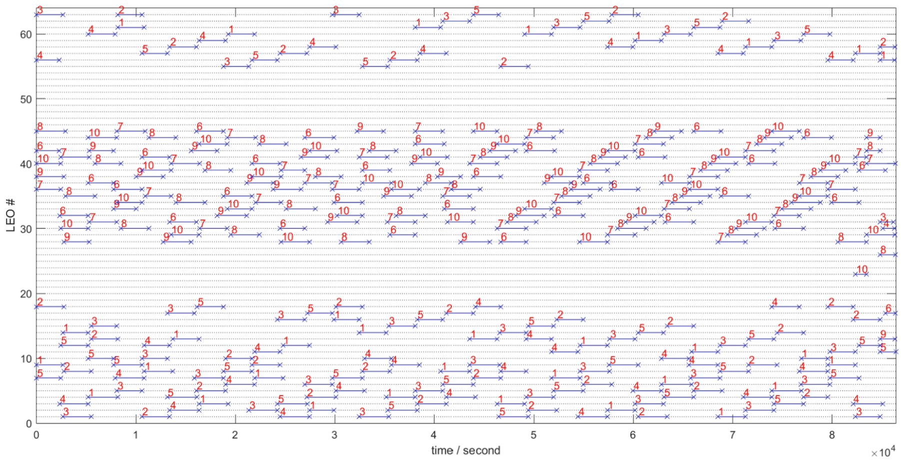


Fig. 4. The MEO satellites to which LEO satellite ILLs is connected

From Fig. 4, it can be seen that the proposed ILL establishment strategy will make the ILLs of LEO satellite idle for certain periods of time, i.e., it cannot establish an ILL with the MEO. Moreover, the ILL of some LEO satellites are always in an idle state, i.e., these LEO satellites can never establish an ILL with MEO satellites.

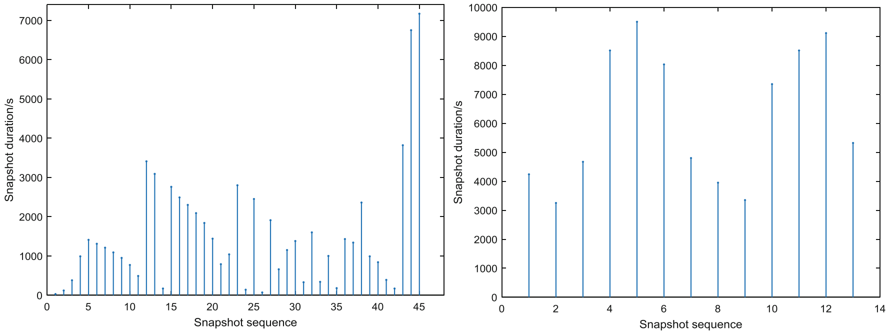
3.2 IGSO/MEO

The constellation configuration of the IGSO/MEO DLSN selected is shown in Table 3, in which MEO adopts the walker 24/3/1 constellation and IGSO adopts a constellation with the same satellite sub-point track.

Figure 5 shows the system snapshot sequence generated by two ILL establishment strategies. Figure 5(a) shows the simulation result of traditional ILL establishment strategy, and Fig. 5(b) shows the simulation result of proposed ILL establishment strategy. Similar to the LEO/MEO constellation, it can also be seen from Fig. 6 that the system snapshot generated by the proposed strategy is less and longer than that of traditional strategy.

Table 3. Constellation parameters of IGSO/MEO DLSN

Constellation parameter	MEO	IGSO
Inclination (°)	55	55
Altitude (km)	21500	35768
Number of planes	3	3
Number of satellites per plane	8	1



(a) (b)

Fig. 5. System snapshot sequence generated by two ILL establishment strategies (a) low-orbit-centric, (b) high-orbit-centric

