A Time Synchronization Scheme for Large Scale Low Earth Orbit Satellite Network

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Abstract. For the application of time synchronization of large-scale low earth orbit (LEO) satellite networks, we propose a time synchronization scheme for LEO Satellite Network based on the Iridium constellation. In this scheme, we select the time reference nodes with the least weighted clock hierarchies based on the changes in network topology. The time reference nodes selection scheme calculates the time reference nodes' position in an approximately well-distributed method on each orbital plane. By weighting the nodes' clock hierarchies, the time reference nodes with the least clock hierarchies are obtained. This scheme can comprehensively calculate one or multiple time slices to obtain the optimal time reference nodes. In the nodes selection of a single time slice, three time reference nodes for each of the six orbital planes of the Iridium constellation is set as an example in this scheme. In some time slices, it is possible to achieve the maximum clock level of 1 for all satellites. Additionally, the switching of time reference nodes affects the effect and efficiency of time synchronization between satellites, therefore, we also comprehensively consider the number of switching times of the time reference nodes. We calculated the value of switching times when the time reference nodes change during the next several time slots. Furthermore, while keeping the time reference nodes unchanged for a whole cycle, we obtained the optimal combination of time reference nodes.

Keywords: Low Earth Orbit Satellite Networks · Time Synchronization · Time reference nodes Selection

1 Introduction

With the rapid constructing of large-scale satellite communication constellation, inter-satellite time-sensitive services have played an important role in the fields of finance, telemedicine, intelligent transportation, etc. Inter-satellite time synchronization is the base of the development of inter-satellite time-sensitive services, which directly affects the network bandwidth and jitter parameters of available services [1–6]. Highly stable atomic clocks are expensive, fragile and lifetime limited, meanwhile the sizes and weights increase the burden on satellites. Based on the global navigation satellite constellation, the onboard navigation receiver can also realize time synchronization with

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relatively high precision [7]. However, due to the limitation of cost and the influence of ionospheric scintillation in space environment, it is difficult to realize the synchronization of all nodes in large-scale communication satellite constellation for a long time only with the time synchronization of satellite navigation system. Deploying satellite navigation equipment in every node is also costly. How to reduce the number of satellite nodes with satellite navigation function and reduce the time synchronization levels of the whole communication satellite network is an important issue that needs to be studied emphatically. In the low orbit satellite network, the topology structure is time-varying, and the link between satellites is constantly established and interrupted [8, 9]. Therefore, the time reference node needs to be switched to achieve better time synchronization.

In this paper, a time synchronization scheme for LEO satellite network is proposed. Taking the Iridium constellation as example, it has 66 LEO satellites divided into 6 orbital planes, as shown in Fig. 1. The LEO satellites in the Iridium constellation can establish inter-satellite links with two adjacent satellites in the same orbit, and establish inter-satellite links with other LEO satellites in the different adjacent orbits. At the same time, when the satellites in high latitude areas, due to the relative speed increasing in relative motion between adjacent orbit satellites, the inter-satellite links between adjacent orbit satellites are disconnected. In the simulation, when the latitude is larger than 70°, the inter-satellite links between adjacent orbit LEO satellites are set to be disconnected. With the movement of satellites, the inter-satellite links between adjacent orbit satellites are disconnected as entering high latitude areas, and the inter-satellite links between adjacent orbit satellites are established when leaving high latitude areas. The network topology constantly changes with the latitude of the satellites. Each minute is designated as a time slice. The satellites orbit the earth once every 133 time slices. The minimum weighted clock hierarchies are used to evaluate the synchronization performance of the proposed scheme.

