Modeling and Analysis of Inter-Satellite Link based on BeiDou Satellites

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***Abstract*—According to the development planning of BeiDou Navigation Satellite System (BDS), a triple-layered satellite network architecture serving as relay satellite is studied. On this basis, the spatial information system of satellite network architecture is analyzed; the satellite network dynamic topology model is established. The geometrical properties of inter-satellite links (ISLs) are studied deeply with comparing the encounter duration of satellites in different orbits. Having analyzed the simulation results by Satellite Tool Kit (STK), the connectivity features of the ISLs were acquired, and topology structure evolution laws of satellite network were also obtained. The simulation result shows that adopting IGSO satellites as relay satellites enables better stability of elevation angle, which is convenient to trace the antenna of satellite and establish high quality links. Moreover, full-time ISLs could be established by using MEO satellites serve as relay satellites and is able to ensure that at least 15 inter satellite links could be established.**

Keywords-satellite relay; dynamic topology model; encounter duration; inter-satellite link.

I. INTRODUCTION

Due to the Earth's curvature and the linear propagation characteristics of radio waves, for observation satellites at low Earth orbit, the transmission efficiency (ratio of real-time transmission time and satellite on orbit time) is being in an extremely low state. The expansion of base station can not fundamentally solve the problem [1].

Artificial Earth Satellite can be divided into several types considering its orbit altitude, as low Earth orbit (LEO) satellite, medium Earth satellite (MEO) and geostationary Earth orbit satellite (GEO). Relay satellites are generally GEO satellites, and the information between the user spacecraft and the Earth station is transmitted by it. Its favorable geometric position solves the above problems effectively, which makes it has many advantages such as good real-time performance and high coverage. This greatly improves the transmission efficiency of LEO observation satellites.

BeiDou Navigation Satellite System plans to build 5 satellites in GEO, 27 satellites in MEO and 3 in inclined geosynchronous satellite orbit (IGSO) [2]. The system will be able to provide a powerful autonomous navigation and positioning service when it is completely deployed. The abundant satellite resources of the BeiDou could be used in relay services, which will greatly shorten the delay of satellite data transmission.

The key technology of the BeiDou satellite as data relay service is the establishment of inter-satellite links. However, due to the complexity and dynamic characteristics of the satellite network topology, inter-satellite link (ISL) handoff problem becomes more serious [3]. No matter it is a multi-layer satellite network, or a single-layer satellite network, the relative motion between satellites on different orbital planes, leads to the change of ISL is more frequent, and thus brings serious challenges for the design of network protocols [4]. Therefore, ISL design is an essential part of satellite network research, since it affects the overall performance of the network. Z. Wang proposed the positional relationship and the necessary conditions using two satellites to establish a permanent ISL [4]. Liu proposed the theoretical formula of the ISL performance of non-geostationary Earth orbit (NGEO), and analyzed the variation law of ISL performance with the change of constellation parameters [5]. Gao made a thorough study on satellite network geometry model, and deduced the equation of link distance and elevation angle [6]. Based on the analysis of the geometric parameters between LEO and MEO satellite layer, L. Wang proposed an analytical formula of ISL spatial geometry parameters with time variation [7]. However, these studies did not take into account the effect of relay satellites in different orbit altitude. We proposed triple-layered satellite network architecture based on BeiDou Navigation Satellite System, and analyzed inter-satellite connectivity and elevation angle to investigate the possibility of BDS satellites serving as relay satellites in this paper.

The rest of the article is structured as follows: In section II, the network architecture of BeiDou Navigation Satellite System is studied and dynamic topology network model is proposed; in section III, a comparison is discussed among satellites of different orbits to serve as relay satellites; in section IV, the performance of BeiDou Navigation Satellite System is analyzed. Finally, the conclusion and future work are given in section V.

