Software-Defined Space-Air-Ground Integrated Network Architecture with the Multi-Layer Satellite Backbone Network

Chao Guo[1], Cheng Gong[2], Juan Guo[3], Zhanzhen Wei[1,*], Yanyan Han[1] and Sher Zaman Khan[4]

Abstract: Under the background of the rapid development of ground mobile communication, the advantages of high coverage, survivability, and flexibility of satellite communication provide air support to the construction of space information network. According to the requirements of the future space information communication, a software-defined Space-Air-Ground Integrated network architecture was proposed. It consisted of layered structure satellite backbone network, deep space communication network, the stratosphere communication network and the ground network. The Space-Air-Ground Integrated network was supported by the satellite backbone network. It provided data relay for the missions such as deep space exploration and controlled the deep-space spacecraft when needed. In addition, it safeguarded the anti-destructibility of stratospheric communication and assisted the stratosphere to supplement ground network communication. In this paper, algorithm requirements of the congestion control and routing of satellite backbone protocols for heterogeneous users' services were proposed. The algorithm requirements of distinguishing different service objects for the deep space communication and stratospheric communication network protocols were described. Considering the realistic demand for the dynamic coverage of the satellite backbone network and node cost, the multi-layer satellite backbone network architecture was constructed. On this basis, the proposed Software-defined Space-Air-Ground Integrated network architecture could be built as a large, scalable and efficient communication network that could be integrated into space, air, and ground.

Keywords: Space-Air-Ground integrated network, network architecture, software-defined network, multi-layer satellite backbone network.

---

[1] Department of Electronics and Communication Engineering, Beijing Electronics Science and Technology Institute, Beijing, 100070, China.

[2] School of Computer and Communication Engineering, University of Science and Technology Beijing, Beijing, 100083, China.

[3] Vocational and Technical College of Guilin University of Electronic Technology, Beihai, 536000, China.

[4] Institute of Business Administration, Gomal University, Dera Ismail Khan, 29220, Pakistan.

[*] Corresponding Author: Zhanzhen Wei. Email: wzz@besti.edu.cn.

Received: 19 January 2020; Accepted: 05 April 2020.

1 Introduction

In order to realize the space exploration plan and support the existing ground network, the space information network needs to be built into an integrated network system of space, air, and ground [Liu, Shi, Fadlullah et al. (2018)]. The Space-Air-Ground Integrated network (SAGIN) not only combines ground and space information but also needs to provide corresponding support to different services according to different user requirements. As a result, the improvement of the ability including information integrated management and transport processing function will be achieved. By splitting the data plane and the control plane, Software-Defined Network (SDN) provides a feasible solution for data transmission and resource scheduling in heterogeneous, complex, large-scale networks [Wan, Yao, Jing et al. (2018); Wang, Wang, Zeng et al. (2017)]. Therefore, the design of the SDN-based SAGIN architecture includes satellite backbone networks, deep space communication networks, the stratosphere communication network, and the way of information transmission between the layers. With the advent of the big data era, the congestion control of information in the transmission layer becomes more important [Ferrús, Koumaras, Sallent et al. (2016)]. The effective congestion control mechanism can greatly improve the efficiency of the network. Combining congestion control mechanism with the routing scheme of the satellite backbone network can further improve the network reliability and anti-destroying ability.

After the concept of the SAGIN has been put forward, it has attracted worldwide attention [Khawaja, Guvenc, Matolak et al. (2019); Zhang, Zhang, Wang et al. (2018)]. The space network information technology research has been carried out in all space powers. In recent years, the explosive growth of network data, the rapid development of the mobile network, the connection of all things and the popularization of the concept of intelligent life have been spread around. The number of devices connected to the network has been rising at a high speed. It is not enough to rely only on the ground network to provide efficient, global and destruction-resistant network functions. The SAGIN provides a scheme for solving these problems [Kato, Fadlullah, Tang et al. (2019)]. By moving the ground relay station up into the air, a larger scale coverage of communication can be achieved through using the high altitude platform (HAP). The multi-layer satellite backbone network achieves global coverage, so as to reach the goal of connecting anyone anywhere at any time.

The SAGIN was proposed for the purpose of supplementing and improving the functions of the ground network. Most SAGIN architectures consist of ground terminals, aerial platforms, and a large number of earth-orbiting satellites [Yan, Fu, Zhang et al. (2019)]. On the basis of the development of the existing ground network, low time delay, flexible, scalable and efficient global communication can be achieved through the installation of air and space communication systems. The complexity of SAGIN structure and the diversity of user requirements results in high cost of communication equipment and system maintenance. In addition, space exploration is being actively carried out all over the world [Gardikis, Koumaras, Sakkas et al. (2017)]. New requirements of the transmission mode of network information are presented by future space missions such as manned space missions, the moon, and Mars exploration programs. The space communication mode will be extended to the information transmission mode of software-defined SAGINs architecture with the multi-layer satellite backbone network (SSMN), which connects the ground network, includes the stratospheric, satellite backbone network, deep space communication and various kinds of spacecraft interconnections.