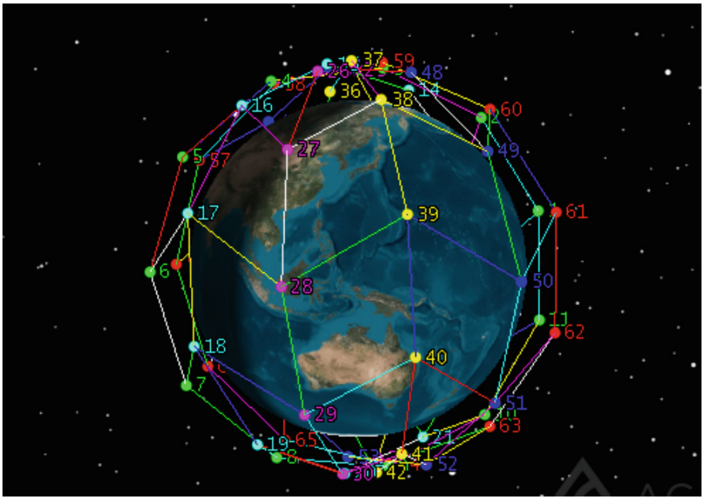

Fig. 1. Schematic diagram of Iridium constellation

In order to realize cooperation of satellites, this paper proposes a time reference nodes selection scheme for LEO satellite constellation. This selection scheme is based on the topology of the Iridium constellation. Three satellites are selected as time reference nodes in each orbital plane. Then a spanning tree can be calculated. The minimum weighted clock hierarchies is used as the goal, and the optimal time reference nodes selection scheme within a cycle is simulated. Afterwards, considering that the constellation topology changes over time, the weighted clock hierarchies also changes accordingly. In order to minimize the weighted clock hierarchies, it is necessary to select the time reference nodes for each time slice. Taking into account the clock weighted hierarchies and the number of times reference nodes switching, the minimum clock hierarchies is used as the target to switch the time reference nodes for every 1, 2, and 3 time slices, and the number of time reference nodes switching in the whole period is obtained. The results show that, although switching the time reference nodes once every time slice, the method can minimize the value of time reference nodes switching times throughout the entire cycle.

2 Time Synchronization Scheme

Building a spanning tree based on constellation topology with 3 time reference nodes selected for each orbit. In this article, we set a weighted clock hierarchies, as follows:

$$s_{j,k} = \sum_{i}^{N} a_{i,j,k} \tag{1}$$

$s_{j,k}$ represents the weighted clock hierarchies of the k-th time reference nodes combination in the j-th time slice, and N represents the number of time reference nodes in the constellation. In this article, N is 18. $a_{i,j,k}$ is the clock hierarchies of the i-th satellite in the k-th time reference nodes combination.

In order to achieve better clock synchronization accuracy, we expect clock weighting levels $s_{j,k}$ is the smaller the better. Therefore, the smaller clock hierarchy for each satellite is preferred. By evenly distributing three time reference nodes satellites on each orbital plane, with intervals of 2, 3, and 3 satellites, the clock hierarchies of the satellites can be minimized. In this way, there are 11 combinations for selecting time reference nodes for each orbital plane, and a total of 116 combinations for 6 orbital planes. We use 1–66 as the numbers for 66 satellites, with the first orbital plane numbered 1–11 and the second orbital plane numbered 12–22, and so on. Table 1 shows the 11 combinations of time reference nodes in the first orbital plane under an approximately uniform distribution. The numbers represent the satellite numbers used as the time reference nodes, with every 3 time reference nodes forming one group. So there are 18 time reference nodes in the Iridium constellation. By increasing the number of each satellite in Table 1 by 11, the time reference nodes combinations in the second orbital plane can be obtained, while the time reference nodes combinations in the other four orbital planes can be obtained using similar methods.

There are 11^6 time reference nodes combinations for each time slice, namely 1771561. We calculate the weighted clock hierarchies for each combination in each

Table 1. Time reference nodes combination for the first orbital plane

1 4 8	1 5 8	1 5 9	2 5 9	2 6 9	2 6 10	3 6 10	3 7 10
3 7 11	4 7 8	4 8 11					

time slice. For the first time slice, we calculate $s_{1,1}$-$s_{1,1771561}$. Firstly, we select 18 time reference nodes from 6 orbital planes. Secondly, based on the satellite topology of the first time slice, we obtain the connection relationship between satellites and generate a tree with time reference nodes satellite number. Finally, we calculate $s_{1,k}$ based on the spanning tree.