II. ANALYSIS AND MODELING OF SPACE INFORMATION SYSTEM STRUCTURE

The topology of Spatial Information System is the basis of information exchange and sharing, and it is also the primary problem to be faced by dynamic network topology. In this section, a triple-layered MEO/IGSO/GEO satellite network architecture serving as relay satellites based on BeiDou Navigation Satellite System is studied firstly, and

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the spatial information system of satellite network architecture is analyzed.

A. Structure Analysis of Spatial Information System

The space segment of BeiDou Navigation Satellite System is constituted of MEO group satellites, IGSO satellites and GEO satellites. The spatial information system can be regarded as triple-layered satellite network structure shown in Figure 1. It is composed of the MEO constellation, IGSO constellation, GEO constellation and ground stations. Ground stations communicate with each other via wired networks.

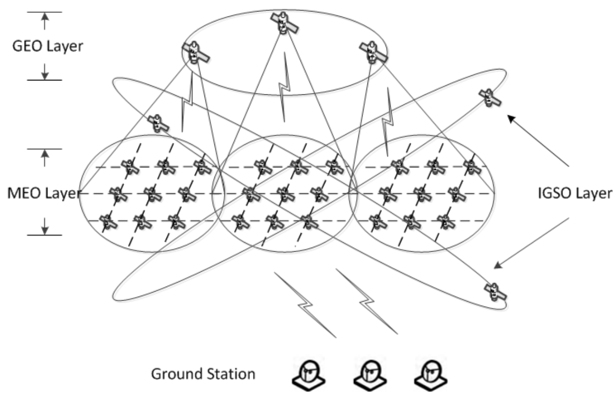

Figure 1. Satellite network structure with MEO / IGSO / GEO

According to the design of BeiDou satellite constellation, the whole spatial information systems can be divided into three satellite layers.

- GEO layer. Geosynchronous orbit lies directly over the equator and the satellite in the orbit is relatively stationary to the Earth. GEO satellite network has advantages over fewer switching, simple control of satellite tracking and global coverage. Suppose the total number of satellites in GEO layer is N_G, single GEO satellite is expressed as G_i, $i=1,2,\cdots N_G$.
- IGSO layer. IGSO was designed primarily to meet the needs of the information transmission for Polar areas. IGSO satellites have the same orbital altitude as GEO satellites; therefore they possess the same orbital period as the Earth's rotation period. IGSO constellation possesses a high efficiency use of the regional constellation, ranging between GEO and MEO. Suppose the total number of IGSO satellites is N_I, single IGSO satellite is expressed as I_i, $i=1,2,\cdots N_I$.
- MEO layer. The visibility time of single MEO satellite up to 1h ~ 2h. Although the two-hop transmission delay is longer than LEO satellite, concerning the entire length of the inter-satellite links, on-board processing ability and other factors, the delay performance of MEO constellation may be better than LEO constellation. Relative to LEO constellation, MEO constellation owns a lower switching probability, reduced Doppler Effect, simplified space control system and antenna tracking system. Suppose the total number of MEO satellites is N_M, single MEO satellite is expressed as M_i, $i=1,2,\cdots N_M$. Triple-layer satellite network maintains three types of full-duplex links.

Inter satellite link is the foundation of satellite communication, and ground station establishes a data link connection to the satellite when it is in the coverage of the satellite.

B. Dynamic Topology Modeling of Spatial Information System

The body of BeiDou Navigation Satellite System is 27 MEO satellites, which are distributed in 3 orbital planes according to the walker constellation. Assuming that the configuration code of a Walker constellation is N / P / F, which respectively corresponds to the number of satellites, orbital plane number and phase factor [8]. Configuration code of MEO constellation in BeiDou Navigation Satellite System is: 27/3/1, that is, there are three orbital planes, each of which has nine satellites, and the phase factor is 1. The right ascension and angular distance of the ascending node are described by (1), in the equation i represents the number of plane while j represents the number of satellite in one orbit plane.