The remainder of this paper is organized as follows. The related work is presented in Section 2. SDN-based SAGIN architecture is described in Section 3. Section 4 deals with the simulation experiment and analysis of the satellite backbone structure. Section 5 is put at last to conclude the paper.

2 Related work

In the SAGIN, the satellite constellation of different orbital height accomplishes different communication functions. The existing satellite backbone structures can provide user differentiated services through the characteristics of different orbital satellites to meet different service quality requirements. As early as 20 years ago, there had been many research results on the design of a multi-layer satellite network [Akyildiz, Ekici and Bender (2002); Hu, Li and Wu (2000); Lee and Kang (2000)]. Most of the literatures focused on the establishment of geosynchronous earth orbits (GEO), middle earth orbits (MEO) and low earth orbit (LEO) satellite constellations. At the same time, these schemes designed satellite links that were easy to establish and topologically stable as shown in Tab. 1. However, due to the high delay, low bandwidth and high construction and maintenance costs of satellite communication, the development of technology was limited.

Table 1: The satellite backbone structures

Designer/ country	Akyildiz (United States) [Akyildiz, Ekici and Bender (2002)]	Lee (Korea) [Lee and Kang (2000)]	Hu (China) [Hu, Li and Wu (2000)]
Satellite type/number	LEO: 72 MEO: 18 GEO: 3	LEO: 72/288/1152 MEO: 4	LEO: 63 MEO: 16
inter-satellite links	LEO->LEO: 4 LEO->MEO: 1 LEO->GEO: >1 MEO->MEO: >1 MEO->GEO: >1 GEO->GEO: 2	LEO->LEO: 4 LEO->MEO: 1 MEO->MEO: 2	LEO->MEO: 2 MEO->MEO: 4
Constellation and orbital type	LEO: Polar orbit MEO: Polar orbit GEO: Synchronous orbit	LEO: Polar orbit MEO: Equatorial orbit	LEO: Walker delta MEO: Walker delta
orbital altitude (km)	LEO: 1375 MEO: 8000 & 12000 & 16000 GEO: 35786	LEO: 1000 MEO: 10000	LEO: 1400 MEO: 10353
orbit inclination	LEO: 90° MEO: 90° GEO: 0°	LEO: 90° MEO: 0°	LEO: 48° MEO: 45°

The number of satellites in orbit	LEO: 12 MEO: 6 GEO: 1	LEO: 6/12/24 MEO: 1	LEO: 7 MEO: 4
coverage area	global coverage	global coverage	60° north and south of the equator

With the rapid development of ground network computer and communication technology, space and air communication technology are once again concerned by academia and industry. Compared with the ground network Su et al. [Su, Lin, Zhou et al. (2015)], the air communication layer has the advantages of large coverage areas, long communication distance and high anti-destroying ability. It provides support and supplement for information transmission of ground communication network. Space communication is mainly realized by satellite networks. The biggest advantage is that it is not interfered with by ground conditions and has the characteristics of global coverage. Meanwhile, the satellite communication system has been applied more widely with the decrease in the cost and the increase in the success rate of launch. A large amount of literatures have been devoted to solving problems in the architecture of the SAGIN.

Shi et al. [Shi, Cao, Liu et al. (2019); Zhang, Zhang, Yang et al. (2017); Zhou, Feng, Zhang et al. (2018)] designed the SDN-based network architecture for the SAGIN by combining SDN technology and SAGIN application background. These schemes provided standardized satellite, air and ground services through network slicing. A cross-domain SDN architecture with controllers deployed on the ground, air platforms and satellites were developed in Shi et al. [Shi, Cao, Liu et al. (2019)]. It considered the increasing number of SAGIN users and the control traffic caused by frequent switching, and the reduction in data transmission bandwidth. In Zhang et al. [Zhang, Zhang, Yang et al. (2017)], the resources of each segment were sliced through network slices to achieve service isolation. In Zhou et al. [Zhou, Feng, Zhang et al. (2018)], to satisfy dynamic traffic demand and limited network capacity supply, resources of space, air, and ground were combined in a complementary way. However, literature [Shi, Cao, Liu et al. (2019)] mentioned that inconsistent user density and Quality of Service (QoS) requirements would lead to uneven traffic distribution and unbalanced controller deployment. The schemes proposed in Zhang et al. [Zhang, Zhang, Yang et al. (2017); Zhou, Feng, Zhang et al. (2018)] were limited to vehicle networks and mobile cells, lacking service considerations for other types of network users. Some studies put forward SDN-based Satellite-Terrestrial network or simple satellite network architecture [Feng, Zhou, Zhang et al. (2017); Ferrús, Koumaras, Sallent et al. (2016); Li, Zhou, Luo et al. (2018); Yang, Wu, Chu et al. (2016)], which lacks the global design of SAGIN.

