



Research and Simulation Analysis on the Characteristics of Walker Constellation Network for Global Networking Real-Time Telemetry, Track and Command

Yong Xu^(✉), Siyang Zhao, Luyuan Wang, Nan Pei, Hongcheng Yan,
Ming Gu, Liang Qiao, Cuilian Wang, Ling Tong, and Wei Wu

Beijing Institute of Spacecraft System Engineering, Beijing 10094, China

Abstract. The resources of ground TT&C (Telemetry, Track and Command) and data transmission station are limited in China, and the visible arc section of satellite is short, which greatly limits the timeliness of satellite on orbit operation control and information return, and affects the full play of satellite efficiency. As a means of response, the relay satellite was born to meet the needs of the full-arc TT&C of key tasks. However, the flexibility of the use of the relay satellite and the number of service objects are still difficult to meet the requirements of ordinary, large number of satellites. Therefore, it is very urgent to realize the real-time telemetry and command of all satellites in the system based on constellation system. In order to meet the requirement of real-time telemetry and command in global network, this paper designs constellation network simulation system, studies the transmission characteristics of ground telemetry and command data and autonomous telemetry and command data in typical constellation configuration, and carries out quantitative simulation analysis. It provides a reference for the optimization of network topology, node cache configuration, routing algorithm and data generation strategy in system design.

Keywords: Walker constellation · TT&C · Global networking

1 Introduction

Due to the advantages of uniform coverage and regular topology, the current satellite constellation system generally adopts Walker Constellation, and constructs inter satellite network in the satellite itself to realize the interconnection between the whole constellation and the ground system [1].

During the operation of satellite system in orbit, the monitoring of working state is basically transmitted to the ground through telemetry parameters. After receiving the data, the monitoring and command station will process and analyze it, and inject the processing parameters and on orbit task arrangement through the remote control channel. Although the autonomous operation technology is adopted, most of the satellite's on orbit operation still depends on the monitoring and task allocation on the ground.

However, for the ground TT&C station and data transmission station, due to the occlusion of the earth, the link and data transmission can only be established in the visible arc or through the relay satellite during the whole orbit period of the satellite. This kind of short arc and intermittent telemetry and command method has many impacts on the use of satellites. From the perspective of satellite safety, it is impossible to obtain the satellite health data outside the visible arc in real time, and the failure cannot be handled in time, resulting in the spread of failure or threatening the safety of the whole satellite. From the perspective of angle of use, it is necessary to wait until the next visible arc comes when temporary demand comes, and receive the downward observation data in next visible arc segment, which seriously affects the use efficiency of the satellite [2, 3].

For this reason, it is an inevitable trend to use the inter satellite link to network the satellite system, to provide telemetry and command services to the whole network satellite through the domestic satellite in the visible arc section, and to realize the global network telemetry and command application. Taking a 24 star constellation system as an example, the global real-time telemetry and command constellation system consists of the space-based constellation network part and the ground-based telemetry and command station, the data transmission station, the mobile station and the data center [4-8].

2 Constellation Network Simulation System Design

Different from the simple communication service mode of traditional ground or relay satellite direct TT&C satellite, it is more difficult to analyze the service capacity, transmission capacity, delay characteristics and node cache of satellite networking transmission. In the design of real-time global TT&C system, in order to facilitate the analysis of the load capacity, transmission delay, node cache setting capacity and other design parameters of the network system. Reasonable, all above design items need to be analyzed and verified by simulation [9, 10] (Fig. 1).

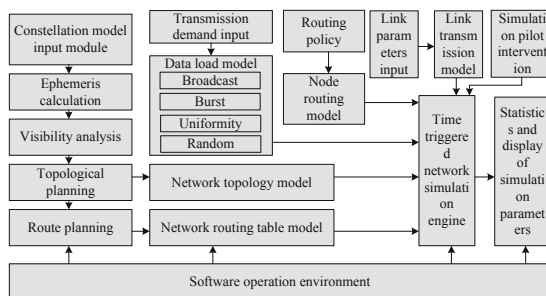


Fig. 1. Framework Design of constellation network simulation system

The figure above shows the structure of constellation networking communication simulation software, mainly including several parts.

2.1 Simulation Input

It includes constellation model input module, transmission demand input module, route processing strategy module, link parameter input module, link parameter input module, which used to set simulation related input parameters and policies.

2.2 Pilot Intervention Assembly

Simulation pilot intervention module is mainly used to adjust simulation start time, end time, simulation step length, simulation process control, fault injection and abnormal event injection.