$$\begin{cases} \Omega_{ij} = \dfrac{360}{P}(i-1) \qquad (i=1,2,\cdots,P) \\ u_{ij} = \dfrac{360P}{N}(j-1) + \dfrac{360}{N}F(i-1) \qquad (j=1,2,\cdots\dfrac{N}{P}) \end{cases} \tag{1}$$

According to trajectory equations of circular orbit satellite in ECI coordinates, the trajectory equation of satellite in the space described as Equation (2) could be deduced via geometric analysis of orbital dynamics and spherical geometry [9].

$$\varphi = \arcsin[\sin(i)\sin(\theta)] \tag{2}$$

$$\lambda = \Omega_0 + \arctan[\cos(i)\tan(\theta)] + \begin{cases} -180^\circ (-180^\circ \le \theta \le -90^\circ) \\ 0^\circ (-90^\circ \le \theta \le 90^\circ) \\ 180^\circ (90^\circ \le \theta \le 180^\circ) \end{cases} \tag{3}$$

In Equation (3), φ, λ represent satellite latitude and longitude on the celestial sphere; θ represents the angular distance of the ascending node; γ_0 represents the initial phase of the satellite; ω represents the angular velocity of the satellite rotation around the Earth; Ω_0 represents satellite

Right Ascension of Ascending Node (RAAN); i represents the orbital inclination angle.

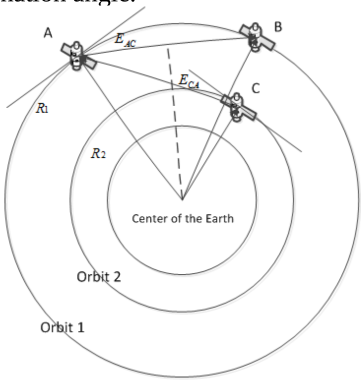

Figure 2. Link length and visibility schematic

As shown in Figure 2, A and B are two satellites lie in the same orbital altitude, and satellite C lies in a lower orbit, the link between satellite A and B is intra-plane ISL, while the link between satellite A and C is a cross-layer link, inter-plane ISL. Distance between satellites can be calculated through spherical geometry, and the distance of intra-plane ISL is deduced by(4).

$$d_{AB} = \sqrt{2}R_1\sqrt{1-\cos\angle AOB} \tag{4}$$

Specially, when A and B are two adjacent satellites in the walker constellation, the distance equation is transformed into (5).

$$d_{AB} = \sqrt{2}R_1\sqrt{1-\cos\frac{2\pi P}{N}} \tag{5}$$

The distance of inter-plane ISL is:

$$d_{AC} = \sqrt{R_1^2 + R_2^2 - 2R_1R_2\cos\angle AOC} \tag{6}$$

$\angle AOC$ and $\angle AOB$ can be calculated according to the latitude and longitude of the two satellites [10], and the representation of $\angle AOB$ is described as (7).

$$\begin{aligned}\angle AOB = \arcsin[&\sin(\varphi_A)\sin(\varphi_B) + \\ &\cos(\varphi_A)\cos(\varphi_B)\cos(\lambda_A-\lambda_B)]\end{aligned} \tag{7}$$

Elevation angle is of great significance for inter-satellite data transmission, since with the elevation increases, multipath and shadowing problems will be eased so that the quality of the ISL is improved. Transient elevation angle E_{AC} and E_{CA} can be expressed as (8) and (9).

$$E_{AC} = \arccos[\frac{R_2\sin(\theta)}{d_{AC}}] \tag{8}$$

$$E_{CA} = \arccos[\frac{R_1\sin(\theta)}{d_{AC}}] \tag{9}$$

Multi-layer satellite ISL connectivity is determined by the running status of satellites, at the same time, the Earth and the atmosphere covered the ISL, so orbit altitude and satellite distribution should be taken into consideration when designing satellite constellation, making it possible to obtain more inter satellite visible time. In judging whether the Earth will obstruct to the ISL, the ISL protection clearance should be taken into consideration as well [9]. Assuming that H is the protection clearance, and d is the distance between ISL and the center of the Earth, to meet the satellite ISL is not covered, H and d should satisfy (10).

$$d \geq R + H \tag{10}$$

Among them, R is the radius of the earth.

