The Design of Inter-satellite Link Topology Based on Time-Slot Allocation Technology

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Abstract. Inter-satellite networking is the development trend of satellite navigation system through inter-satellite link technologies. How to schedule inter-satellite link resources is the key to whether the navigation satellite constellation network has the best performance in the time division multiple access system. To achieve this goal, this paper assumes a linking rule based on a multi-layer satellite constellation and constructs a corresponding mathematical model to describe the linking process of inter-satellite links. Based on the assumed linking rule and the proposed mathematical model, a time-division topology design scheme is proposed. The process of data transmission is simulated with the simulation software MATLAB and STK. The results show that the inter-satellite network topology generated under this scheme gets a very considerable promotion on inter-satellite measurement accuracy and transmission characteristics.

Keywords: TDMA · Inter-satellite link · Time-division topology Simulation

1 Introduction

In the navigation satellite system, the topology of the inter-satellite network depends on factors such as constellation configuration, the shaped-beam and scanning range of onboard antenna, and network topology control strategy [1]. The interaction between satellites relies mainly on inter-satellite links for connecting satellite nodes. The inter-satellite link (ISL) plays an important role in satellite constellation communication networks. Especially in satellite navigation systems, it is mainly used for inter-satellite communications and inter-satellite ranging. At present, only GPS is used to apply the inter-satellite link technology more skillfully when other navigation systems are still at a preliminary stage of development in this technology [2].

The inter-satellite links work under the TDMA system in GPS, with the frame as the minimum period and the time slot as the minimum unit. The communication channel resources are used by all satellites in the constellation in the form of frame-timeslot. How to generate the topology of the inter-satellite link network in time-division multiplexing mode to minimize data transmission time is one of the most important issues in satellite network management.

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The design of time-division topology in satellite networks is based on time-slot allocation of inter-satellite links. At present, the research results for the time-division inter-satellite link topology generation issues are as follows: Literature [3] proposed a slot seize-able TDMA mechanism under the definition of a new TDMA frame structure and preemptive mode, using the vertex coloring in graph theory to allocate time-slots. Although this method can reduce the communication time-delay, there is no guarantee that the inter-satellite links will work efficiently. In literature [4], the time-division inter-satellite link topology generation problem based on Walker constellation is studied, and the topology structure that minimizes the data transmission time while satisfying the transmission constraints is proposed. The literature [5] presented an inter-satellite links time-slot allocation and design based on STDMA.

Most previous works have focused on the inter-satellite topology design of a single-layer constellation, and there are few researches for time-division topology of multi-layer constellations. This paper adopts MEO + GEO/IGSO constellation model, inter-satellite links are divided into intra-layer ISLs and inter-layer ISLs by orbit altitudes of satellites [6]. Within the simulation analysis of the constellation, this paper proposes an inter-satellite link time-slot allocation scheme to obtain the time-division topology of satellite network, which provides a basis for further research.

2 Constellation Network Topological Characteristics Analysis

2.1 Double-Layer Satellite Network Structure

The spatial system studied in this paper consists of twenty four MEO satellites, three GEO satellites, three IGSO satellites and three ground stations. According to the altitude of orbits, it can be divided into the following two satellite layers:

1. Medium Earth Orbit Satellite

All MEO satellites in this layer are organized in the form of Walker constellation. The satellite orbits of Walker constellation use equal height and inclination. The satellites are evenly distributed across the orbits. The constellation configuration is $N/P/F$, where N represents the number of satellites in the whole constellation, P denotes the number of orbits, and F represents the phase of the eastern orbital over the western side [7]. The system in this paper adopts the configuration of Walker $24/3/1$.

2. High Earth Orbit Satellite

GEO is located above the equator. It has the advantages of global coverage, less switching and simple control. IGSO have the same altitude as GEO and have the same inclination angle as MEO. They mainly provide coverage of polar regions in high latitudes [8].