In this paper, Software-defined Space-Air-Ground Integrated network architecture with the multi-layer satellite backbone network is introduced. It expands the dimension of SAGIN service objects according to personalized service requirements.

3 An SSMN architecture

According to the requirements of the future network service, an SSMN architecture is proposed. It consists of the layered structure satellite backbone network, the deep space communication network, the stratosphere communication network and the ground network. The structure is shown in Fig. 1. In the logical domain, the software-defined network is embodied in the separation of system data plane and control plane. In order to comprehensively schedule computing, storage and transmission resources of heterogeneous networks in the SAGIN network, a dynamic virtual resource pool is designed in the data plane. The software-defined network collects all resource states of the entire system. Therefore, resources can be invoked globally to achieve efficient network performance. In the physical domain, all the equipment in the space, air, and ground communication networks form the physical basis of the SAGIN. SSMN integrates these devices while improving data transfer efficiency. The specific network structure and transmission control requirements of each network layer are as follows.

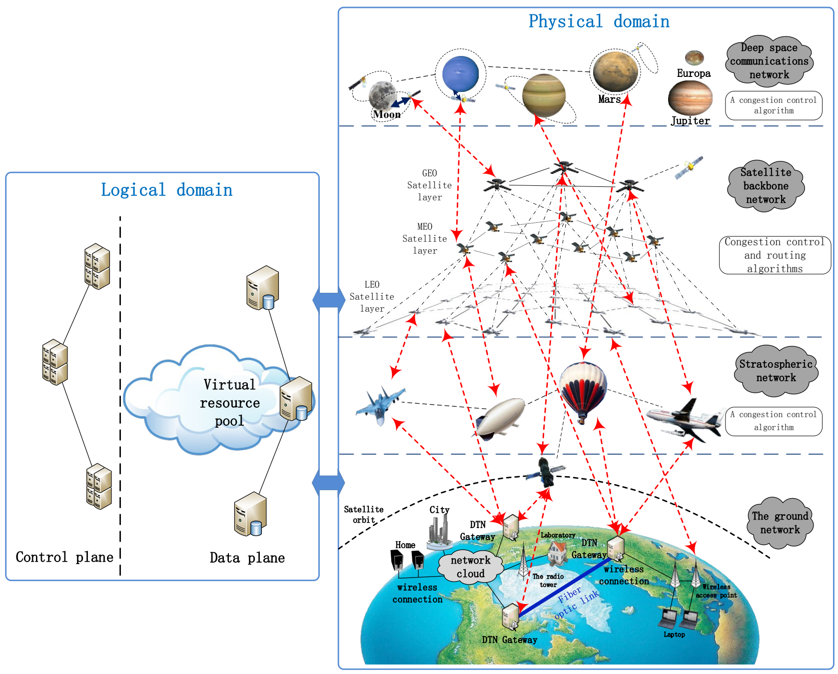

Figure 1: The SSMN architecture

3.1 Satellite backbone structure of the SSMN

The satellite backbone network is centered on the earth, expanding to the depths of the universe [Lin, Liu, Zhou et al. (2014); Lin, Zheng, Zhou et al. (2015)]. The stable satellite backbone network is composed of LEO, MEO and GEO. The satellite orbital layer and the number of satellites are selected according to different requirements. In order to realize the multi-service of the SAGIN, this paper designs a satellite backbone network consisted of three-level orbiting satellites. In the LEO satellite layer, the scheme references the iridium system and improves it. While reducing the number of satellites, dynamic global coverage can be achieved. The Iridium satellite system consists of the LEO satellite layer only, with no high-level satellite support. There must be enough sufficient quantity of LEO satellites to reach global coverage. The multi-layered structure satellite backbone network designed in this paper not only has the LEO satellite layer but also has been supported by MEO and GEO satellite layer. Therefore, the LEO satellite layer is composed of six polar orbit planes, each of which consists of six satellites. The number of 66 LEO satellites in the iridium system has been reduced nearly by half. Although the designed LEO satellite layer can only achieve approximately 50% of the global coverage in instantaneous, the coverage scale keeps increasing with the operation of the constellation. After running 27 minutes, it will still maintain the same global coverage as Iridium. Our scheme reduces the cost of networking and achieves the same effect. The MEO satellite layer is designed to be two orthogonal inclined satellite orbits. Each of orbits has six satellites, and supports the LEO satellite layer. Polar orbit LEO satellite constellation has a pair of retrograde orbits. Satellites in these two orbits are difficult to establish inter-satellite links due to their high relative speeds, resulting in communication barriers. The MEO satellite layer provides communication assistance and improves the efficiency of information transmission for the LEO layer. The GEO satellite layer is still above the earth, and the three satellites are evenly distributed, improving the overall structure of the network and connecting the deep space communication network.