III. TOPOLOGY NETWORK SIMULATION AND ANALYSIS

In the simulation experiment, BeiDou satellites are selected as the relay satellites; the monitoring satellite lies in low Earth orbit is selected as the access satellite; three ground stations, Beijing, Sanya and Mudanjiang are selected as data receive station. A comparison is discussed among satellites of different orbits to serve as relay satellites in the possibility of link establishment and elevation angle.

A. *GEO Satellites as Relay Satellite*

Geostationary satellite lies in high orbit position, and its relative position is stable regardless of the Earth's movement, its relatively static properties make it possible for GEO satellite to serve as a data relay satellite. As is shown in Figure 3, the visibility between GEO satellites and three ground stations is permanent, so only the visibility between LEO and GEO satellites needs to be considered, then we can determine the feasibility of the inter satellite link.

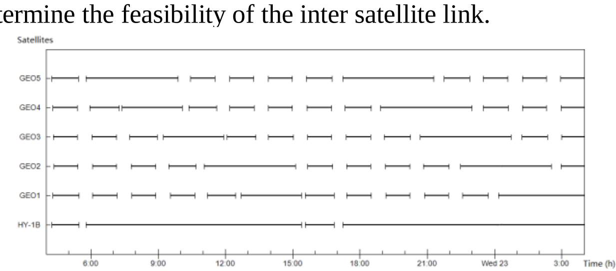

Figure 3. LEO satellite - GEO satellite visibility

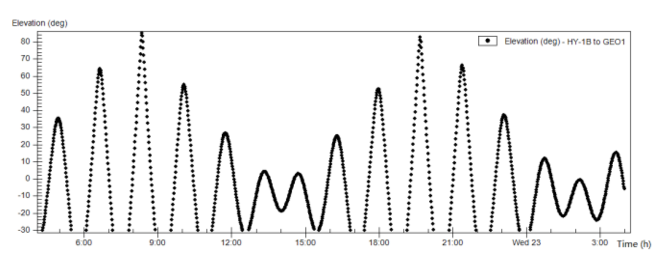

Figure 4. Elevation Angle between LEO satellite and GEO satellite

In Figure 3, LEO satellite can establish a long time inter satellite link with GEO satellites. Total coverage time between LEO and GEO satellites is 82341s, accounting for 95.30% of the total time, and each of 5 GEO satellites has a long time visibility, the shortest time is 64317s, accounting for 74.50% of the total time. GEO satellites are able to establish more permanent connection to the LEO satellite. For the most of time, more than one GEO satellite exists in the visibility range of the LEO satellite, the selection between satellites depends on the visibility time in order to reduce handover. Due to the high orbital position, inter-satellite links do not exist between GEO satellites. The elevation angle between LEO satellite and single GEO satellite is shown in Figure 4, changes periodically.

B. *IGSO Satellite as Relay Satellite*

IGSO satellite shares the same orbit altitude with GEO satellite. Different from GEO satellites, due to the orbital plane is inclined; its star point track on the Earth surface is '8' shaped, and this kind of satellite make up for the deficiency of the GEO satellite's incomplete coverage in polar areas. Adopting IGSO satellite as a relay satellite, single satellite cannot achieve full-time coverage to the ground station, but 3 satellites working together can achieve full-time coverage; Figure 5 shows the visibility between LEO satellite and IGSO satellites.

