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Delay performance comparison across seven low-earth-orbit (LEO) satellite constellations

Zhiwei Hu[a], Feng Wen[*a], Juan Yong[a], Feng Fan[b], Baojian Wu[a] and Kun Qiu[a]

[a] Key Lab of Optical Fiber Sensing and Communication Networks, Ministry of Education
University of Electronic Science and Technology of China, Chengdu 611731, China
[b] Beijing Institute of Telemetry Technology, Beijing 100076, China

ABSTRACT

We carry out the thoughtful investigations on the end-to-end delay comparison based on seven proposed low-earth-orbit (LEO) satellite constellations, i.e., GlobalStar, Iridium, TeleSat, Kuiper, StarLink, OneWeb with 720 and 1764 satellite nodes, which include two major constellation types-polar and inclined orbits. The discussion focuses on the future satellite operation in space by gradually increasing the number of satellite nodes, and analyzes the impact of the constellation scale on the performance of the inter-communication delay. The shortest path algorithm is used to simulate both international (Beijing to New York) and domestic (Beijing to Chengdu) scenarios for each constellation to calculate the shortest transmission delay and its corresponding hop count. Our results show that with the expansion of the number of satellites, the end-to-end delay could touch the floor. The optimized delay is achieved when the number of satellites is close to 1000 for both international and domestic scenarios, which values are 44ms and 6ms, respectively. There is no impressive improvement on the delay performance when further expanding the constellation scale. Moreover, as the number of satellites continue to accumulate, both the long-distance and short-distance communication scenarios, the large-scale star chain clusters aggravate the frequency of inter-star switching, easily leading to unstable transmission delay, which is not conducive to obtaining the best delay benefits. Therefore, for the delay performance-driven service, it is necessary to reasonably optimize the constellation structure to meet the user's communication needs through the appropriate number of satellites in the constellation.

Key words: LEO satellite constellation, Constellation scale, Delay performance, Shortest path algorithm, Delay optimization

1. INTRODUCTION

The low-earth-orbit (LEO) satellite system is regarded as a mobile communication system in space, not only as a supplementary means of terrestrial communication, but to support wireless communication on the high mountains and oceans that cannot be reached on the ground. Through inter-satellite networking and inter-satellite laser links, the low-orbit

[*] Address all correspondence to Feng Wen, fengwen@uestc.edu.cn

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satellite Internet has excellent performance like large capacity, low latency, and wide coverage, which improves the user-end communication experience and gets rid of the constraints of the huge communication volume on the ground [1]. In this regard, start-up communication companies and commercial satellite companies in various countries continue to explore deep space, setting off a boom in low-orbit satellite communications. As early as the end of the 20th century, American Communications Corporation started research on low-orbit satellite systems and built a small-scale low-orbit satellite network headed by Iridium and GlobalStar that fall short of success finally [2]. In recent years, with the rapid development of the aerospace industry and the continuous maturity of satellite Internet technology, the increasing large-scale constellation structures have emerged one after another. SpaceX's "60 satellites with one arrow" carrier technology has greatly accelerated the deployment of satellite network, built emerging mega-constellation systems such as StarLink [3], and intensified the competition for space orbit resources among countries.

The low-orbit satellite system architecture has been continuously proposed and constructed, making the low-orbit space resources increasingly scarce. According to authoritative experts quoted by CCTV, the current orbit altitude of 400-2,000 kilometers in low-Earth orbit can accommodate a total of about 60,000 satellites [4]. However, according to the orbit data released by the Federal Communications Commission (FCC), the total number of StarLink plans submitted by SpaceX is as high as 42,000 [5]. At present, low-orbit resources are in a relatively crowded state. The huge satellite volume consumes a lot of space resources as well as increases the complexity and security of on-board processing technology. Therefore, it's necessary to seek a balance between satellite scale and network performance. The communication delay is one of the core indicators to measure the communication performance, which has sparked heated discussions among scholars.