2.2 Visibility Analysis

For running satellites, the necessary and sufficient condition for visibility is that the line that connects two satellites does not intersect the earth [9]. Figure 1 is a schematic diagram of the inter-satellite link. Assuming the earth is a sphere, then O is the earth core, R_e is the radius of the earth, S_1 and S_2 are two satellites on the orbit, respectively, and their orbital radiuses are respectively r_1 and r_2. Among them, the elevation angle of S_1 is ε, θ is geocentric separation angle, d and h are the instantaneous distance and vertical distance of the two satellites, respectively.

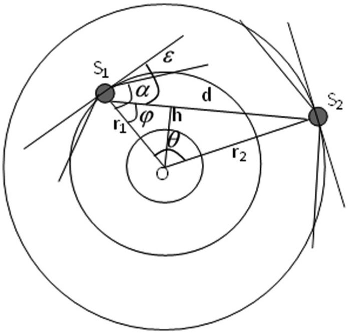

Fig. 1. Inter-satellite link schematic diagram.

According to the sine theorem, the following formula can be obtained.

$$\frac{d}{\sin\,\theta} = \frac{r_2}{\sin\,\varphi}. \tag{1}$$

According to the cosine theorem, the following formula can be obtained.

$$d = \sqrt{r_1^2 + r_2^2 - 2r_1 r_2 \cos\,\theta}. \tag{2}$$

According to the geometric relationship in Fig. 2, we get the following equation.

$$h = r_1 \cos\,\varepsilon = r_1 r_2 \sin\,\theta/d. \tag{3}$$

The function that describes whether two satellites are visible to each other is defined as follows.

$$\Delta h = h - R_e. \tag{4}$$

On the other hand, the satellite will not be visible because of the antenna scanning range constraint (α), so the satellite and link normal angle should satisfy the following relationship.

$$\varphi < \alpha. \tag{5}$$

So the inter-satellite visible satellite set is $\gamma_S = \{S|\Delta h > 0 且 \varphi < \alpha\}$, and only the satellites that meet the visibility conditions can establish the inter-satellite links.

3 Time-Division Topology Design

3.1 Time Division Multiple Access Mode

The Ka-band is adopted to establish the links between satellites in this paper, and the satellite antenna is a kind of narrow-beam antenna. Thus, the ISL adopts the connection mode of point-to-point in the TDMA mode. Each satellite links with other satellites in turn according to the allocated time-slots in a frame. In order to reduce the interference among beams, it is assumed that there is only one antenna on each satellite for linking between satellites, that is, each satellite has only one inter-satellite link in each time-slot. A time slot reflects a linking of satellite networks, the topology of the inter-satellite link may change only when the time-slot changes.

The satellite-site link is not the main research content of this paper. In order to reduce its influence on the inter-satellite link, it is assumed that the satellites use the additional frequency band and antenna to transmit data with ground stations. The ground stations do not participate in the time-slot allocation.

3.2 Link Characteristics Analysis

Due to the large orbital radius, GEO satellites and IGSO satellites will have large time delays, it is sensible to consider using ISL within the MEO layer for information forwarding. Since the characteristics of the satellites in Walker constellation are consistent, taking MEO21 as an example to describe the characteristics of inter-satellite links. From the inter-satellite visibility analysis in Sect. 2.2, each MEO satellite has eight satellites that are continuously visible. These satellites can be used as the linking objects of complete links. Among them, four satellites are in the same orbit as MEO21, and the remaining four are evenly distributed on the other two orbits.

The system model can be established quickly by STK. Then let STK connect with MATLAB through STK/MATLAB interface. Establishing a connection between the objects and producing a report is achieved through the command ‘stkAccReport’ which can return the related information when there is a path between the two objects. Use the command ‘stkFindData’ to export the required data from the report, such as the visible time and distance of the two objects. It is known from STK that the average visible MEO satellite number of each MEO satellite is about sixteen.

3.3 Time-Division Topology Design

The inter-satellite link system designed in this paper is using the time-division transmission mode. Assuming that the slot-size is five seconds, the time for each MEO satellite to link with all visible satellites respectively is about 16 time-slots, then the frame-size is eighty seconds.