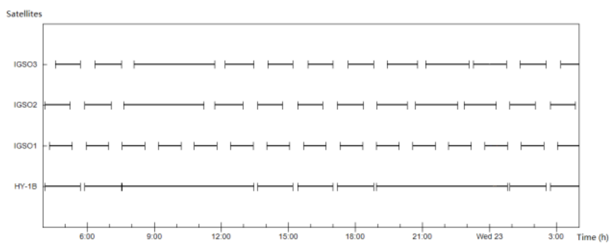

Figure 5. LEO satellite - IGSO satellite visibility

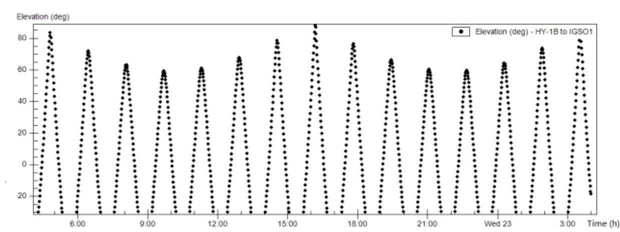

Figure 6. Elevation Angle between LEO satellite and IGSO satellite

As is shown in Figure 5, total coverage time between LEO and IGSO satellites is 81485 s, accounting for 94.31% of the total time. Due to the business characteristics of observation satellite, data from Polar Regions is particularly significant. IGSO satellites can provide data relay services for blind area [11], where GEO satellite failed to provide total coverage in polar areas. However, as is shown in Figure 6, the elevation angle between LEO satellite and single IGSO satellite stays in a high level compared changes with GEO satellites, which is benefit to the establishment of high-quality ISLs.

C. *MEO Satellites as Relay Satellite*

The problem will be more complicated when the MEO satellite group serves as relay satellites. Two types of ISLs, intra-plane ISL and inter-plane ISL exist in MEO constellation, intra plane ISL connecting satellites within the same orbit and inter-plane ISL connecting satellites in adjacent orbits [12].

1) *Analysis of ISLs in MEO constellation*

In circular orbit satellite constellation, the distance between adjacent satellites is constant within same obit plane; but the length of inter-plane ISL is alterable periodically according to the satellite network topology. Figure 7 shows the distance of intra-plane ISL and inter-plane ISL if Sat_{ij} is used to denote the orbit number of the satellite j in plane i .

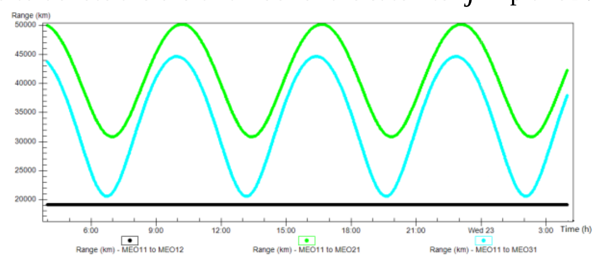

Figure 7. MEO-MEO ISLs analysis

As is shown in Figure 7, the distance between Sat_{11} and Sat_{12} is stable, about 19088 km, and the distance between Sat_{11} and Sat_{21} changes periodically, the distance between satellites is different because of the existence of phase factor and the inclination of the orbit. Multi-ISLs could be established while the visibility is constrained, but this will greatly increase the system cost and receive low profits. In the existing satellite system, only the Iridium constellation [13] uses ISL technology: two intra-plane ISLs and two inter-plane ISLs. The Iridium system using polar orbit satellite constellation, which makes inter-plane ISLs stable, and satellite antenna tracking can be realized reliably.

2) *Visibility analysis bewteen MEO satellite group and LEO satellite*

The same with IGSO satellite, single MEO satellite could not cover ground stations at any time, but MEO satellite group working together can achieve full-time coverage. In the MEO constellation, satellites are evenly distributed in 3 orbital planes. The visibility analysis between LEO satellite and satellites in one orbital plane can represent the whole constellation. Figure 8 shows the visibility between LEO satellite and MEO satellites in one orbital plane.