The sum of the minimum weighted levels for the first time slice is $\min_1 = \min\{s_{1,1}, s_{1,2}, \cdots, s_{1,1771561}\}$, and its corresponding optimal time reference nodes combination is found by the command of find($s_{j,k} == \min_1$). The minimum weighted clock levels for the first three time slices are 48, 48, and 50, respectively, and the corresponding combination numbers k are shown in Table 2. The first and second time slices each have 10 same optimal combinations. The reason is that the network topology of the first and second time slices is the same. But the topology of the third time slice network is changed with 59 optimal clock combinations.

Table 2. The clock combination sequence number with the smallest weighted level of the first three time slices

Time slice	Combination number k				
1	87913	88579	88639	95839	95899
	87913	88579	88639	95839	95899
2	87913	88579	88639	95839	95899
	87913	88579	88639	95839	95899
3	87913	88301	88712	88723	88735
	88737	89111	101597	101598	101599
	101611	107745	107757	268796	268808
	429847	429859	604341	604729	605128
	605140	605151	605539	605551	795461
	795473	795484	976078	976101	1151370
	1151382	1151770	1151793	1152181	1152192
	1152580	1166011	1166023	1166411	1166434
	1166822	1166833	1167221	1341703	1341715
	1663805	1663817	1669940	1669951	1669963
	1669965	1682451	1682825	1682826	1682827
	1682839	1683250	1683261	1683649	

The optimal combination number 87913 corresponding to the time reference nodes satellite number for the first time slice in Table 2 is shown in Table 3. The spanning tree corresponding to the 87913th combination of the first time slice is shown in Fig. 2. The hierarchies of satellites 1, 4, 8, 14, 17, 21, 23, 26, 30, 34, 37, 41, 47, 50, 54, 56, 59, 63 are all 0. The hierarchies of the rest 48 satellites of the constellation are all 1. Therefore, the $s_{1,87913}$ is 48.

Table 3. Time reference nodes numbers for six orbit planes

Orbital plane	Time reference nodes		
1	1	4	8
2	14	17	21
3	23	26	30
4	34	37	41
5	47	50	54
6	56	59	63

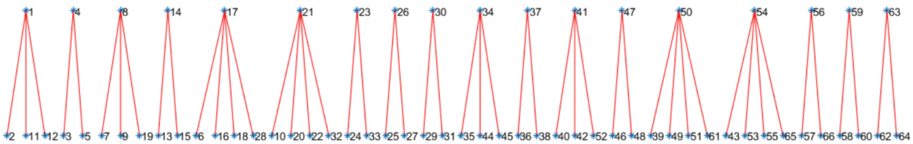

Fig. 2. The spanning tree corresponding to the 87913th combination of the first time slice.

Based on the spanning tree, we get the clock hierarchies of each satellite as shown in Table 4.

Different combinations have different spanning trees in different time slices, and the spanning tree of the 83971th combination in the 5th time slice is shown in Fig. 5 as an example. In Fig. 3, the clock hierarchy of the time reference nodes satellite 17 is 0, the clock hierarchy of satellite 18 is 1, and the clock hierarchy of satellite 19 is 2. Therefore, $a_{17,5,83971} = 0$, $a_{18,5,83971} = 1$, and $a_{19,5,83971} = 2$.