Yong [6] mainly analyzed and discussed the channel influencing factors of the laser satellite inter-satellite link, and simulated the degradation of signal quality under different influencing factors through simulation. Three different channel factors in the spatial channel are analyzed in turn. However, for the analysis of satellite Internet, there is a lack of simulation on the performance of the inter-satellite network. Ekici [7] used the length of the inter-satellite link to measure the transmission delay, and implemented pathfinding for fixed topologies based on the geographic location relationship; Handley [8] analyzed the delay difference between the two international cities from New York to London under the specific constellation structure of StarLink through ground transmission and satellite Internet transmission. By comparing the average Round-Trip Time (RTT) of the two, the RTT result obtained by the satellite Internet of 55ms is lower than the RTT value of 76ms obtained by the ground Internet, indicating that the satellite Internet has certain advantages; Kempton [9] analyzed the influence of three different network connection designs of +grid, sparse and ideal network on the delay characteristics under a given constellation structure, and concluded that the ideal network design provides the lowest possible delay on all measurement paths. The average delay is about 45ms when the straight-line distance between Newport News and Tokyo is 9,700 kilometers.

However, the current simulation of satellite constellations is mostly limited to the analysis of different routing algorithms for a single constellation or the analysis of network performance in different scenarios. Nevertheless, only in terms of the performance of the delay, a single constellation analysis is not enough, and more detailed and comprehensive conclusions can be obtained from the analysis and comparison of different constellation structure types in the view of the delay. At the same time, the change of the constellation structure also affects the adaptability of the routing algorithm and the network performance. The conclusions drawn from the simulation under the environment of various constellation structures are more meaningful. In the meanwhile, this paper simulates seven typical commercial constellations with different structures, and discusses the delay performance between the two scenarios of transnational communication and domestic communication on the earth. The issues discussed are as follows: (1) Analysis of the influence of different constellation structure on ground coverage with the gradual change of dimension; (2) Discuss the increase of the order of LEO satellites on the communication delay between terrestrial cities, and calculate the average delay and the corresponding mean square error results; (3) In the communication process, the shortest path method is used to obtain the routing table, analyze the routing of cross-border long-distance communication and domestic short-range communication. Under the shortest path algorithm, study the impact of communication distance and constellation scale changes on delay performance, to lay the foundation for future in-depth research on satellite Internet.

2. CONSTELLATION ARCHITECTURE

2.1 Constellation parameters

Table 1 lists seven typical commercial constellation structures in recent years, which are used in various business scenarios. Among them, GlobalStar and Iridium are the early satellite mobile systems in the United States, providing mobile communication phone business scenarios. TeleSat and Kuiper are satellite service operators in Canada and the United States, respectively, aiming to provide global satellite broadband. StarLink and OneWeb are SpaceX company and UK company that oriented the broadband data transmission business scenario [10]. Different commercial constellation structure parameters are as shown in Table 1 [11].

Table 1. Different constellation structure parameters

Constellation	GlobalStar	Iridium	TeleSat	Kuiper	StarLink	OneWeb
Period(ms)	6846	6028	6327	5839	6929	6566
Altitude(km)	1414	780	1015	630	550	1200
Inclination	52	86.4	98.98	51.9	53	87.9
Phase_shift	1	0	0	1	1	0
Plane_nums	6	6	27	34	72	40/36
Sats_plane	8	11	13	34	22	18/49
Sat_nums	48	66	351	1156	1584	720/1764

It can be seen from Table 1 that there are two types of constellation-polar orbit constellation and inclined orbit constellation, which are represented by phase shift factors 0 and 1 respectively. Normally, LEO satellites orbit at altitudes ranging from 500km to 2000km. The lower the orbit height of the satellite, the smaller the corresponding transmission delay and path loss, and the constellation composed of multiple satellites can achieve real global coverage, so as to obtain better real-time performance.

2.2 Constellation visualization

In order to realize the effect of satellite dynamics and visualization simulation, the Constellation Simulation Software (CSS), is used for simulation in the form of co-simulation with Matlab. According to the different satellite constellation parameters of seven kinds of satellite orders of magnitude from low to high, the space is simulated. The three-dimensional schematic diagram of different constellation structures shown in Figure 1 is obtained.

