An Effective Topology Design Based on LEO/GEO Satellite Networks

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Abstract. The time-varying topology brings great challenge to the design of the satellite network routing. The key to designing high performance routing is how to handle the time-varying topology. Considering comprehensive advantages of both LEO and GEO satellite networks, a novel double-layered satellite network suitable for space networking is established in this paper. In this model, the ideas of virtual node strategy and satellite grouping are adopted, and the coverage of each LEO satellite is regarded as a virtual node of the network. Different from previous work, the influence of the polar boundary on the division of the satellite footprint is taken into account, such that the upper management satellites are able to accurately acquire the topology of the lower satellites. Using the improved virtual node strategy, the time slices in the network has significant changes, which are better than those in other models in terms of quantity, length and other aspects. The fact is verified by simulation.

Keywords: Satellite networks · Time slices · Coverage unit
Satellite grouping

1 Introduction

Space information network is a network system constructed for acquiring, transmitting and processing spatial information, which plays an important role in communication, navigation, and timing, positioning and monitoring [1]. In the network, all kinds of nodes continue to move, and the links are intermittently connected, such that the whole network has complex time-varying topology. As the backbone of space information network, satellite network, to some extent, affects the overall performance of space information network. Recently, satellite network has attracted more and more attention because of its wide coverage, broadcast capability and high bandwidth service level,

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which will become the bridge of global information transmission and access at a lower cost no matter when and where, so it is an important part of the next generation of Internet [2, 3]. According to the altitude of the satellites, satellite orbits can be divided into geostationary earth orbit (GEO), middle earth orbit (MEO) and low earth orbit (LEO). GEO satellites are about 36 thousand kilometers above the equator, and remain relatively stationary. The longer distance enables the larger coverage, such that only one GEO satellite can cover 40% of the entire earth surface. But it is the distance that leads to larger propagation delay between the GEO satellites and the ground [4]. On the contrary, LEO satellites with orbit altitudes of 500 km to 1500 km have small coverage and shorter distance from the ground. Larger movement speed of LEO satellites results in dramatic topology change over time [5]. An advantage of LEO satellites is that smaller propagation delay is true of real-time transmission service. Thus, the use of only LEO constellation or GEO constellation cannot give full play to their own advantages. In this paper, a novel double-layered satellite network suitable for space networking is established in consideration of the advantages of both LEO and GEO satellites.

Traditional routing schemes cannot be directly applied in satellite networks due to complex topological changes. Routing has become a difficult problem to be resolved in satellite networks and the key is how to deal with the time-varying topology.

Despite those, satellite motion is periodic and predictable, and the nodes and links in network have good symmetry. In order to make it more convenient to design superior routing, many effective methods to deal with the time-varying topology have been proposed and studied. The virtual node strategy proposed in [6] can well deal with the motion of satellite nodes. The idea is to divide the earth surface into several logical regions, each of which is bounded to the satellite that is nearest to it. Each time the satellite leaves a logical area, it is replaced by the next incoming satellite known as the succeeding satellite. For satellite network with a simple and regular structure, the method can shield the mobility of satellites, and what is only considered is logical region instead of mobile satellite nodes. [7] discusses the handover topic between the ground and the satellites, and it enables one ground area served by multiple LEO satellite nodes simultaneously. [8] lowers the complexity of routing computation by utilizing the feature of grid topology, but ignores the survivability of LEO satellite. The virtual node strategy can effectively deal with mobility of nodes, but only aims at the simple and regular topology such as polar LEO constellation. In addition, it is difficult to be extended to general multilayer satellite network.

Another typical approach to handling the time-varying topology is virtual topology strategy. The idea is that the network system cycle is divided into several discrete time slices, in each of which the network topology is regarded as fixed, and then routing can be designed based on these time slices [9]. The method based on dynamic detection [10], in essence, is a typical routing algorithm based on virtual topology strategy, which determines whether the link is normally connected using the periodic detection and confirmation of the number of packets in the queue of the sending satellites. [11], based on virtual topology, solves the problem that the time contact window cannot be fully utilized in the process of downloading data from multiple satellites to the ground station. The virtual topology strategy helps calculate the time slices in advance, but a large number of time slices may require a large amount of storage space.