In this way, we obtained a matrix with 133 × 1771516 numbers, which is the weighted hierarchies of 1771516 time reference nodes combinations in 133 time slices. Using Eq. (2), we sum the matrix by columns to obtain the sum of weighted levels for each combination of 133 time slices, with the combination of the smallest weighted levels called the Global best with the number of 1669940. The weighted time hierarchies over 133 time slices of the Global best are shown in Fig. 4. For each time slice, we also calculated the average of 1771516 combinations corresponding to the weighted clock hierarchies by Eq. (3), which is called Average, as shown in Fig. 4.

$$Globalbest = \left\{ S_{j,k} | \sum_{j=1}^{133} S_{j,k} = \min \left\{ \sum_{j=1}^{133} S_{j,k} | k = 1, 2, 3, ..., 1771516 \right\} \right\}. \quad (2)$$

Table 4. Clock levels and values for each satellite

Hierarchy		Hierarchy		Hierarchy		Hierarchy		Hierarchy	
$a_{1,1,87913}$	0	$a_{15,1,87913}$	1	$a_{29,1,87913}$	1	$a_{43,1,87913}$	1	$a_{57,1,87913}$	1
$a_{2,1,87913}$	1	$a_{16,1,87913}$	1	$a_{30,1,87913}$	0	$a_{44,1,87913}$	1	$a_{58,1,87913}$	1
$a_{3,1,87913}$	1	$a_{17,1,87913}$	0	$a_{31,1,87913}$	1	$a_{45,1,87913}$	1	$a_{59,1,87913}$	0
$a_{4,1,87913}$	0	$a_{18,1,87913}$	1	$a_{32,1,87913}$	1	$a_{46,1,87913}$	1	$a_{60,1,87913}$	1
$a_{5,1,87913}$	1	$a_{19,1,87913}$	1	$a_{33,1,87913}$	1	$a_{47,1,87913}$	0	$a_{61,1,87913}$	1
$a_{6,1,87913}$	1	$a_{20,1,87913}$	1	$a_{34,1,87913}$	0	$a_{48,1,87913}$	1	$a_{62,1,87913}$	1
$a_{7,1,87913}$	1	$a_{21,1,87913}$	0	$a_{35,1,87913}$	1	$a_{49,1,87913}$	1	$a_{63,1,87913}$	0
$a_{8,1,87913}$	0	$a_{22,1,87913}$	1	$a_{36,1,87913}$	1	$a_{50,1,87913}$	0	$a_{64,1,87913}$	1
$a_{9,1,87913}$	1	$a_{23,1,87913}$	0	$a_{37,1,87913}$	0	$a_{51,1,87913}$	1	$a_{65,1,87913}$	1
$a_{10,1,87913}$	1	$a_{24,1,87913}$	1	$a_{38,1,87913}$	1	$a_{52,1,87913}$	1	$a_{66,1,87913}$	1
$a_{11,1,87913}$	1	$a_{25,1,87913}$	1	$a_{39,1,87913}$	1	$a_{53,1,87913}$	1		
$a_{12,1,87913}$	1	$a_{26,1,87913}$	0	$a_{40,1,87913}$	1	$a_{54,1,87913}$	0		
$a_{13,1,87913}$	1	$a_{27,1,87913}$	1	$a_{41,1,87913}$	0	$a_{55,1,87913}$	1		
$a_{14,1,87913}$	0	$a_{28,1,87913}$	1	$a_{42,1,87913}$	1	$a_{56,1,87913}$	0		

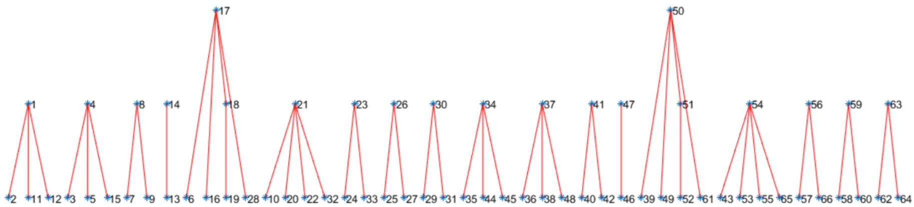

Fig. 3. The spanning tree of the 83971th combination in the 5th time slice

$$Average = \left\{ s_{j,a} | j = 1, 2, 3, \ldots, 133, \ s_{j,a} = \frac{\sum_{k=1}^{1771561} s_{j,k}}{1771561} \right\}. \quad (3)$$

Among 133 time slices, the average weighted clock hierarchies for each time slice is between 57.0874 and 58.5244. As shown in Fig. 4, the Global best is always smaller than the Average.