2.3 Model and Data Generation Module

The model and data generation module generates the data and models needed for simulation, including topology model, routing table model, data load model, link transmission model and node routing processing model, based on track, visibility, chain building planning, routing planning and other domain algorithms.

2.4 Simulation Engine Module

The simulation engine module is the core part of the simulation system, which is responsible for model loading, running, time triggered event deduction, time triggered state transition and update.

2.5 Simulation Parameter Statistics and Display Module

The simulation parameter statistics and display module is used for statistics and visualization of important parameters in the process of network simulation. It supports users to extract statistics and visualization of parameters such as cache queue depth, link load, node load, delay, forwarding hops, congestion, etc. of each node and link in the simulation model at each simulation time, and supports parameter collection and user-defined statistical processing functions.

2.6 Software Operation Environment Module

The software operation environment provides the integration and operation environment of the above modules. In this project, Matlab is used to provide the software integration operation environment.

The simulation process includes input parameter settings such as scene, constellation scale, constraints and transmission load characteristics, statistical parameter extraction and display settings, and finally running network simulation software, which

can support network routing rules, algorithms, design correctness, feasibility network load capacity and other simulation evaluation.

3 Modeling of Simulation Model for the Characteristics of Walker Constellation Network

In our study, the 24-star scale constellation network is used as the simulation research scene. The commonly used Walker Constellation, 1500 km altitude orbit and 60° tilt orbit are used. The number of links between stars is no more than 3–4 per satellite, and the network topology map is generated by the strategy of ring chain establishing in orbit plane and dynamic chain establishing across orbit plane (Fig. 2).

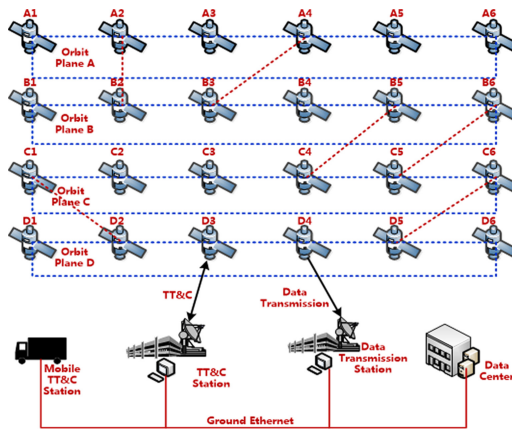


Fig. 2. Global real time telemetry and command constellation system

Generally speaking, Walker Constellation is used in the global network satellite system, which is characterized by circular orbit, uniform distribution of multiple orbital planes, and even arrangement of satellites in the orbital plane. As shown in the figure above [11].

In the aspect of communication demand, as the network load, the telemetry and command data mainly includes the real-time periodic satellite telemetry data, on-demand burst task instruction data, on orbit maintenance data and observation processing task result data transmission. The original load data with a large amount of data is generally not transmitted through the network, but through the data transmission link after using the local star cache (Table 1).

In the above scenarios, the influence of constellation configuration, link bandwidth, number of cross orbit links, transmission requirements, data source characteristics on network performance is studied, which provides basis for the rationality, feasibility and engineering optimization of constellation network design.

Table 1. Characteristics of satellite networking transmission requirements

Type of network load	Transmission requirements	Timeliness	Characteristic	Data volume
Satellite periodic telemetry	Down to the ground	High, average	Periodic	Small
Task instruction	Transmission to satellite	High	On demand burst	Small
On orbit maintenance data	Up star	Commonly	On demand burst	In
Observation processing results	Down to the ground	High	Task burst	In
Multi star state synchronization information	Webcast	High	Sudden task, frequent cycle	Small

4 Influencing Factors and Optimization of Constellation Network Transmission Performance

There are 5 requirements in network performance simulation as follow.

4.1 Support Constellation Configuration Optimization Simulation

Network simulation provides the ability of constellation configuration optimization comparison, taking 24 constellation design as an example, under the fixed link bandwidth situation, for the purpose of network transmission optimization, through the simulation data, analyzes and compares the advantages and disadvantages of 4 orbital plane \times 6 satellite and 3 orbital plane \times 8 satellite two typical constellation configurations.

4.2 Support Link Bandwidth Verification

In constellation design, there is often a problem, how much is the appropriate inter satellite link rate design, enough, and how much is the margin. Because of the complexity of network topology, it is difficult to analyze and calculate by theoretical means. Therefore, in the design of constellation system, it is necessary to verify the key parameters of inter satellite link, the matching of constellation communication requirements, communication load, and the correctness of link bandwidth design by simulation.