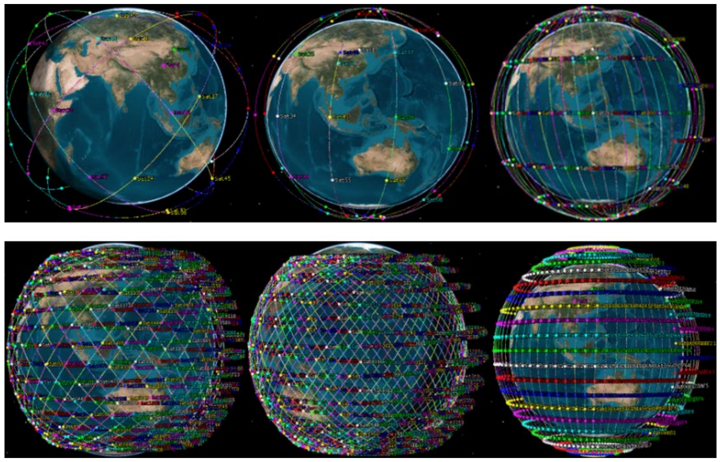

Figure 1. the three-dimensional schematic diagram of different constellation structures

2.3 Constellation coverage

Coverage performance is the ability to characterize the satellite capacity required for a constellation in a satellite communication system to dynamically concentrate in time and place, and is used to evaluate the coverage characteristics of a constellation system to a certain territory [12]. Here, for the current two mainstream constellation structures, the inclined orbital type and the polar orbital type, the coverage changes with the dimensional changes are researched. The conical half angle of the sensors in each constellation is set to the default value of 45°, and the coverage results of each constellation with latitude in Figure 2 are obtained. At the same time, the communication between Beijing and New York and the communication between Beijing and Chengdu are discussed in turn. In some cases, each city can realize all-weather communication to establish a stable link connection for communication services.

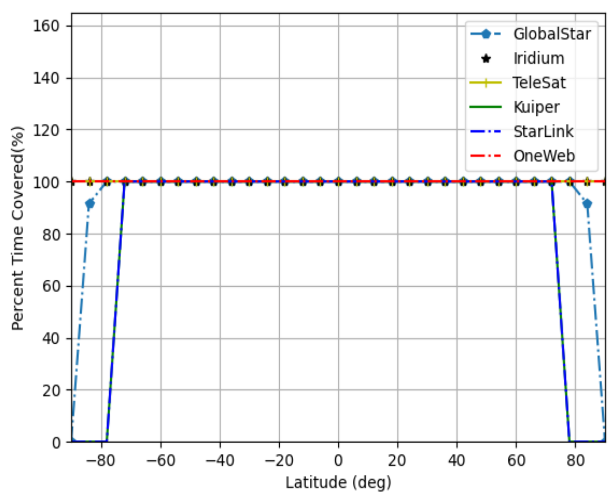

Figure 2. Result display graph of coverage rate as a function of dimension

From the results in Figure 2, it can be seen that the constellation is built with inclined and polar orbit types, and the polar orbit methods of Iridium, TeleSat and OneWeb can achieve 100% global coverage. The remaining inclined orbits cannot achieve 100% complete coverage, only covering 80° north and south latitudes, turn out that communication is basically impossible in the polar regions of the earth.

3. CONSTELLATION DELAY PERFORMANCE

3.1 Performance Analysis Framework

According to the networking characteristics of each constellation structure and the connection relationship between the inter-satellite links, the topology communication delay status at each moment in the cycle is stored, and the calculated delay data is used to analyze the communication transmission delay between different nodes. The delay result is mainly obtained by calculating the ratio of the straight-line distance between nodes to the speed of light. The calculation method of the straight-line distance between nodes as follows. First, the spherical coordinate system is converted into a rectangular coordinate system by Equation 1, where r represents the sum of the earth's radius and altitude, θ represents the result obtained after the latitude is processed, and φ represents the result obtained after the longitude is processed

$$\begin{cases} x = r\sin\theta\cos\varphi \\ y = r\sin\theta\sin\varphi \\ z = r\cos\theta \end{cases} \tag{1}$$

The formula for the straight-line distance between two points in the three-dimensional coordinate system is shown in Equation 2. According to the three-dimensional coordinates of the constellation nodes, the straight-line distance between any two nodes is calculated, and the delay information is obtained through the distance ratio to the speed of light under the laser link.

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \tag{2}$$

The end-to-end delay adopts the shortest path algorithm. The delay between adjacent satellite nodes obtained by calculation on the grid graph is used as the basis for path finding. If there is a connecting path between the nodes, the shortest path algorithm is activated to obtain the final shortest delay with the path in the pathfinding process [13]. Figure 3 draws the specific implementation process, referring to the StarPerf network performance simulation platform [14]. The constellation is created through the co-simulation of CSS and Matlab, and the delay between links is calculated according to the networking structure, and the transmission process between nodes and the shortest delay method are further analyzed with Python software.