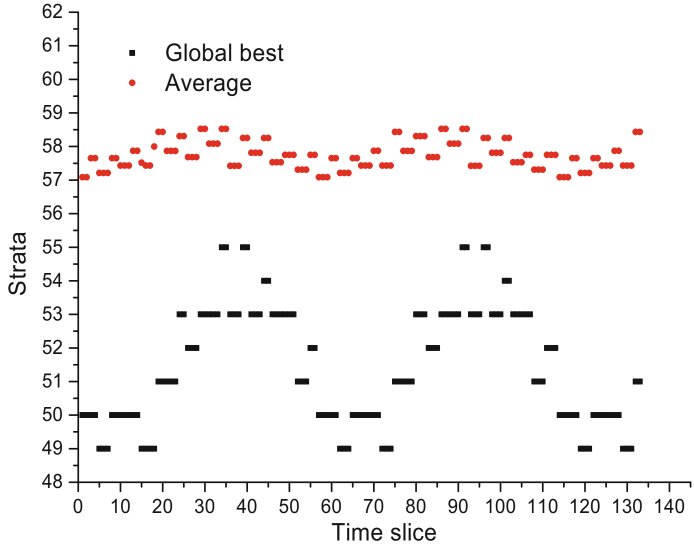

Fig. 4. The average weighted time hierarchies of 1771561 time reference nodes selection methods for each time slice, and the Global best represents the combination with the smallest weighting level value for 133 time slices

The minimum weighted time hierarchies One best in Fig. 5 for one time slice was calculated by Eq. (4).

$$\left\{\min_j | j = 1{,}2 \cdots, 133,\ \min_j = \min\{s_{j,1}, s_{j,2}, \cdots, s_{j,1771561}\}\right\} \tag{4}$$

The minimum number of weighted time hierarchies for every 2 consecutive time slices, namely the Two best is calculated by Eq. (5).

$$\begin{aligned}&\{\min_j, \min_{j+1}, \min_{133} | j = 1, 3, 5, \cdots, 131,\ \min_j + \min_{j+1} = \min\{s_{j,1} + s_{j+1,1}, s_{j,2}\\ &\quad + s_{j+1,2}, \cdots, s_{j,1771561} + s_{j+1,1771561}\}\}\end{aligned} \tag{5}$$

The minimum number of weighted time hierarchies for every 3 consecutive time slices, namely the Three best is calculated by Eq. (6).

$$\begin{aligned}&\{\min_j, \min_{j+1}, \min_{j+2}, \min_{133} | j = 1, 4, 7, \cdots, 130,\ \min_j + \min_{j+1} + \min_{j+2}\\ &= \min\{s_{j,1} + s_{j+1,1} + s_{j+2,1}, s_{j,2} + s_{j+1,2} + s_{j+2,2}, \cdots, s_{j,1771561} + s_{j+1,1771561} + s_{j+2,1771561}\}\}\end{aligned} \tag{6}$$

In Fig. 5, the strata(hierarchies) of the One best, Two best, and Three best are the same with the different time reference nodes. We calculate the minimum weighted clock hierarchies for each time slice, and calculated the switching times of time reference nodes combinations corresponding to the minimum weighted hierarchies for each 1, 2, and 3 time slices, which is shown in Fig. 6.