In satellite networks, the number, length and uniformity of the time slices have significant influence on the network performance. The number of time slices reflects the degree of frequent changes in network topology, and the length reflects the duration of contact between the satellites and the ground or between the satellites and the satellites. The topology performance of the satellite network can be improved by reducing the number of time slices, increasing the length of the time slices and increasing the uniformity of the time slices. According to the traditional way of dividing the time slices, as soon as any link is switched, one new time slice is generated. [12] studies the time slices of satellite network in detail according to the method of virtual topology. And the results show that the number of time slices is large and the length is uneven, which is particularly evident in multilayer networks. For example, for the double-layered network consisting of 7×9 polar LEO constellation and 2×4 MEO constellation with orbit inclination of 45°, the network topology changes 1892 times, and the maximum length of the time slices is only 29 s in the 7 h of simulation.

Satellite grouping and group management strategy is widely studied in multilayer satellite network. [13] applies virtual nodes into lower layer of multilayer network. Lower-layer satellites that can directly communicate with one upper-layer satellite form one group of this upper-layer satellite. But a large number of discrete time slices are generated because of complex connection relation between lower and upper layer, resulting in huge storage overhead. [14, 15], to some degree, reduce the number of time slices by merging time slices. Similarly, [16] also uses satellite grouping methods. Unfortunately, one of the common defects of these methods is that the lower-layer topology information may not be accurately obtained by the upper-layer management satellites.

In order to further solve the problem of time-varying topology of satellite networks, this paper improves the virtual node strategy in consideration of the influence of the polar boundary on the division of the satellite footprint, and this makes it possible that the upper satellites can get accurate topology of lower-layer network. So it will bring convenience to the design of multilayer satellite network routing. In this way, the network topology has been greatly improved, and produces a small number of uniform time slices, which can further improve the performance of network routing.

The remainder of the paper is organized as follows. Section 2 introduces the double-layered satellite network model and the related definitions, while Sect. 3 is the analysis of the network topology. Performance evaluation is given in Sect. 4. Section 5 summarizes main conclusions.

2 Model and Related Definitions

2.1 Real Network Model

A double-layer satellite network composed of LEO and GEO satellite constellation is shown in Fig. 1. The GEO constellation consists of 3 GEO satellites equally spaced over the equator. The LEO constellation is slightly modified from the Iridium system, a typical LEO constellation widely used [17]. The LEO constellation used in the paper is composed of 72 LEO satellites, uniformly distributed in 6 polar orbit planes. The other parameters of the constellation are the same as those of Iridium system.