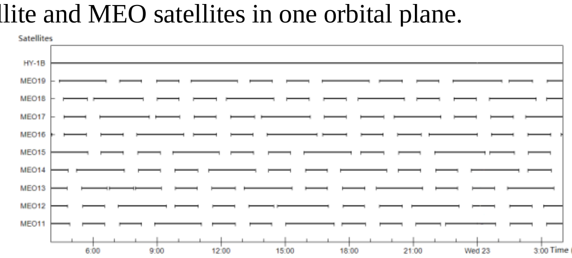

Figure 8. LEO satellite - MEO satellite visibility

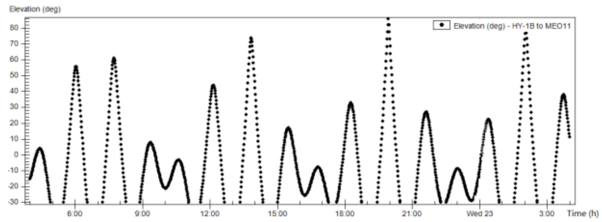

Figure 9. Elevation Angle between LEO satellite and MEO satellite

As is shown Figure 8, due to the shelter of the Earth, full-time ISL could not be established between LEO satellite and single MEO satellite, but for one orbit plane in the MEO satellite constellation, full-time ISL could be established, and be able to ensure that at least 5 MEO satellites in the LEO visibility range and this number goes up to 15 for the whole constellation.

Figure 9 shows the elevation angle between LEO satellites and MEO satellites, and the angle stays in low level for the most of time compared with GEO satellites. Moreover, MEO satellites do not possess the strong ability as GEO satellite, complicated antenna tracking technology and strong communication ability are required.

IV. PERFORMANCE ANALYSIS

In this section, the experiment parameters are given firstly, and then the performance of relay satellites in different orbits is analyzed especially in satellite connectivity.

A. *Data Trasmission Without Relay Satellite*

The BeiDou satellite constellation consists of 5 GEO satellites and 30 non-GEO satellites, which contains 27 MEO satellites and 3 IGSO satellites. 27 MEO satellites are evenly distributed on three orbit planes, and every 9 satellites are evenly distributed in an orbit; the monitoring satellite lies in low orbit, as a data collecting satellite. Specific parameters are shown in Table I.

TABLE I. SATELLITE ORBIT PARAMETER

Orbit type	LEO	MEO	IGSO	GEO
Altitude (km)	973	21528	35786	35786
Inclination Angle(degree)	99.34	55	-	0
Period (s)	6626.17	46393.9	86170.5	86170.5
Satellite Number	1	27	3	5
Orbit Number	1	3	3	1
Phase factor	-	1	-	-

Figure 10 shows the visibility between LEO satellite and ground stations, as we can see from the figure, the visible time between the satellite and the ground station is very short. The time for LEO satellite to cover ground stations is 9023 s, accounting for 10.44% of the total time, and in the rest of the time, the link is failed to establish. So, for a long period of time, data could not be transmitted to the ground station, and the satellite needs to transmit the data to ground stations until the satellite cross the border again. In this situation, limited resources of the satellite will be occupied and the burden on satellite will be increased when the satellite cross the border again.

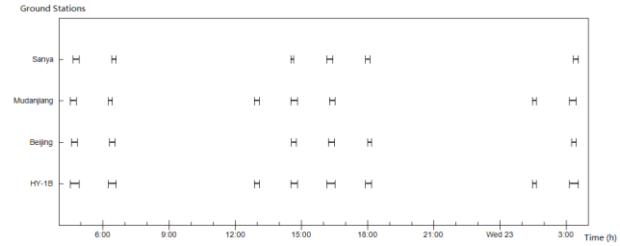

Figure 10. LEO satellite- Ground visibility

From the visibility analysis between LEO satellite and ground stations, it is concluded that only the satellite and the ground station satisfy visibility conditions, inter satellite link could be established. However, the establishment of the inter satellite link is related to the quality of the channel, the antenna elevation and so on, so the visibility between the satellite and the ground station is the necessary condition for the inter satellite link. At the same time, observation satellites are mostly polar orbiting satellites, whose running speed are fast and orbital altitude are relatively low. From Figure 10, we can see that covering time of three ground stations is relatively concentrated, which is due to geography, political and other factors limit the choice of the ground station’s location. In a lot of spare time, satellite data cannot be transmitted in real time, meanwhile, due to characteristics of satellite service, launching a large number of satellites will greatly increase the cost of system.