4.3 Support Cross-Orbit Link Optimization

In the optimization of the number of cross-track links, cross-track links is not the more the better, when broadcast data flooding, the more cross-track links, the more copies of broadcast data; However, when used for point-to-point transmission, the more cross-track links, the more conducive to network transmission and data forwarding.

Therefore, after the user determines the data amount requirements of constellation satellite broadcasting and point-to-point data transmission requirements, according to the characteristics of transmission requirements, simulation can be used to optimize the cross-orbit link and design more matching cross-orbit link building rules with transmission sources.

4.4 Analysis of Supporting Transmission Demand Satisfaction Degree

Network load capacity is closely related to the transmission demand of data source, and the data amount of data source is the input of system design. Firstly, the system design needs to comb out the capacity boundary of network transmission service and the transmission demand of users, i.e. Transmission type and transmission packet quantity;

For the demand of broadcast transmission between satellite nodes, the strategy based on flooding will cause a large number of packets replication in the network, each replication will lead to exponential growth in the number of network packets, increase the load of network transmission, lead to node buffer queue growth and path congestion;

The point-to-point transmission demand is linear. After the data source is sent out, the number of data packets will not increase with the transmission process. When the destination node is reached, it will disappear in the network.

Whether the design of constellation network system can meet the transmission requirements of upper applications is also difficult to calculate with theoretical models, so simulation verification and design optimization are needed.

4.5 Support Time Distribution Analysis of Data Source

In addition, the network source node transmission packet generation time characteristics, is also a major factor affecting the network transmission load, network simulation software support for randomness, uniformity, burst high load source node packet generation characteristics of simulation, analysis of its impact on network transmission performance, and gives recommendations to optimization of the source node data output.

5 Simulation and Analysis of Transmission Characteristics of 5 Constellation Network

Different simulation scenarios are constructed according to the network transmission factors, and various design factors are evaluated and optimized in simulation experiments.

5.1 Simulation Analysis of the Influence of Network Topology on Transmission Performance

See Figs. 3, 4 and Table 2.

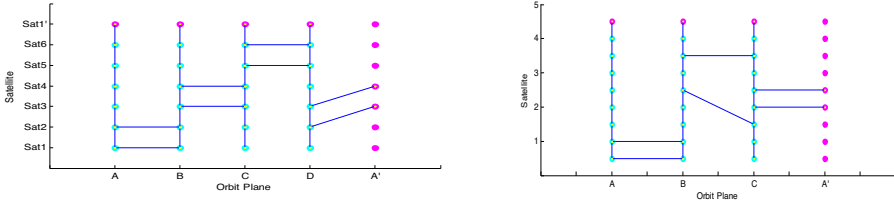


Fig. 3. 4 × 6 and 3 × 8 constellation configurations typical network topology

Table 2. Average queue depth (bandwidth of Inter-satellite-Link is 10 Mbps)

Average queue depth (package)	Single satellite communication requirement (Mbps)			
	3	4	5	6
4 × 6 topology	1.4688	41.1187	281.3026	718.7000
3 × 8 topology	0.0078	17.3990	169.4260	576.2031

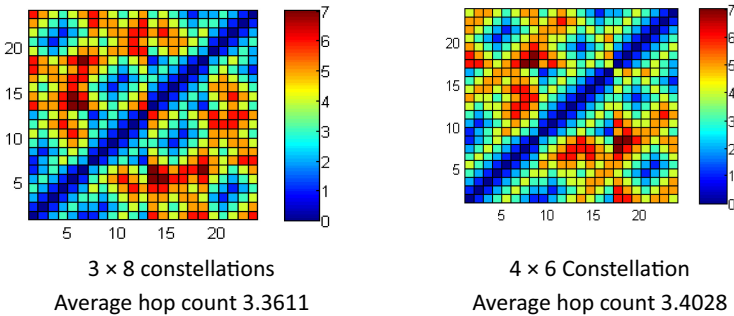


Fig. 4. End-to-end average routing hops

5.2 Simulation Analysis of the Impact of Link Bandwidth on Network Capacity

The simulation study of the impact of link bandwidth on network capacity can help system designers to design a reasonable transmission bandwidth of inter-satellite links under certain transmission requirements constraints, which not only ensures to meet the transmission requirements, but also optimizes the inter-satellite transmission power and antenna size (Fig. 5 and Table 3).