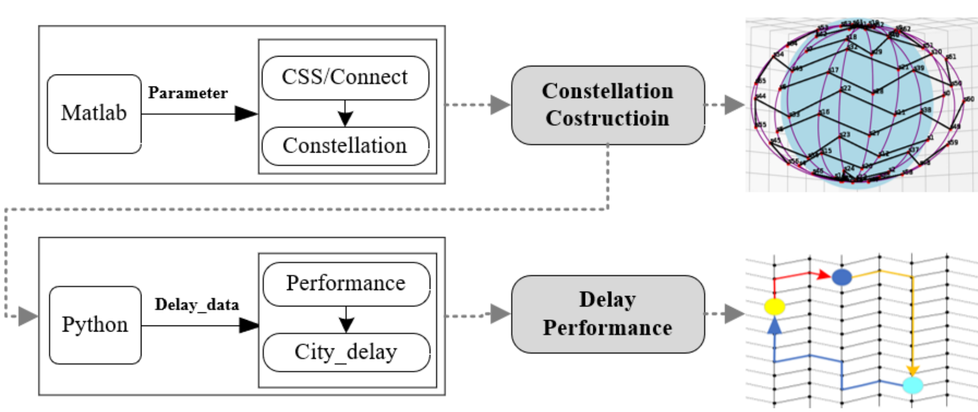

Figure3. Satellite network simulation work flow chart

3.2 Shortest Routing Algorithm

The shortest path algorithm in graph theory is also called the Dijkstra algorithm [15]. This algorithm can not only find the shortest path between the specified nodes (a, b), but also give the shortest path from node a to all vertices in Figure 4.

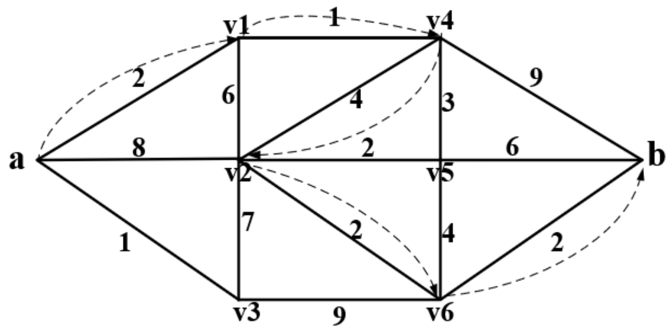

Figure4. Schematic diagram of shortest circuit algorithm

The implementation process is shown in Figure 4, which shows the edge weighting graph of satellite nodes. It aims to find the shortest path to node b according to node a. First, calculating the sum of the weights of node a to find its nearest neighbors, and then find the minimum sum value by comparison as the punctuation of the next node, and so on until the node b is reached, the shortest path value of the edge weighted graph can be obtained. In this simulation, the weights on the edges of the grid graph represent the delays on the inter-satellite links. When the shortest path is found, the delays of each link are superimposed in turn to obtain the final delay result.

3.3 International city communication delay

The end-to-end delay calculation adopts the shortest path algorithm, and the calculated delay between adjacent satellite nodes on the grid map is used as the basis for pathfinding, and the distance between Beijing and New York in a single cycle under different constellation structures is analyzed. The communication delay between Beijing and New York is calculated to be 9675 kilometers, and the inter-city communication delay reaches 44ms under the order of 1000 satellites.