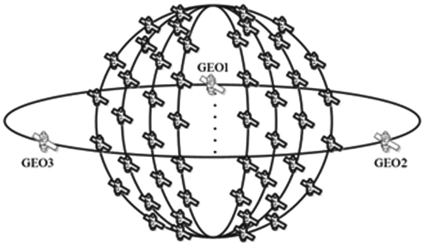

Fig. 1. Real double-layered satellite network model

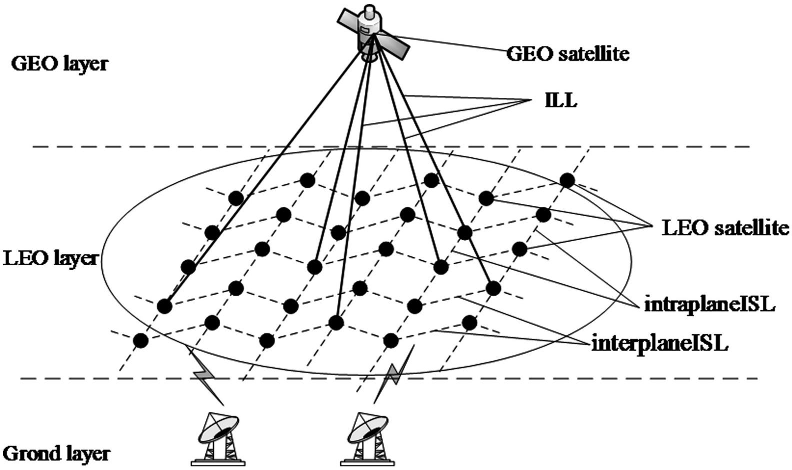

Fig. 2. Network nodes and links

There are several types of nodes and links in the network, as shown in Fig. 2. The network nodes include ground terminals, LEO satellites, and GEO satellites. Links include: (1) The inter-layer links (ILL) consisting of links between LEO and GEO satellites. One LEO satellite can communicate with one GEO satellite if and only if the LEO satellite is in the coverage area of the GEO satellite. (2) The intra-plane links (intra-ISLs) between two adjacent satellites through the same orbital. Clearly, each orbit of LEO layer has intra-ISLs with the same number as satellites through it, while the GEO layer has only 3 intra-ISLs. (3) The inter-plane links (inter-ISLs) between adjacent satellites through adjacent orbits. It should be noted that the motion direction of the satellites through the first LEO orbit is in opposition to those through the last orbit, and so there is no inter-ISLs between these satellites. In addition, there is no inter-ISL in high latitude areas, because the relative angular velocity of satellite motion is larger, and the pointing and tracking of antennas cannot meet the demand. Obviously, inter-ISL does not exist in GEO layer. (4) The user data links (UDLs) connecting terminals and satellites. One ground terminal can communicate with one satellite if and only if the ground terminal is within the minimum elevation angle of the satellite.

2.2 Related Definitions

To facilitate the description and analysis of network topology, the following concepts need to be given.

One coverage unit of one LEO satellite is defined as a set of ground nodes that can directly communicate with the satellite at a given moment. One coverage set is a set consisting of the coverage units of all LEO satellites at a given moment. Standard position refers to the position where the prime meridian and the first orbit of LEO layer are in the same plane, and the first satellite through the orbit is in the same plane with the equator. One standard coverage unit is one element of one coverage set when the LEO layer is in the standard position. Obviously, at any given time point, any LEO satellite has one standard coverage unit that may not belong to itself. In addition, we say one down-satellite link exists between the two standard coverage units of two LEO satellites if one of the following two conditions is satisfied. The conditions are: (1) there is intra-ISL between the two satellites, and (2) the two satellites are not in polar region and there is inter-ISL between them.

A virtual LEO satellite network (VLSN) is a graph G(t) = (V, E(t)), where V and E(t) are the set of coverage units and down-satellite links at time t, respectively. A normal virtual LEO satellite network (NVLSN) is one VLSN where LEO layer is in the standard position.

The NVLSN of the LEO layer in this paper is shown in Fig. 3. The latitude of the polar boundary is 80° and the reason is explained in Sect. 3. In Fig. 3, each vertical line represents a satellite orbit; each dot represents one LEO satellite. The unit in the picture is angular distance. A circle with a radius of 30° represents a standard coverage unit.

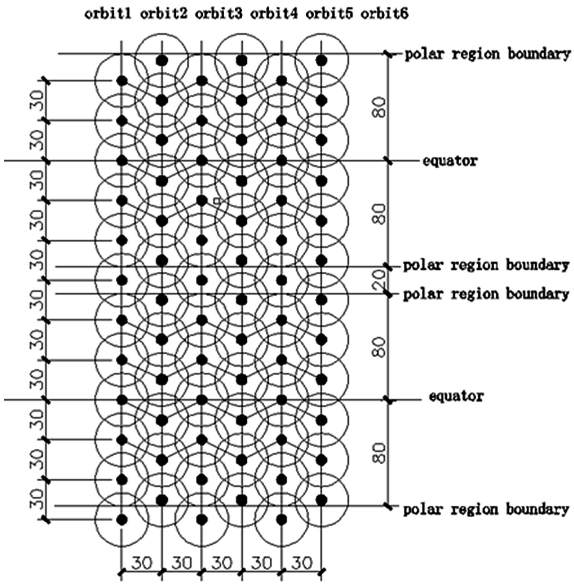

Fig. 3. Description of NVLSN

Orbit 1, orbit 3 and orbit 5 are traversed by the first and seventh satellite above the equator. The satellite directly connected with the first satellite through orbit 1, orbit 3 or orbit 5 is the corresponding first satellites through orbit 2, orbit 4 or orbit 6.