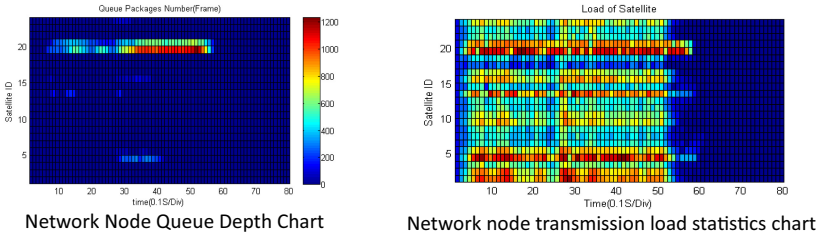


Fig. 5. 4×6 Constellation network transmission load (4 Mbps transmission load, bandwidth of inter-satellite-link is 10 Mbps)

Table 3. Average queue depth

Bandwidth of inter-satellite-link	Source node rate (Mbps)				
	1	2	3	4	5
6 Mbps	0	1.68	148.91	570.14	1094.6
8 Mbps	0	0	28.07	238.57	610.27
10 Mbps	0	0	0.23	36.87	239.16
15 Mbps	0	0	0	0	1.87
18 Mbps	0	0	0	0	0.49

The average queue depth represents the congestion situation of the transmission path in the network. In the ideal situation, there should be no queue or the queue depth is very small to ensure the real-time transmission of important data. Therefore, under the current set satellite scale, the transmission demand of 2 Mbps per satellite should be configured with no less than 8 Mbps bandwidth of inter-satellite link. For the demand of 3 Mbps per satellite, the bandwidth of inter-satellite link should be configured at least 10 Mbps. For the requirement of 5 Mbps per satellite, the bandwidth of inter-satellite link should be at least 18 Mbps.

5.3 Simulation Analysis of the Impact of Cross-Track Link Configuration

The more the cross-orbit links are, the more the single-satellite links are required. If the cross-orbit links are too few, it will become the bottleneck of the network communication and interconnection between different tracks. Therefore, it is very important to select the appropriate cross-orbit link for building a constellation system with appropriate scale and adequate performance. Broadcast capacity and routing hops, so that the network system can choose the appropriate link planning strategy according to the demand (Table 4).

Table 4. Number of cross-orbit links

Number of cross-track links	Congestion free upper limit		Route hops	
	Broadcast transmission	End-to-end transmission	Average	Maximal
1	560 kbps	7 Mbps	3.8264	8
2	320 kbps	10 Mbps	3.4028	7
3	600 kbps	16 Mbps	2.7639	5
4	1.12 Mbps	17 Mbps	2.4688	4

As shown in the table above, an increase in the number of cross-rail links helps to reduce the number of route hops and increases the end-to-end transmission capacity. The impact of broadcast data is more complex, because the lifetime of broadcast data caused by the increase of links affects the number of data flooding replication, but the more link branches, the more broadcast packets are replicated in the network, showing a non-monotonic property.

5.4 Simulation Analysis of the Influence of Data Transmission Mode

Table 5. Maximum source node broadcast communication service capability

Link bandwidth	Inter-satellite link bandwidth				
	6 Mbps	8 Mbps	10 Mbps	15 Mbps	18 Mbps
Broadcast transmission	60 Kbps	80 Kbps	110 Kbps	160 Kbps	200 Kbps
End-to-end transmission	1.5 Mbps	2.2 Mbps	2.8 Mbps	4.1 Mbps	4.9 Mbps

The increase of network nodes leads to the increase of the longest hop and the lifetime of broadcast frame, which is not conducive to the improvement of network broadcast performance. The broadcast communication service capacity of source node is about 1/100 of the bandwidth of inter-satellite link, so in the design of application layer, broadcast communication should be reduced as much as possible, and end-to-end transmission mode should be adopted as far as possible, which is more efficient in terms of transmission capacity occupation of inter-satellite link (Table 5).

5.5 Simulation Analysis the Influence of Data Generation Time Distribution

The impact of the time distribution characteristics of satellite communication data sources on the network transmission is mainly reflected in the impact on the depth of buffer queue in the network, using the same bandwidth, topology and average source data rate, the network transmission characteristics of evenly distributed source and randomly distributed source data are simulated, and the simulation results are shown in the following figure (Figs. 6 and 7):

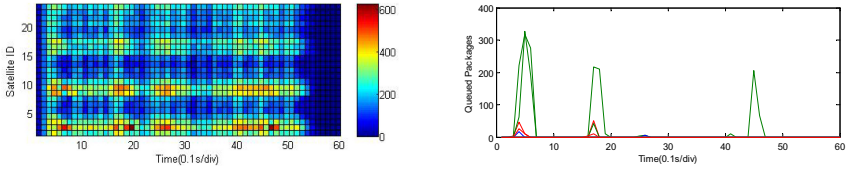


Fig. 6. Influence of randomly distributed sources on the load of network transmission nodes