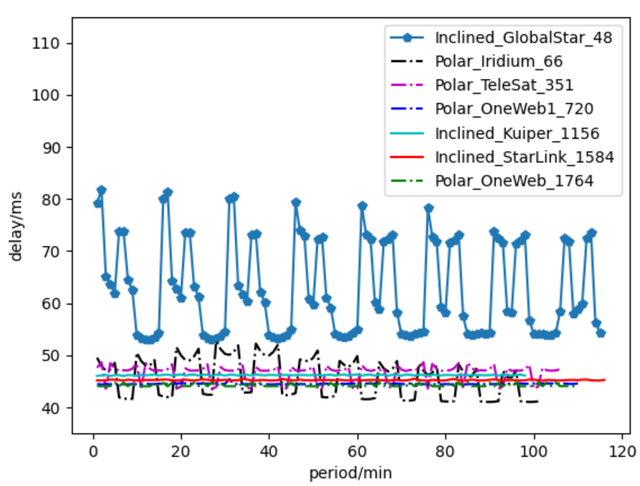

Figure 5. Communication delay diagram from Beijing to New York

According to Figure 5 international inter-city communication can be obtained: (a) When the scale is small and the number of satellites is in the order of tens or hundreds, the constellation structure is unevenly distributed, and results in the inter-national communication delay fluctuates up and down. With the gradual increase of the number of satellites, the fluctuation has gradually leveled off. When the number of satellites reaches the range of 1000, the topological structure of the constellation is evenly distributed, and the communication delay is basically in a stable state; (b) The orbit types of constellations are mainly inclined orbit (GlobalStar, Kuiper, StarLink) and polar orbit type (Iridium, TeleSat, OneWeb), which are indicated by solid and dashed lines in Figure 5. (c) If only the delay performance is discussed, and the user is more sensitive to the delay of communication services, the number of constellation satellites considered is basically around 1000 to achieve reliable low-latency transmission. When the number continues to increase on a large scale, the space for communication delay improvement is limited, and there will be no significant improvement. On the contrary, the increase in the number increases the complexity of operating costs and constellation control.

3.4 Domestic urban communication delay

The difference in communication delay is not only related to the current satellite constellation structure, but also to the transmission distance. The longer the transmission distance, the more switching paths between nodes and the longer the delay. Under short-distance transmission, the satellite switching frequency is basically the same under different constellation structures, and the difference in communication delay time is mainly determined by the satellite constellation structure. Consequently, the effect of the communication delay between Beijing and Chengdu in different constellation periods is analyzed. The straight-line distance on the ground is about 1509 kilometers, and the corresponding communication delay under the constellation structure of 1000 satellites is 6ms.

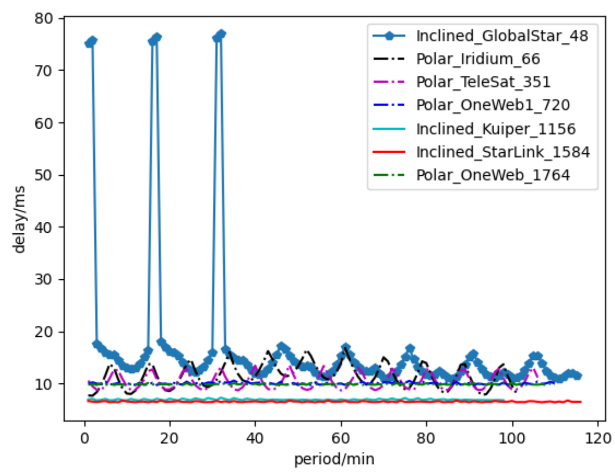

Figure 6. Communication delay diagram from Beijing to Chengdu

The following conclusions can be drawn from the intercontinental communication delay results between domestic cities in different constellations in Figure 6: (a) For the constellation structure of the same orbit type, the corresponding short-distance communication delay when the number of satellites is small there is a large fluctuation. When the number of satellites increases, the coverage area surrounded by the constellation is more uniform, and the communication delay tends to be stable; (b) Under the constellation structure of the same number of satellites, the design of inclined orbit type is more suitable for our normal actual communication scenario, the communication needs of the client are mainly concentrated in the area within the Tropic of Cancer, and the communication needs in the polar regions are feeble little. In contrast, the inclined orbit type is more practical and has better end-to-end communication delay.

3.5 Satellite routing transmission

For each constellation structure grid, analysis of two scenario delay situations. As the order of magnitude of hundreds or thousands of satellites increases, the constellation structure becomes larger and larger, and the grid nodes become denser and difficult to observe. Taking the Iridium constellation as an example, the node number 66 in Figure 7 corresponds to Beijing city, the node number 67 corresponds to New York, and the node number 68 corresponds to Chengdu. The nodes marked in green represent the shortest communication delay path between Beijing and New York International, the nodes marked in yellow represent the shortest delay path between Beijing and Chengdu, and the nodes marked in red are intermediate nodes that the two repeatedly pass through.