B. *Data Trasmission with Relay of BeiDou Satellites*

Through the analysis of the previous sections, it is concluded that using BeiDou navigation satellite system as the relay of observation satellites can greatly reduce the latency of satellite data transmission, and can achieve the timely transmission of satellite data in the absence of new ground stations. Due to the fact that relay satellites could achieve full-time coverage to the ground stations, the feasibility of data transmission depends on the visibility time between satellites. In this paper, we mainly discuss single layer satellites serving as relay satellites, since multi-layer relay satellites would perplex the problem and increase the system cost. Table II shows the result of analysis and comparisons by using GEO satellites, IGSO satellites, MEO satellites as relay satellites respectively.

TABLE II. RELAY SATELLITE PERFORMANCE ANALYSIS

Relay satellite	Non	GEO	IGSO	MEO
Connectivity	10.44%	95.30%	94.31%	100%
Visible number	-	0-5	0-3	15
Routing hops	-	1	1	indefinite
Technical difficulty	low	medium	high	high
System cost	low	medium	medium	high

The model we proposed focuses on the link distance and elevation angle, and these two factors are fundamental for link establishment. Surely, more factors should be considered when judging whether the link could be established, such as perturbation of the orbit, antenna tracking, etc. And these should be considered in a more complicated model.

From the perspective of the feasibility of establishing a link, GEO, IGSO and MEO satellites can provide long-term visibility. So, the use of relay satellites can solve the problem that LEO satellite could not transfer data to ground stations when it's not in the visibility zones.

When GEO or IGSO satellites serve as relay satellites, the transmission delay will be large, since the distance of ISL is long. Therefore, for real-time data transmission, MEO satellites will be better choice. However, in the current BeiDou satellite system network architecture, the link bandwidth of ISLs is rather small and can't meet the acquirement of large-scale data transmission. Compared to MEO satellites, the number of GEO and IGSO satellites is small and only one hop that we can have data transmitted to the ground stations, the routing control is rather simple; on the contrary, this problem becomes complex when MEO satellites serving as relay satellites since there are more than one ISLs could be established between satellites at the same time. The satellite to be selected is under a series of criterions such as to choose the satellite with the greatest elevation angle to possess the best communication quality; the longest service time to minimize handoff times, etc. It will involve a series of more complex problems of satellite handoff.

Experimental results indicate that the proportion of satellite visibility rises to 95.30% when GEO satellites serve as relay satellites. The GEO satellite has been widely used as a relay satellite around the world, due to its high orbit altitude and complex on-board processing capability; adopting IGSO satellites to serve as relay satellites solves the problem that GEO satellite has blind areas around Polar Regions; choosing MEO satellites serve as relay satellites could provide a full-time relay service. The number of visible satellites is 15 at least, so we can choose the best among them to achieve better service. Yet choosing MEO satellites as relay satellites faces many difficulties including complicated antenna tracking technology, complex on-board processing capability, and high system cost.

V. CONCLUSION AND FUTURE WORK

BeiDou Navigation Satellite System is one of the most important navigation satellite systems in the world, and will provide global coverage in the future. Due to the limited space resources the new satellite has to be limited launching. So make use of existing satellites to complement new functions is a feasible solution. In this paper, the Inter-Satellite Link based on BeiDou satellites is analyzed. Firstly, the network architecture of spatial information system studied, and the dynamic network topology model is proposed. Then, by simulation the running of BeiDou satellites, the connectivity features of ISLs were acquired. Meanwhile, the topology structure's evolution laws of satellite network and a selection suggestion of relay satellites were also obtained by analyzing the simulation results. We will explore the more practical computing model of link distance by tracing and research handoff algorithm of ISL in MEO constellation to choose the optimal satellite to achieve acceptable relay performance in future work.

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