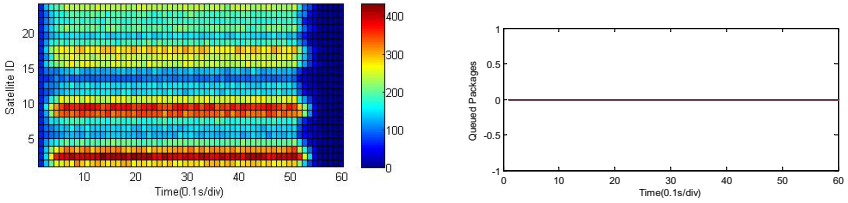


Fig. 7. Influence of uniformly distributed source on network transmission node load

Satellite telemetry, engineering parameters and other state data are uniform periodic communication demand in the time distribution, with less data loads than the network communication load capacity, the network is in a steady state balance, the packet queue will not appear on each satellite node, which means high transmission timeliness.

On the other hand, if the data transmission is on-demand or burst, such as remote control and application event data, it presents the characteristics of random distribution, and in the case of less than the network communication load, the data packet queuing phenomenon will still occur on the high-load nodes because of the uneven data distribution, but because the average communication load is still less than the network capacity, the queuing situation of the intermediate forwarding satellites will still not be continuously accumulated. The network is still smooth, but there is a short-term queuing phenomenon in the burst data concentration period.

6 Conclusion

In constellation network simulation system, the Walker constellation network model, network transmission model, routing and forwarding model, time-driven simulation engine and simulation parameter statistics and display module are designed. The simulation system is built and the simulation scene is run. Through the Walker constellation network simulation system, simulation research is carried out, focusing on the transmission characteristics of ground TT&C data and autonomous TT&C data in the network, which provides reference for network topology, bandwidth capacity configuration, node cache configuration, routing algorithm and data generation strategy design optimization and network transmission capacity analysis and verification in system design.

References

1. She, C., Wang, J., Liu, L., Zhou, M.: Topological dynamics analysis of Walker constellation satellite networks. *J. Commun.* **27**(8), 45–51 (2006)
2. Liu, B.G., Wu, B.: Application of TDRSS in Chinese space TT&C. *J. Spacecr. TT&C Technol.* **31**(6), 1–5 (2014). (in Chinese)
3. Li, Y., Sun, H., Zheng, J.: Using tracking and data relay satellite for low and middle earth orbit satellite launch and on-orbit control. *Chin. J. Space Sci.* **35**(5), 611–617 (2015)
4. Yang, T., Wu, Y., Li, M.: Global satellite mobile communication constellation system space-based inter-satellite-link TC&R scheme. *Chin. Space Sci. Technol.* **33**(3), 77–82 (2013)
5. Schaire, S., Horne, B., et al.: NASA near earth network (NEN) and space network (SN) CubeSat communications. In: *Proceeding of 2016 International Conference on Space Operations*. Daejeon, Korea, pp. 1–19. IEEE (2016)
6. Jiang, L.: Development and trends of foreign TT&C and communication networks for small satellites. *Telecommun. Eng.* **57**(11), 1341–1348 (2017)
7. Sobchak, T., Shinnars, D.W., Shaw, H.: NASA space network project operations management: past, present and future for the tracking and data relay satellite constellation. In: *15th International Conference of Space Operations*, 28 May–01 June 2018, Marseille, France, pp. 1–12 (2018)
8. Yang, T., Wu, Y.X., Li, M.F.: Global satellite mobile communication constellation system space-based inter-satellite-link TC&R scheme. *Chin. Space Sci. Technol.* **33**(6), 77–82 (2013). (in Chinese)
9. Li, J., Shao, Q.: Design and optimization on walker constellation based on STK/Matlab. *Ord. Ind. Autom.* **36**(12), 67–70 (2017)
10. Xiao, X., Shang, X., et al.: Evaluation scheme design for the key performance of inter-satellite link. *Space Electron. Technol.* **15**(3), 81–86 (2018)
11. Zhang, J., Xi, X., Wang, W.: Sufficient condition and characteristic analysis for a spacecraft rendezvous with walker constellation satellites without orbital. *J. Natl. Univ. Def. Technol.* **32**(6), 87–92 (2010)