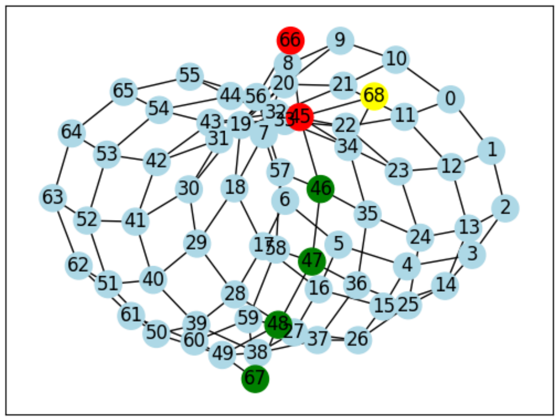

Figure 7. Iridium constellation grid analysis diagram

By comparison, the average delays in the two scenarios of cross-border communication from Beijing to New York and domestic communication from Beijing to Chengdu were calculated under different constellations. With the gradual increase in the number of satellites, the impact of constellation structure and satellite scale on different communication distances was investigated. The average delay in the scene, the results are shown in Figure 8. As the scale of satellites continues to expand, the end-to-end transmission path in the same scenario changes accordingly.

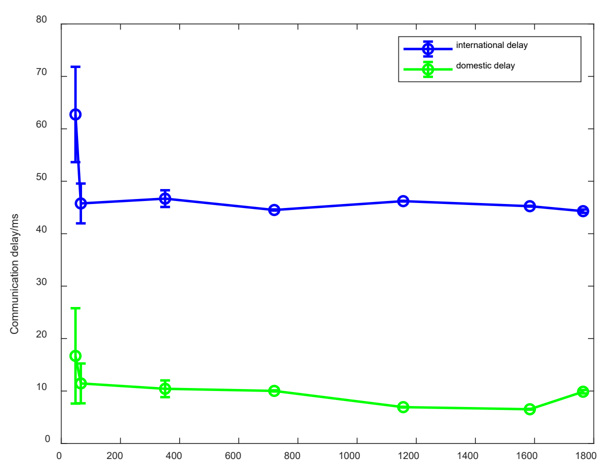

Figure 8. The graph of the relationship between the number of satellites and the delay

It can be seen from Figure 8 that the size of the satellite constellation affects the delay between communications, and the overall delay gradually decreases with the increase of the number of satellites. When the number of satellites is small, the communication delay is unstable, and the corresponding delay mean square error is large. After the number of satellites increases to a certain extent, as the scale of constellation satellites continues to expand, the mean square error gradually approaches zero, and the delay performance tends to be flat. When the number of satellites in individual constellations increases, the switching frequency between nodes increases, and the process of intermediate switching paths increases, resulting in the delay no longer maintaining the law of decreasing with the increase of the number of satellites. Table 2 shows the transmission routing table under different constellations in two scenarios of international and domestic communication on the shortest path problem.

Table 2. The shortest delay path in two scenarios with different constellation structures

Constellation	Beijing-NewYork	Beijing-Chengdu	Jump
GlobalStar	[48, 10, 18, 26, 49]	[48, 3, 50]	5/3
Iridium	[66, 57, 58, 59, 67]	[66, 56, 68]	5/3
TeleSat	[351, 5, 4, 3, 2, 352]	[351, 274, 353]	6/3
OneWeb1	[720,607,608,609,610, 611,612,613,614, 721]	[720, 525, 722]	10/3
Kuiper	[1156,381,382,383,384,385, 419,453, 487, 521, 1157]	[1156, 11, 1158]	11/3
StarLink	[1584,702,703,682,683,684,685,1585]	[1584, 3, 1586]	8/3
OneWeb	[1764,1331,1332,1333,1334,1335, 1336,1337,1338,1339,1340, 1765]	[1764,1279,1766]	12/3

It can be seen from the simulation results that when facing short-distance communication between domestic cities, the corresponding transmission hops between nodes are the same, and information exchange between domestic cities can be realized in two hops. The larger the constellation scale, the shorter the distance hops can be used for data transmission, and the better the delay performance. When the number of satellites is close to the order of 1000, the corresponding delay performance of polar orbit constellation and inclined constellation is no longer improved. At this time, the overall delay of inclined constellation is better than that of polar orbit constellation. When it is used for long-distance communication between international cities, the number of corresponding transmission hops between nodes increases as the scale increases, the delay fluctuation is also small when it close to the order of 1000 satellites, and is stable in the range of 44ms.