The advantage of the GEO layer satellite is that it can provide global coverage with fewer satellites. It also ensures fewer switches and easier tracking of satellites. The disadvantage is that the link loss is large, the transmission time is high and the orbit resources are short. Therefore, the design scheme uses as few GEO layer satellites as possible to achieve full coverage of the earth. In this paper, three GEO satellites are utilized to build a network, which is the designing scheme with the minimum number of satellites. It is able to establish a GEO layer inter-satellite links.

The mainstream design of the MEO layer satellite constellation is uniformly symmetrical. The Delta constellation is constructed with such a concept. It is characterized by high coverage and low complexity. With the concept, the number of satellites can be reduced whilst maintaining the same coverage degree. Our design is based on the classic model Inmarsat-P system and fine-tuning, according to the situation of the LEO satellites, to implement the optimal design of the system.

LEO satellites are generally small and relatively easy to launch. A large number of satellites are used in the LEO layer. In a multi-layer satellite system, LEO satellites are more responsible for the task of access, so they are normally expected to provide excellent coverage. Considering the weakness of the GEO layer satellite coverage at high latitudes, our scheme adopts the inclined orbital MEO layer satellites and the polar-orbiting LEO satellites with a tilt of nearly 90 degrees.

MEO and LEO satellites should be designed with more consideration for their combined network characteristics and the conditions for their permanent links. The structure of the MEO layer and LEO layer satellites is presented for the coverage problem. The final optimization results are shown in Tab. 2.

Table 2: Satellite backbone network structure

Orbit	GEO	MEO	LEO
Constellation	Geostationary orbit	Walker-δ	Walker-δ
Orbit altitude	35786km	10355km	1414km
Orbit inclination	0.0°	45.0°	86.4°
Orbit period	1436min	359min	114min
Tracks	1	2	6
The number of satellite	3	12	36
The number of links in the same layer of a single satellite	2	2 in the orbit 2 between the orbits	2 in the orbit 1 between the orbits
The same layer link state	Permanent link	Permanent link	Permanent link
The number of links between layers of a single satellite	GEO->MEO 4	MEO->GEO 1 MEO->LEO 4	LEO->MEO 1
Interlayer link state	Permanent link	MEO->GEO Permanent link MEO->LEO Non-permanent link	Non-permanent link
Coverage area	The equator 61.8°	Global coverage	Global coverage

3.2 Deep space communication network structure of the SSMN

A deep space communication network refers to a network of vehicles, satellites or other communications equipment that are not less than 2×10^6 km from the earth. The Mars exploration program is deep space exploration. In order to implement the deep space exploration task and be able to develop deep space resources in the future, the SSMN architecture proposed in this paper must include the deep space communication network. However, the complexity of deep space and long communication distance limit the stable network communication for deep space communication equipment. Therefore, the deep space communication network in the SSMN shown as Fig. 1 is mainly composed of planetary surface detectors, deep-space shuttle, and various satellites. The information transmission of deep space communication equipment is mainly implemented by accessing the satellite backbone network.

3.3 Stratospheric communication network composition structure of the SSMN

The stratospheric communication network is 17~22 km from the ground, consisting mainly of high altitude platforms such as balloons, airships or aircraft. This layer plays a significant role in providing ancillary services to terrestrial networks and connecting with LEO satellites. Compared with the construction of the satellite backbone network, the stratospheric communication network has low cost, while communication delay is relatively small and the transmission reliability is higher. However, because the stratospheric communication network is close to the ground, the target is obvious and vulnerable to attack. Therefore, the stratospheric communication network needs to be established in the support of satellite backbone network and becomes the intermediate layer of the SSMN connecting the ground with the satellites.

3.4 Data transmission requirements of each communication network layer in SSMN

The satellite backbone occupies an important position in the SSMN, which is the link between the universe and the current human activities. Considering the expansion of future space business requirements, it is very important to propose a targeted congestion control algorithm and implement efficient routing of the satellite backbone network. Based on the framework of Consultative Committee for Space Data System (CCSDS) and IP protocol, this paper puts forward the congestion control and routing algorithm of the satellite backbone network based on business classification and improves the effectiveness and reliability of the SAGIN. In Guo et al. [Guo, Gong, Xu et al. (2017)], an optimal routing based queuing game theory for heterogeneous users over space information network (RQGH) algorithm was designed.

The node's profit was

$$Z(\varphi_j) = \lambda\left[1-\Psi\left(\varphi_j+\omega_j(l)\right)\right](1-p_n)\varphi_j \tag{1}$$

where $\omega_j(l)$=C$\dfrac{l+1}{\mu}$. $\left[1-\Psi\left(\varphi_j+\omega_j(l)\right)\right]$ denoted the probability of a user joining the queue of the node.