As the satellites keep moving, their inter-satellite visibility also changes. Through finite state thought, two satellites that are visible at any moment in each frame are defined as visible, and they are defined as invisible once they are not visible at a certain moment. After processing in this way, the distribution strategy of inter-satellite links is simplified.

Mathematical Definition and Description. 24 MEO satellites are numbered by 1–24. GEO satellites are numbered by 25–27, and IGSO satellites are numbered by 28–30. The definition and description of the symbols involved in the algorithm are as follows.

(1) There are three ground stations in the system. Define the matrix $V_1 = \left[v_{ij}\right]_{30\times3}$ to be a visibility matrix of satellite-site in a frame.

$$v_{ij} = \begin{cases} 1, & \mathrm{S}_i \text{ and } \mathrm{P_j} \text{ are visible} \\ 0, & \mathrm{S}_i \text{ and } \mathrm{P_j} \text{ are unvisible} \end{cases}. \tag{6}$$

The satellite with the number 'i' is denoted by S_i and the ground station with the number 'i' is denoted by P_i. In this paper, a satellite that is not visible to all three ground stations is defined as an overseas satellite, and a satellite visible to at least one ground station is defined as a domestic satellite.

(2) Define the matrix $V_2 = \left[v_{ij}\right]_{30\times30}$ to be an inter-satellite visibility matrix in a frame.

$$v_{ij} = \begin{cases} 1, & \mathrm{S}_i \text{ and } \mathrm{S_j} \text{ are visible} \\ 0, & \mathrm{S}_i \text{ and } \mathrm{S_j} \text{ are unvisible} \end{cases}. \tag{7}$$

(3) Define the matrix $C = \left[c_{ip}\right]_{30\times16}$ as the time-slot allocation matrix of all the satellites within a frame, where the element c_{ip} represents the linking satellite of S_i in the $p-th$ time-slot. It should be noted that C_M denotes the time-slot allocation matrix of MEO satellites. Because the links are bidirectional, the elements in C must satisfy the following formula.

$$c_{c_{ip}p} = i. \tag{8}$$

(4) Define the matrix $T = \left[t_{ij}\right]_{30\times30}$ as the inter-satellite network topology matrix in a time-slot.

$$t_{ij} = \begin{cases} 1, & \text{ISL established between } \mathrm{S}_i \text{ and } \mathrm{S}_j \\ 0, & \text{No ISL established between } \mathrm{S}_i \text{ and } \mathrm{S}_j \end{cases}. \tag{9}$$

Link Priority. For the multi-layer satellite network designed in this paper, there are multiple types of inter-satellite links. In order to achieve the best performance of time-slot allocating, adopt the principle that the links with high quality link first. The priority analysis of inter-satellite links is performed below.

The inter-satellite link can be divided into inter-layer links and intra-layer links according to the different orbit altitudes of the satellites. Inter-layer links include GEO-MEO links and IGSO-MEO links. The inter-satellite distance is too large, resulting in poor link quality and lower priority than intra-layer links.

The intra-layer links include IGSO/GEO intra-layer links and MEO intra-layer links. For links in sub-constellations consisting of GEO satellites and IGSO satellites, since the high-orbit satellites are mainly used as relay satellites in the system, time-slots are not allocated for this type of links. The links in MEO layer can be divided into complete links and incomplete links according to whether the two satellites are continuously visible during a constellation period or not. Because the complete link can remain unblocked throughout the period, it can be used as the basis for link design, and its priority is higher than incomplete link. Complete links can be further subdivided into same-track links and off-track links. The same-track links have slow-changing inter-satellite distance and fixed topology attributes. Therefore, the priorities are greater than the complete links of the different tracks.

Intra-ISL Design. According to the inter-satellite visibility analysis, each MEO satellite has eight completely visible satellites and eight incompletely visible satellites during a constellation period. Taking MEO21 as an example, the design process of its links in a certain frame is as follows.