At a certain moment, if the LEO satellite is within the footprint of one GEO satellite, the standard coverage unit below the satellite is a member of the GEO satellite. Obviously, any GEO satellite has many members. A set of all members forms a group of one GEO satellite group manager. It is important to note that the concepts of group member and group manager are different from those in other literatures.

2.3 Virtual Network Model

A virtual terminal-LEO-GEO satellite network system (VTLGN) refers to the network consisting of ground nodes, standard coverage units of LEO layers, GEO satellites, and links between them, which is defined as a graph G = (V, E), where V = {v | v is terminal or standard coverage unit or GEO satellite}, E = {e | e is down-satellite link or ILL or UDL}.

3 Topological Analysis of VTLGN

The VTLGN network model has the advantages over other networks in many ways. The flowing topology analysis is carried out based on VTLGN.

Theorem 1: If G = (V, E) is VTLGN network, G1 is one GEO satellite, and S is one standard coverage unit, then group members of G1 and group manager of S are both uniquely determined at any time point.

Proof: According to the definition of group member, the essence of group member is the standard coverage unit, and the GEO satellite is relatively stationary to ground. So, any GEO satellite and any member of its group remain relatively stationary at any time point, that is, any standard coverage unit and group manager remain relatively stationary at any time point. So group members of G1 and group manager of S are uniquely determined at any time point.

Theorem 1 shows how to use VTLGN to avoid the mobility of actual physical satellite nodes in satellite networks. If one standard coverage unit in VTLGN is regarded as a virtual node, then dynamic property of satellite network is completely shielded. So what needs to be considered is only standard coverage unit when designing routing.

Theorem 2: In VTLGN, when there are some failed LEO satellite nodes, the maximum number of time slices that can accurately reflect the network topology is equal to the number of satellites through one LEO orbit, and the length of the time slices is uniform.

Proof: Each GEO satellite is stationary relative to its members, i.e., there is no link handover, so only LEO layer topology needs to be considered. The time interval required for a LEO satellite to move from the current position to that of the next satellite is noted as dt, then dt = T/m according to the synchronization of satellite motion, where T is the orbital period of LEO satellites, and m is the number of satellites through one orbit. The worst case is that whenever a failed satellite moves to the next position, the standard coverage unit of the next location fails. If the system period of LEO layer is discretized into m time slices [0, dt), [dt, 2dt), …, [(m–1)dt, mdt], at each time slice, the topology of the network can still be considered as a static topology even when some LEO satellite nodes fail. So the m time slices can reflect the network topology of the LEO layer.

As mentioned in section one, general satellite grouping strategy cannot accurately describe the topology of LEO layer. Figure 4 shows the influence of polar region on the topology of LEO layer. At a certain moment, an inter-ISL exists between LEO satellite S11 and S21, but it disappears after very small time. However, during the small time interval, if the two satellites are still in the same group of one manager, then the change of the link state cannot be captured by the manager.

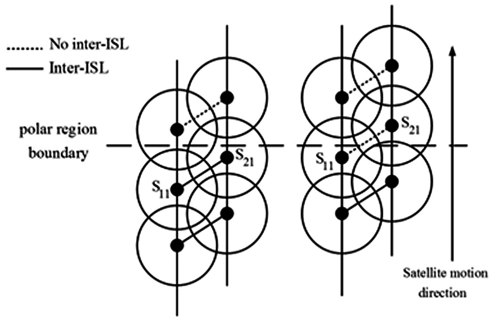

Fig. 4. The influence of polar region on the topology of LEO layer

The VTLGN network proposed in this paper can solve the above problems perfectly. Since any LEO satellite is idealized as a standard coverage unit fixed on the earth, it does not change as the satellite moves. Therefore, as long as a standard coverage unit is affected by a polar region, there is no down-satellite (inter-ISL, in essence) between it