The whole welfare $W(\varphi)$ of the system could be specified as

$$W(\varphi_j) = \lambda\sum_{l=0}^{n} p_l\left[1-\Psi\left(\varphi_j+\omega_j(l)\right)\right]\left[E\left(R\middle|R>\varphi_j+\omega_j(l)\right)-\omega_j(l)\right] \tag{2}$$

where $\left[E\left(R\middle|R>\varphi_j+\omega_j(l)\right)-\omega_j(l)\right]$ denoted the sum of the user's gain and the node's profit when the queue length was l.

The RQGH scheme modeled the whole welfare of the system through the queuing game theory. It calculated the optimal admission fee to make sure that the network performance achieves the theoretical optimal state. According to the restriction of user's gain being no less than a constant, the average maximum queue length was evaluated with the corresponding optimal admission fee.

In the deep space communication network layer, the congestion control algorithm of the satellite backbone network is extended. A novel congestion control based on queuing game with impatient users (CCQGI) algorithm was proposed in the literature [Guo, Lin, Yao et al. (2015)] for the fast access and service requirements of deep space communication users. It described the likelihood that the user would choose to leave the service node after waiting for a period of time due to the change of relative position, etc. The algorithm took full account of the unstable service requirement of deep space communication and improved the service quality of the SAGIN to the deep space communication users.

In the first condition, the profit of the Congestion Control Platform (CCP) was

$$Z_{nf}(l)=\left[\lambda(1-q_l)-\beta\Delta_l\right]\varphi(l) \tag{3}$$

where β was a constant optimization factor, and $0<\beta<0.218$. q_l was the probability of observing l users in the queue.

In the second condition, the CCP's profit was

$$Z_f(l_\alpha)=Z_f(l_{th})+\lambda q_{l\in(l_{th},l_\alpha]}\varphi(l_\alpha) \tag{4}$$

where l_{th} was the threshold length of the queue such that users' gain was non-negative. l_α was the actual queue length, and $l_\alpha>l_{th}$.

The CCQGI scheme modeled the profit of CCP through the equilibrium queuing theory and calculated the threshold queue length to ensure the user's gain being non-negative. Once the queue length reached the threshold, a preliminary queue was opened to the new arrival user. The user chose the service node which announces the maximum user's gain. The limited resource in space information networks was scheduled reasonably and the network achieves optimal performance by using the CCQGI scheme. Meanwhile, the congestion problems were solved to a certain degree.

The main function of stratospheric communication is to assist the ground network to carry out information transmission [Hui, Zhou, Xu et al. (2020)]. Considering the compatibility with the ground network, and the difference between uplink and downlink, the stratospheric congestion control algorithm based on dynamic windows was proposed in Guo et al. [Guo, Zhou, Lin et al. (2015)]. It improved the transmission layer protocol of the SSMN.

The optimization problem with the dynamic non-cooperative game could be modeled as follows.

$$\max_{w_i(t)}\left\{\int_{t_0}^{T}e^{-\gamma(t-t_0)}\left[\frac{w_i^2(t)}{a_i^2\cdot c_i}-x(t)\right]dt+e^{-\gamma(T-t_0)}qx(T)\right\} \tag{5}$$

where γ was the discount rate.

The non-cooperative differential game was used to build a model considering the SSMN actual environment which suffered from high delay-bandwidth product and link failure rate. Then the feedback Nash equilibrium was solved to obtain the optimal strategy for congestion window size.

4 Simulation experiment and analysis of SSMN structure

The larger satellite networks are generally designed to be divided into separate but interrelated layers. Due to the large dynamic change of the LEO coverage area, the establishment of a reasonable multi-layer satellite structure can better compensate for this defect and minimize the restrictions. The LEO satellite has become the main carrier of data processing. MEO satellites are responsible for monitoring data, as well as data transmission at the LEO satellite reverse slot. The GEO layer satellites are only responsible for monitoring working satellites.

In the SSMN, the Satellite backbone network is connected by the LEO Satellite, MEO

Satellite, and the GEO Satellite through inter-satellite Links (ISLs). It forms a network structure with stable topology. GEO satellites are responsible for routing information collection, management of link-state information and to keep a record of the SSMN operation. It provides information exchange services for the connected MEO satellites and supports fixed users with large terminals as a supplement to the ground network. LEO constellation provides access, information exchange and ancillary services for the stratospheric and ground communication network. The ISLs are established between LEO satellites to implement dynamic global coverage. The designed satellite backbone network structure is shown as Fig. 2. The simulation rendering is obtained through Satellite Tool Kit (STK).