(1) Read the matrix V_2 to obtain all the satellite numbers that are permanently visible and intermittently visible with MEO21, and arrange the eight complete links into the first eight time-slots of the time-slot allocation matrix according to the link priority. The incomplete links are arranged into the last eight slots. Due to the instability of the topology of incomplete links, the time-slot arrangement changes with time and is represented by $s(t)$, and the matrix C_M can be obtained as follows

$$C_M = \begin{bmatrix} \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 1 & 6 & 11 & 12 & 14 & 15 & 17 & 20 & s(t) \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix}_{24\times 16}. \tag{10}$$

(2) The eight complete links of the MEO satellite consist of four same-track links and four off-track links. In accordance with the link priority, the complete same-rack links are placed in the first half of the first eight slots, and the complete off-track links are put into the second half of the first eight slots. Then the matrix C_M can be obtained as follows.

$$C_M = \begin{bmatrix} \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 11 & 12 & 14 & 15 & 17 & 20 & 6 & 1 & s(t) \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix}_{24\times16}. \tag{11}$$

(3) Considering that the purpose of introducing the inter-satellite link technology is to enhance the communication of domestic and overseas satellites, for the two satellites within the borders at the same time, the existence of inter-satellite links reduces the data transmission efficiency on the contrary. Read the satellite-site visibility matrix V_1 to obtain the probability that other satellites will be visible to the ground stations when the MEO21 is out of the borders, and arrange them in descending order to obtain the following matrix C_M.

$$C_M = \begin{bmatrix} \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 12 & 14 & 11 & 15 & 1 & 17 & 6 & 20 & s(t) \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{bmatrix}_{24\times16}. \tag{12}$$

Since these links are always present, all the frames in the constellation period can be arranged in this way.

For incomplete links, the inter-satellite visibility changes with time, so the time-slot allocation also changes accordingly. Each MEO satellite in the frame has eight satellites that are intermittently visible. The longer the visible time is, the higher the quality of the incomplete link is. Similar to the method of allocating the complete links, the satellites are listed in the last eight time-slots in descending order of the visible time to the ground stations. The stability of the incomplete link is poor. On this basis, the matrix V_2 restrains the invisible satellites establishing a link. Therefore, the links that do not exist are set to zero in matrix C_M.

Other MEO satellites are arranged according to the above method on the premise of satisfying bidirectional linking, and a complete MEO intra-layer link allocating matrix C_M can be obtained.

Inter-ISL Design. High Earth Orbit satellites are added on the basis of the links within the MEO layer. The HEO satellites have strong coverage. When the number of MEO satellites in the country is insufficient, they can be forwarded to satellites outside the borders through HEO satellites. The allocating method of HEO satellites is as follows: In the condition that two satellites are mutually visible, the satellites with a small number of inter-satellite links are preferentially selected for linking, and a complete time-slot allocation matrix C for all satellites can be obtained.

In order to reduce the number of routes and improve the efficiency of relaying, the domestic and overseas links in C are eliminated, and the corresponding positions of the original links are set to zero. Then connect the free domestic satellites to the overseas satellites and get the final time-slot allocation matrix in the frame as follows:

$$C = \begin{bmatrix} M_i & M_j & M_m & M_n & 0 & M_k & \cdots & G_p \\ \vdots & \vdots & \vdots & \vdots & I_q & M_l & \cdots & \vdots \end{bmatrix}_{30\times 16}. \tag{13}$$

Time-Division Topology Generation. Every satellite is connected to another satellite and switches to another satellite in the new time-slot. It keeps the topology of the network unchanged in a time-slot, but will be regenerated following the time-slot allocating matrix when the next time-slot arrives. The topology matrix is continuously updated during a constellation period to generate the inter-satellite link network topology in TDMA mode.

The element c_{ip} in the time-slot allocation matrix C indicates that S_i and $S_{c_{ip}}$ have an inter-satellite link in the $p-th$ slot of the frame. A complete topology matrix of the satellite network in the time-slot can be obtained from the slot matrix column vector.

$$t_{ij} = \begin{cases} 1, & \mathrm{j} = c_{ip} \\ 0, & \text{others} \end{cases}. \tag{14}$$

Among them, '1' indicates that there is an inter-satellite link between S_i and S_j in the $p-th$ time-slot, '0' indicates that there is no inter-satellite link at this time.