4. CONCLUSION

Based on the shortest routing algorithm, this simulation discusses seven typical satellite constellations with different structures, and draws the following conclusions: (a) The coverage of satellite Internet on the ground depends on the constellation structure. The polar orbit constellation can provide communication services for the ground area in all directions. The two poles of the earth are in the blind area in the inclined constellation and cannot achieve 100% coverage; (b) For long-distance communication transmission, appropriately increasing the size of the satellite constellation helps to reduce the transmission delay, and the end-to-end delay gradually tends to a stable situation. When the number of satellites increases to the range of 1,000, the delay performance basically changes little; (c) For short-distance communication transmission, the change of satellite scale has little impact on the delay performance, and the number of hops in routing transmission between nodes remains basically unchanged. Compared with long-distance transmission, the mega-constellation is more sensitive to the delay of long-distance transmission services. With the increase in the number of satellites, the switching frequency and complexity are greatly increased.

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REFERENCES

[1] Wang, C., Ren, Z. Y., Cheng, W. C., “Time-expanded graph-based dispersed computing policy for LEO space satellite computing,” 2021 IEEE Wireless Communications and Networking Conference (WCNC), 1-6 (2021).

[2] Butash, T., Garland, P. and Evans, B., “Non-geostationary satellite orbit communications satellite constellations history,” International Journal of Satellite Communications and Networking, 39(1), 1-5 (2021).

[3] Wang, X. X., “SpaceX successfully launched 60 satellites with one rocket to build a global satellite communication network,” Satellite TV and Broadband Multimedia, 14(1), 1-1 (2019).

[4] http://www.dehenglaw.com/CN/tansuocontent/0008/024338/7.aspx?MID=0902

[5] Portillo, I. D., Cameron, B. G., Crawley, E. F., “A technical comparison of three low earth orbit satellite constellation systems to provide global broadband,” Acta Astronautica, 159, 123-135 (2019).

[6] Yong, J., Wen, F., Hu, Z. W., “High-Dynamic Transmission Modeling for Laser Inter-Satellite Links (LISLs),” Asia Communications and Photonics Conference/International Conference on Information Photonics and Optical Communications 2022 (ACP/IPOC), 1-6 (2022).

[7] Ekici, E., Akyildiz, I. F., Bender, M. D., “A distributed routing algorithm for datagram traffic in LEO satellite networks,” IEEE/ACM Transactions on Networking, 9(2), 137-147 (2001).

[8] Handley, M., “Delay is not an option: Low latency routing in space”. Proceedings of the 17th ACM Workshop on Hot Topics in Networks. 1-7 (2018).

[9] Kempton, B. S., [A simulation tool to study routing in large broadband satellite networks],” Christopher Newport University ProQuest Dissertations Publishing, Newport News, 1-63 (2020).

[10] Wu, Q. L., Long, K., Zhu, Q. C., "International competition in field of LEO satellites communication networks: dynamics, motivations and strategies," WORLD SCI-TECH R&D, 42(6), 587-597 (2020).

[11] Pachler, N., Portillo, I. D., Crawley, E. F., “An updated comparison of four low earth orbit satellite constellation systems to provide global broadband,” 2021 IEEE international conference on communications workshops (ICC workshops). 1-7 (2021).

[12] Wu, H., Wang Y., "Simulation and coverage analysis of the constellation of the MEO satellite communication system based on STK," Electronic Design Engineering, 25(22), 5 (2017).

[13] Yang, Z. Y., Li, H. W., Wu Q., " Emulation platform for inter-domain protocols validation of integrated space-terrestrial network," Journal of Communications, 40(5), 1-12 (2019).

[14] Lai, Z. Q., Li, H. W., Li, J. H., “Starperf: Characterizing network performance for emerging mega-constellations,” 2020 IEEE 28th International Conference on Network Protocols (ICNP). 1-11 (2020).

[15] Werner, M., Delucchi, C., Vogel, H. J., “ATM-based routing in LEO/MEO satellite networks with intersatellite links,” IEEE Journal on Selected Areas in Communications, 15(1), 69-82 (1997).