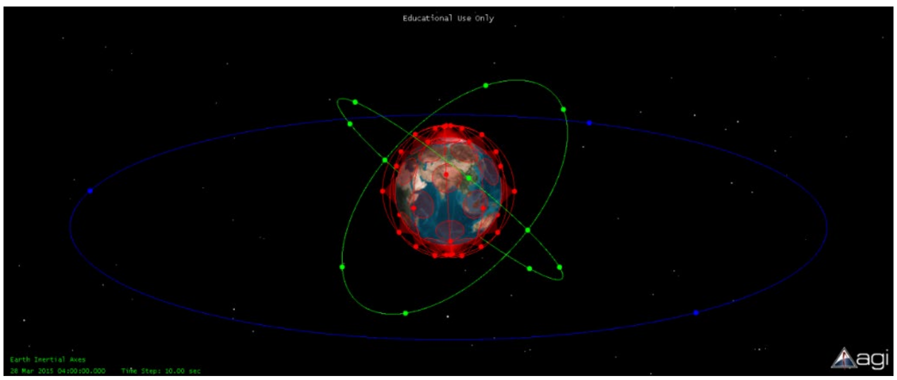

Figure 2: Simulation of the satellite backbone network structure

The designed satellite backbone network structure is mainly modified in the LEO satellite layer. GEO satellite layer adopts the minimum number of satellites to realize coverage in addition to high latitude areas and inter-satellite link communication. MEO satellite layer also reduces the number of satellites whilst meeting coverage and communication requirements. The polar orbit selection of the LEO layer satellite provides a supplement for the weak coverage of the high latitude area by GEO and MEO layer satellites. With the assistance of MEO and GEO satellites, LEO layer satellites can meet the communication requirements of users at any time as long as the global coverage is implemented in the dynamic operation. By comparison with the satellite constellation in Hu et al. [Hu, Li and Wu (2000)], the rationality of the designed satellite backbone network structure was verified.

As shown in Fig. 3, the simulation step is 10 seconds. The red line indicates the LEO satellite layer's instantaneous coverage of the Earth, oscillating approximately 50%, due to the small number of LEO satellites designed. However, the blue line representing dynamic coverage shows that the system implement global coverage after approximately 27 minutes of operation. In order to intuitively show the difference between the designed scheme and the compared scheme, the experimental simulation data is imported into the MATLAB software by using the data export function of STK software. The contrast effect is clear.

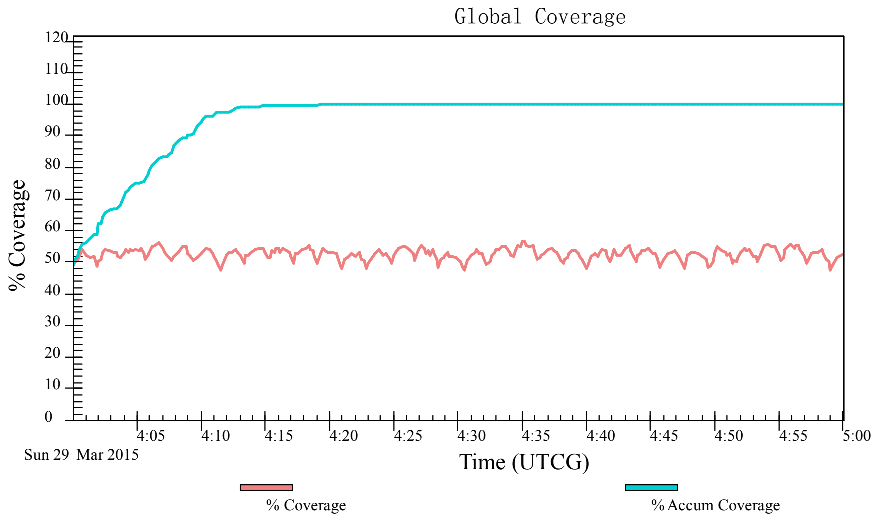

Figure 3: Instantaneous and dynamic coverage of the LEO satellite layer

As shown in Fig. 4, the simulation results show that after approximately 10 minutes, the global dynamic coverage rate reaches the maximum value approximately 89% in the compared scheme. The reason is that the LEO constellation is designed to be a 48 degree inclined satellite, sacrificing the coverage of high latitudes. Although there is less information traffic in the high latitude area, with the further laying of the SSMN, the communication scope will be fully covered. The LEO satellite constellation designed takes expanding coverage into account and utilizes polar-orbiting satellites for networking. It can achieve global coverage in the process of dynamic operation. This design reduces the instantaneous coverage of the system to the earth by 14%. The cost of the LEO satellite layer has been reduced by nearly 50%, with higher cost performance.