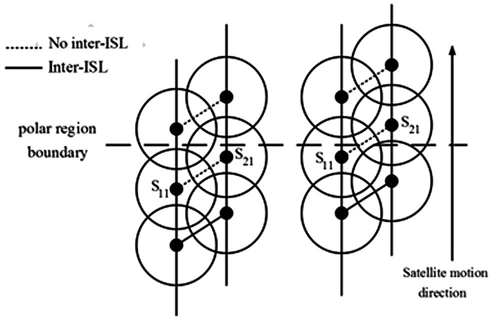

Fig. 5. Polar topology processing in VTLGN

and any other standard coverage unit. As shown in Fig. 5, as long as part of footprint of S21 moves to the polar region, the actual inter-ISL is considered to be absent. One result of this is the decline in the number of inter-satellite links in LEO layers. However, considering the huge routing overhead resulted in dynamic topology, such treatment is suitable. Moreover, by appropriately increasing the latitude value of the polar area boundary, a very small decrease in the number of links cannot significantly affect the performance of the entire network, so the problem is easy to solve.

4 Performance Evaluations

The VTLGN network model proposed in this paper aims to deal with the time-varying topology caused by nodes movement in satellite networks, which is superior to other network topology models in terms of the length and number of time slices. To illustrate this, we carried on the simulation experiment, and the results are compared with those of other classical single-layer and multilayer constellation topologies.

The single-layer constellations mainly include the Walker constellation and the polar orbit constellation. The distribution of time slices in Walker constellation is mainly related to phase factor, while that of polar orbit constellation is only related to the latitude value of polar region boundary [12].

We use Celestri, Teledesic and Iridium constellations for simulation. The results are compared with those in [12] and the simulation parameters are shown in Table 1. The distribution of time slices of several typical single-layer constellations is shown in Table 2, which is obtained by simulation in a complete cycle of each constellation. As can be seen from Table 2, the NVLSN proposed in this paper has the smallest number of time slices, and its time slices are uniform, so it is better than the Celestri, Iridium, and Teledesic constellation.

Table 1. Simulation parameters of single-layer constellations

	Orbit altitude	Orbit inclination	Number of orbit	Satellite number through one orbit
NVLSN	780 km	90^o	6	12
Celestri	1400 km	45^o	7	9
Iridium	780 km	86.4^o	6	11
Teledesic	1375 km	84.7^o	12	24

Table 2. Comparison of topological performance of single-layer satellite networks

	Number of time slices	Maximum length of time slices	Minimum length of time slices
NVLSN	12	500 s	500 s
Celestri	252	49.54 s or 29.34 s	6.64 s or 26.84 s
Iridium	44	213.93 s	60.01 s
Teledesic	48	133.77 s	105.78 s

For general multilayer satellite networks, besides the change of LEO layer topology, the links between layers also affect the distribution of time slices. As mentioned earlier, a large number of uneven time slices are generated in satellite grouping method.

We choose the Tr constellation and the LMSN model as a contrast. In addition to the simulation time, the other parameters are the same as those in [14, 15]. Table 3 lists the distribution of time slices of several typical multilayer constellations. Time cycle of 24 h is adopted for reasonable contrast. It can be found that VTLGN proposed in this paper is very suitable for the satellite network, which cannot produce fewer slices but can still guarantee the uniformity of time slices even when some satellites fail. It is convenient for the design of multilayer satellite network routing.

Table 3. Comparison of performance of multilayer satellite network topology

	Number of time slices	Average length of time slices	Time slices uniformity
VTLGN	173	500 s	Uniform
Post-merger Tr	644	133.77	Not uniform
Pre-merger Tr	5340	16.16 s	Not uniform
Post-merger LMSN	644	133.77 s	Not uniform
Pre-merger LMSN	3776	22.81 s	Not uniform

5 Conclusions

In satellite network, the use of only LEO or GEO constellation for space networking cannot give full play to each constellation. The periodic motion of satellite nodes results in time-varying network topology, which makes it difficult to design high performance routing techniques. In order to solve these problems, the paper establishes a new network model and topology based on LEO and GEO constellation, where the advantages of integrated LEO and GEO constellations are considered and the idea of virtual node strategy is improved. The theoretical and experimental results show that the network topology has more advantages than that of other satellite network models.

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