4 Simulation Analysis

The performance of the designed mixed links and complete links is simulated from two aspects of inter-satellite transmission performance and inter-satellite orbit determination below. The transmission performance reflects in the domestic and overseas communication delays and the positioning accuracy is based on the position dilution of precision of the satellite.

1. Position dilution of precision

The effect of constellation geometry on the pointing accuracy of satellites is usually described by dilution of precision. This paper takes the position dilution of precision as the basis for measuring the link location accuracy. A small PDOP value means that the navigation constellation has a better geometric configuration. Taking the MEO21 satellite as the locating point, the PDOP values were calculated by MATLAB and STK under the complete link and mixed link. The simulation result is shown in Fig. 2.

From Fig. 2, it can be found that the PDOP values of the constellation are distributed between 1.3 and 1.4 in the time division topology scheme using the mixed links proposed in this paper, and that of the complete links are approximately 3 to 5. It can be seen that the inter-satellite link topology obtained by the method designed in this paper has higher accuracy in ranging and the positioning performance is superior to the complete link.

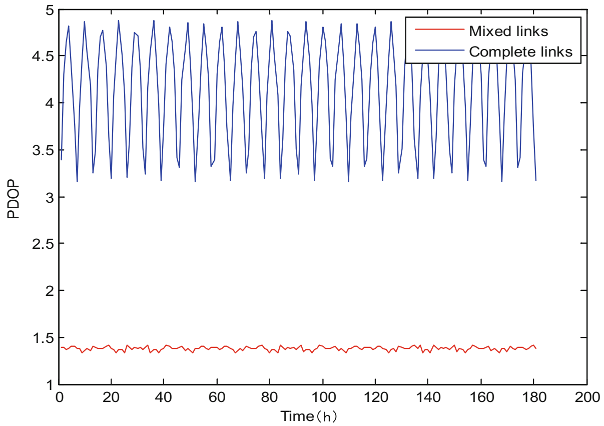

Fig. 2. The comparison of PDOP values.

2. Domestic and overseas communication delay

Figure 3 shows the average communication delay of a ground station to overseas satellites under two linking allocations.

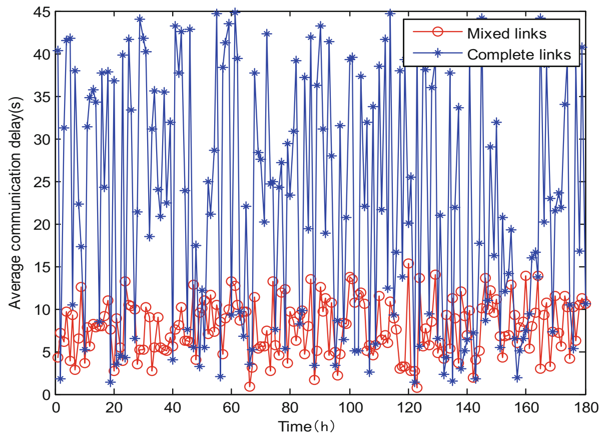

Fig. 3. Communication delay comparison diagram.

It can be seen from Fig. 3 that the average communication delay under the scheme of the mixed links is about 6 s, and that of complete links is about 20 s. It can be seen that the scheme of the mixed links greatly shortens the delay of domestic and overseas communications and improves communication performance.

5 Conclusion

Based on the analysis of the link characteristics and linking feasibility of the 24/3/1 Walker + GEO/IGSO multi-layer satellite constellation, a time-division topology generation scheme for the inter-satellite link network is proposed in this paper. The process of linking is described in detail based on the principle that high-quality links link first. The simulation and performance evaluation of the scheme has proved that the proposed scheme has good communication performance and positioning accuracy.

The topology generation scheme in this paper is only a preliminary result. The next step will continue to improve the proposed model in order to accommodate the more complex transmission requirements in inter-satellite link networks.

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