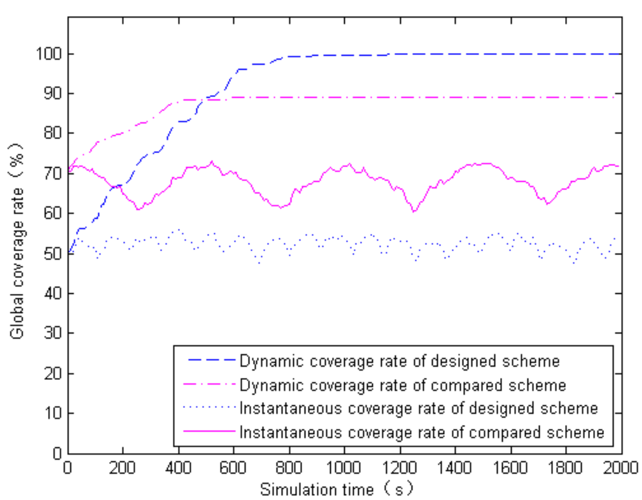

Figure 4: Comparison of global coverage of LEO constellation

As shown in Fig. 5, the blue line indicates that the polar orbit LEO constellation designed has a low coverage near the equator, which is mainly supplemented by the GEO satellite layer. In high latitudes, the coverage of the GEO satellite layer is weak while the LEO satellite layer in polar orbit can achieve better coverage. With the assistance of the MEO satellite layer, the designed satellite backbone network structure of the SSMN implement global coverage and users' access at any time. The proposal is based on a minimum number of satellites. As shown in Fig. 5, the red line denotes the coverage rate of the LEO satellite layer in the compared scheme composed of 63 satellites. The coverage of the area with latitude higher than 66 degrees is 0, while between 30 degrees and 55 degrees it is higher. In terms of global coverage, efficiency is lower than our scheme. The compared scheme can also achieve global coverage by supplementing the MEO satellite layer, which has the same effect as the final implementation of the proposed scheme.

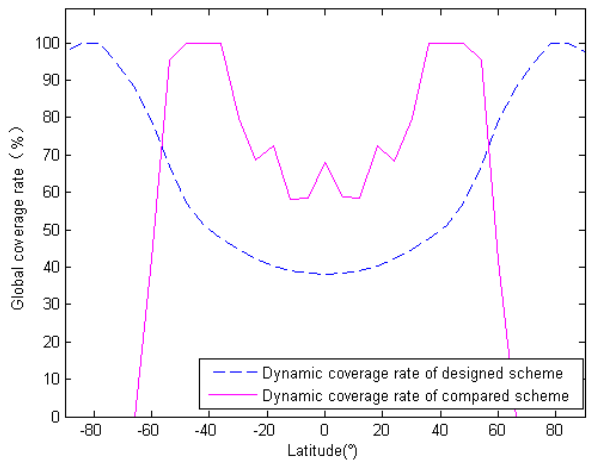

Figure 5: Instantaneous and dynamic coverage of the LEO satellite layer

Through the comparative analysis of the experiment and simulation of satellite backbone network structure, the designed satellite backbone network implements high coverage in high latitude areas under the condition of a small number of LEO satellites. The global coverage effect of the satellite backbone network is coordinated by the GEO satellite layer's advantage of low latitude coverage. The MEO satellite layer connects LEO and GEO satellite layers in the structure. Due to the large coverage of the MEO satellite layer to the earth, a small number of satellites can complete global coverage. The stability and invulnerability of the whole satellite backbone network structure are improved. The multi-component structure of the SSMN reduces the dependency on the functions of each element. By networking and compatibility, various networks or devices with low single functions are integrated into a unified network system. A large-scale information network with mutual assistance and complementary functions is established. Therefore, the designed SSMN mainly considers how to improve the overall performance of the system through multi-layer networking under the condition of the low-functionality of the single-layer satellite. At the same time, the increasing number of the SSMN communication devices in the future will promote the improvement of network functions and communication performance.

5 Conclusion

The proposed SSMN architecture is mainly constructed by 3 GEO satellites, 12 MEO satellites, and 36 LEO satellites. On the premise of fewer satellites, 100% coverage can be implemented by a single LEO satellite in dynamic operation. It is better than 89% dynamic coverage of the LEO satellite in the scheme proposed by Hu et al. [Hu, Li and Wu (2000)]. The establishment of a satellite backbone network structure can support the efficient and reliable transmission of the SSMN data. It connects deep space communication and stratospheric communication to the SSMN as a bridge, which makes the network architecture more complete. Finally, in order to improve the transport layer protocol of the SSMN, specific algorithm requirements are proposed for deep-space communication and stratospheric congestion control.

Acknowledgement: We gratefully acknowledge anonymous reviewers who read drafts and made many helpful suggestions.

Funding Statement: This work is supported by Fundamental Research Funds for the Central Universities of China (328201911) , C. G. (Chao Guo), the Open Project Program of National Engineering Laboratory for Agri-product Quality Traceability, C. G. (Chao Guo), Beijing Technology and Business University (BTBU) No. AQT-2018Y-B4, C. G. (Chao Guo), Higher Education Department of the Ministry of Education Industry-university Cooperative Education Project, C. G. (Chao Guo), and Education and Teaching Reform Project of Beijing Electronic and Technology Institute, C. G. (Chao Guo).

Conflicts of Interest: The authors declare that there is no conflict of interest regarding the publication of this paper.

References

Akyildiz, I. F.; Ekici, E.; Bender, M. D. (2002): MLSR: a novel routing algorithm for multilayered satellite IP networks. *IEEE/ACM Transactions on Networking*, vol. 10, no. 3, pp. 411-424.