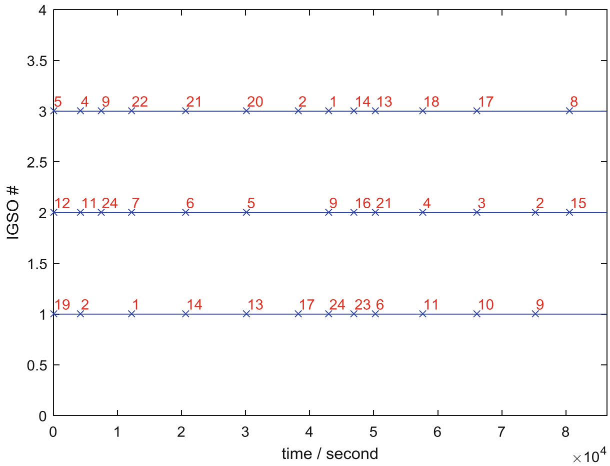


Fig. 6. The MEO satellites to which IGSO satellite ILLs is connected

The number and duration of system snapshots generated by two ILL establishment strategies are shown in Table 4. The system snapshot generated by the proposed strategy has a 29% reduction in number compared to the traditional strategy. In terms of time, the shortest snapshot duration is increased by 112 times, the longest snapshot is increased to 4 times and the average snapshot duration increased by 33%.

Table 4. Statistical characteristics comparison of system snapshots

Snapshots characteristics	Traditional strategy	Proposed strategy
Total number	45	13
Shortest duration/s	29	3250
Longest duration/s	1543	6199
Average duration/s	7170	9500

The visualization of inter-layer topology of IGSO/MEO DLSN is shown in Fig. 6 which shows the MEO satellites to which IGSO satellite ILLs is connected.

The visualization from another perspective of inter-layer topology of IGSO/MEO DLSN is shown in Fig. 7 which shows the IGSO satellites to which MEO satellite ILLs is connected. From Fig. 7, it can be seen that the proposed ILL establishment strategy will make the ILL of MEO satellite idle for certain periods of time, i.e., it cannot establish an ILL with the IGSO. This feature is similar to LEO/MEO constellation. However, in IGSO/MEO constellation, all MEO will establish ILLs with IGSO which is different from LEO/MEO constellation.

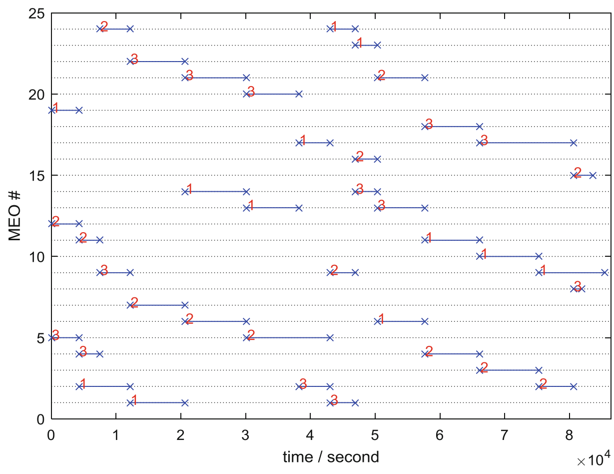


Fig. 7. The IGSO satellites to which MEO satellite ILLs is connected

3.3 Discussion

From the above simulation results we can see that since the number of high-orbit satellites is generally smaller than that of low-orbit satellites, low-orbit satellites will not establish ILL with high-orbit satellites at certain time intervals. Moreover, some low-orbit satellites can never establish ILLs with high-orbit satellites.

Therefore, in the future, we need to study how to make more efficient use of ILLs of low-orbit satellite. For example, we can make all low-orbit satellites alternately establish ILLs with high-orbit satellites to prevent some low-orbit satellites ILLs from being idle; we can also make the idle low-orbit satellites ILLs establish intra-layer links and increase the topology connectivity of low-orbit layer; or, we can just make some low-orbit satellites equipped with less ILLs to saving satellite construction cost, and so on.

4 Conclusions

In this paper, we propose an ILL establishment strategy which is high-orbit-centric. We assume that high-orbit satellites have only one ILL and use this as a precondition to establish ILLs. Then, the system snapshot performances of two ILL establishment strategies under two typical DLSNs constellation configurations are simulated and analyzed. Finally, further research interests are discussed.

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