Each change of the 18 time reference nodes is called one switch. The One slice represents the minimum switching times of two optimal time reference nodes combination

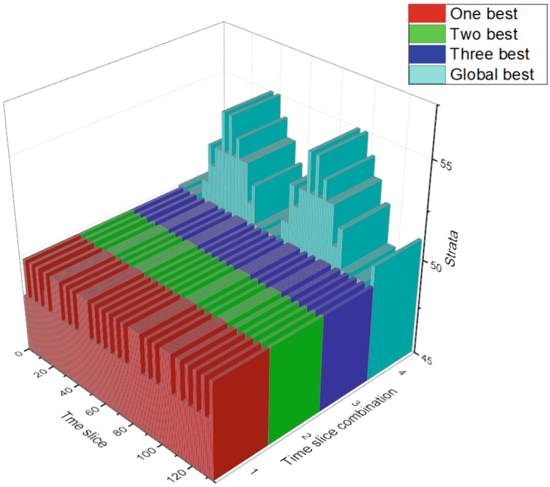

Fig. 5. Minimum weighted time hierarchies for every 1, 2, and 3 time slices (the One best, Two best and Three best) and minimum clock levels for one cycle

with two continue time slices. The optimal combination of the time reference nodes combination has the minimum weighted time hierarchies of the time slice. The Two slices represents the situation that the time reference nodes are changed every two time slices. When switched from the previous two time slices to the next two time slices in the Two slices scheme, the combination is selected by the scheme of the Two best. Similarly, the Three slices represents switching times of the time reference nodes every three time slices. When switching from continuous three time slices to the next three time slices, the combination is selected by the scheme of the Three best. After calculation, a total of 270 switching times are required for the One slice within a cycle. By switching every 2 time slices, a total of 388 switching times are required. By switching every 3 time slices, a total of 483 switching times are required. The switching times of the One slice are less than that of the Two slices and Three slices. The reason is that the optional combinations in the Two best and Three best with the minimum strata are less than that of the One best and the differences between two adjacent combinations in the Two best and Three best are larger than that of the One best.

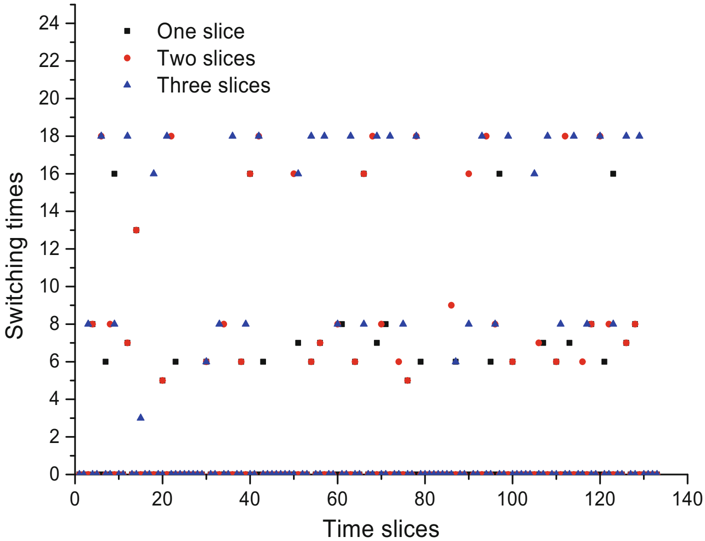

Fig. 6. Switching times of time reference nodes combinations corresponding to minimum weighted levels for each 1, 2, and 3 time slices

3 Conclusion

This article takes the Iridium constellation as an example to consider using 18 time reference nodes for better time synchronization, while also considering the issue of switching time reference nodes in different slices. We divide the operating cycle of the Iridium constellation into 133 time slices. With the motion of the satellites, the links between adjacent satellites in adjacent orbits will connect or break, resulting in changes in satellite topology between different time slices. This article takes three satellites selected from each orbit as an example to distribute the time reference nodes in an approximately even manner within each orbit. In this case, there are a total of 11^6 possible combinations for each time slice. This article obtains a spanning tree for each combination based on the constellation topology of each time slice, and then calculates the weighted clock hierarchies based on the spanning tree. The minimum weighted hierarchies can achieve the best clock synchronization effect. The number of switching times between different time slices to obtain the minimum weighted hierarchies is also calculated, taking into account the clock synchronization effect and time reference nodes switching.

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