Feng, B.; Zhou, H.; Zhang, H.; Li, G.; Li, H. et al. (2017): HetNet: a flexible architecture for heterogeneous satellite-terrestrial networks. *IEEE Network*, vol. 31, no. 6, pp. 86-92.

Ferrús, R.; Koumaras, H.; Sallent, O.; Agapiou, G.; Rasheed, T. et al. (2016): SDN/NFV-enabled satellite communications networks: opportunities, scenarios and challenges. *Physical Communication*, vol. 18, pp. 95-112.

Gardikis, G.; Koumaras, H.; Sakkas, C.; Koumaras, V. (2017): Towards SDN/NFV-enabled satellite networks. *Telecommunication Systems*, vol. 2017, no. 66, pp. 615-628.

Guo, C.; Gong, C.; Xu, H.; Yao, Z. (2017): Queuing game theory based optimal routing scheme for heterogeneous users over space information networks. *Mathematical Problems in Engineering*, vol. 2017, no. 1, pp. 1-9.

Guo, C.; Lin, F.; Yao, Z.; Mohadeskasaei, S. A. (2015): Queuing game based congestion control model with impatient users over space information networks. *Journal* *of Information and Computational Science*, vol. 12, no. 8, pp. 3319-3331.

Guo, C.; Zhou, X.; Lin, F.; Mohades Kasaei, S. A. (2015): Novel congestion window control scheme based on differential game model over space information networks. *Journal of Computational and Theoretical Nanoscience*, vol. 12, no. 9, pp. 2885-2890.

Hui, H.; Zhou, C.; Xu, S.; Lin, F. (2020): A novel secure data transmission scheme in industrial Internet of things. *China Communications*, vol. 17, no. 1, pp. 73-88.

Hu, J.; Li, T.; Wu, S. (2000): Routing of a LEO & MEO double layer mobile satellite communication system. *ACTA Electronica Sinica*, vol. 28, no. 4, pp. 31-35.

Kato, N.; Fadlullah, Z. M.; Tang, F.; Mao, B.; Tani, S. et al. (2019): Optimizing space-air-ground integrated networks by artificial intelligence. *IEEE Wireless Communications*, vol. 26, no. 4, pp. 140-147.

Khawaja, W.; Guvenc, I.; Matolak, D. W.; Fiebig, U.; Schneckenburger, N. (2019): A survey of air-to-ground propagation channel modeling for unmanned aerial vehicles. *IEEE Communications Surveys & Tutorials*, vol. 21, no. 3, pp. 2361-2391.

Lee, J.; Kang, S. (2000): Satellite over satellite (SOS) network: a novel architecture for satellite network. *Conference on Computer Communications. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 1, pp. 315-321.

Li, T.; Zhou, H.; Luo, H.; Yu, S. (2018): SERvICE: a software defined framework for integrated space-terrestrial satellite communication. *IEEE Transactions on Mobile Computing*, vol. 17, no. 3, pp. 703-716.

Lin, F.; Liu, Q.; Zhou, X.; Xiong, K. (2014): Towards green for relay in InterPlaNetary Internet based on differential game model. *Science China Information Sciences*, vol. 57, no. 4, pp. 1-9.

Lin, F.; Zheng, Y.; Zhou, X.; Lü, X. (2015): DMMF: dominant and max-min fair allocation in satellite network. *China Communications*, vol. 12, no. 2, pp. 149-154.

Liu, J.; Shi, Y.; Fadlullah, Z. M.; Kato, N. (2018): Space-air-ground integrated network: a survey. *IEEE Communications Surveys & Tutorials*, vol. 20, no. 4, pp. 2714-2741.

Shi, Y.; Cao, Y.; Liu, J.; Kato, N. (2019): A cross-domain SDN architecture for multi-layered space-terrestrial integrated networks. *IEEE Network*, vol. 33, no. 1, pp. 29-35.

Su, J.; Lin, F.; Zhou, X.; Lu, X. (2015): Steiner tree based optimal resource caching scheme in fog computing. *China Communications*, vol. 12, no. 8, pp. 161-168.

Wan, M.; Yao, J.; Jing, Y.; Jin, X. (2018): Event-based anomaly detection for non-public industrial communication protocols in sdn-based control systems. *Computers, Materials & Continua*, vol. 55, no. 3, pp. 447-463.

Wang, K.; Wang, Y.; Zeng, D.; Guo, S. (2017): An SDN-based architecture for next-generation wireless networks. *IEEE Wireless Communications*, vol. 24, no. 1, pp. 25-31.

Yan, C.; Fu, L.; Zhang, J.; Wang, J. (2019): A comprehensive survey on uav communication channel modeling. *IEEE Access*, vol. 7, pp. 107769-107792.

Yang, B.; Wu, Y.; Chu, X.; Song, G. (2016): Seamless handover in software-defined satellite networking. *IEEE Communications Letters*, vol. 20, no. 9, pp. 1768-1771.