Journal of Communications and Information Networks
Vol.1, No.3, Oct. 2016
DOI: 10.11959/j.issn.2096-1081.2016.029

Review paper

Architecture and critical technologies of space information networks

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Abstract: Focusing on its main requirements and challenges and by analyzing the characteristics of different space platforms, an overall architecture for space information networks is proposed based on national strategic planning and the present development status of associated technologies. Furthermore, the core scientific problems that need to be solved are expounded. In addition, the primary considerations and a preliminary integrated demonstration environment for verification of key technologies are presented.

Key words: space information networks, system architecture, distributed satellite clusters

Citation: YU Q, WANG J C, BAI L. Architecture and critical technologies of space information networks[J]. Journal of communications and information networks, 2016, 1(3): 1-9.

1 Introduction

Recently, concomitant with emerging innovative enterprises such as OneWeb[1] and SpaceX[2], large amounts of capital have started to flow into the aerospace field. In particular, with the rapid development of mobile internet, many Internet giants have proposed various space network development plans aimed at providing everyone on Earth with access to the Internet. Thus, "space economy" and "Internet economy" are projected to become new economic development growth points. This projection has resulted in governments beginning to attach substantial importance to the development of space information networks.

Researchers have presented various interpretations for space information networks. In the main research plan of the National Nature and Science Fund, "Space information networks based theory and key technology," "space information networks" are defined as "networks infrastructure that are carried by space platforms (such as geostationary orbit satellites, non-synchronous medium earth orbit satellites, non-synchronous low earth orbit satellites, near-space UAVs (Unmanned Aerial Vehicles), or airships on high altitude platform stations), and which can support real-time data acquisition, transmission and processing of mass data, and achieve systematic information service application through integrated network interconnecting." From this aspect, a

Manuscript received Jul. 4, 2016; accepted Sept. 26, 2016
This work is supported by the National Natural Science Foundation of China (Nos.61231011, 61671478)

space information network is the space segment of integrated space-ground information networks[3,4].

In this paper, we focus on the critical demands and challenges of space information networks and analyze the features of different space platforms in accordance with the strategic planning and technology development situation in China. Then, we propose a system architecture for space information networks and clarify the core science questions to be solved. Finally, the primary considerations and a preliminary integrated demonstration environment for validating critical technologies are presented.

2 Requirements and challenges

A space information network has wider coverage, broader application area, and involves greater technical difficulties than a terrestrial network. Because of its unique location advantage, outer space plays an irreplaceable role in areas such as earth observation, emergency communications, aerospace measurement and control, air transport, and expansion of national strategic interests. Thus, it has gradually become the “high frontier” of national strategic interests[5].

In the area of earth observation, China now has approximately one hundred satellites of various types in orbit[6]. Currently, after observing specific areas, tens of minutes of flight time are expended before satellites arrive at an airspace over ground stations in China’s territory, and communication windows only last for approximately ten minutes. Thus, problems such as long earth observation revisit cycle, non-continuous observation, short over-time, and low transmission rate have arisen. The relaying of massive data during over-time necessitates a transmission rate of gigabits or even dozens of gigabits per second, which is a significant challenge for airborne sensor platforms. This problem can be resolved, to some extent, by constructing a space interconnection information network to enable “transmission-while-observing.”

In the area of emergency communications, as seen in the Wenchuan earthquake in 2008, Yushu earthquake in 2010, and other natural disasters, ground communication networks in the affected areas are easily disrupted in the initial stage of disasters, which result in significant difficulty in rescuing survivors. Implementation of space information networks would enable ground networks to be replaced by spatial networks when ground networks become nonfunctional. It can also play a significant role in the response to all types of emergencies in China.

In the area of aerospace measurement and control, NASA (the National Aeronautics and Space Administration) has built many stations globally and uses space-based monitoring networks to guarantee space launches, the telemetry of overall operations in orbit, and transmission of remote control information. Frequent space launches can thus be well guaranteed[7]. At present, the main protocol used for measurement and control in China is native monitoring combined with temporary stations arranged by the Aerospace China marine observation and control ship “Yuan Wang Hao”. This approach to some extent restricts the growth of the aerospace industry in China because the number of guaranteed measurement and control tasks is very limited. Space-based measurement and control can be implemented by constructing space information networks, which will significantly improve system performance. Accordingly, the construction of space information networks is also essential to the development of the space industry.

In the area of air transport, the routing design in China mainly relies on the layout of ground radar networks and, therefore, the designed routing often needs to be circuitous. These nonlinear routes, however, can be straightened by constructing a space information network and, according to preliminary estimates, millions of dollars could be saved annually in fuel costs alone. In addition to the considerable economic benefits, the flight data recorded in real time by "black boxes (namely, flight data recorder)" can be obtained by controllers. Thus, incidents such as the "missing Malaysia Airlines plane" could be eliminated.

In terms of expansion of national strategic interests, with the promotion of the "Belt and Road" strategy from the "going global" plan, it is necessary to realize that "the information network will cover wherever national interest is existing". A system that achieves this objective using ground infrastructure would be very complex and very expensive. Furthermore, ground networks may fail to cover sea lanes; thus, space networks are a better choice to protect the expansion of national interests.

The development of space information networks has several unique challenges. Firstly, global station arrangement is constrained; unlike the United States, we cannot deploy dozens of worldwide earth-gate-station space system stations. Thus, the space-based interconnection must be realized through network topologies, which will consequently result in new problems. In fact, as the blueprint used by the United States cannot be copied, we must seek innovation that is in line with Chinese characteristics. Secondly, the orbital frequency is limited. Although frequency and orbit resources are the basis and premise of development for space information networks, these resources are becoming increasingly scarce. In China, synchronous orbit resources are less than one-seventh that of America's, and international harmonization of frequency resources for low-orbit communication satellites is extremely difficult. Thirdly, the capacity of a satellite platform is limited. The DFH-4 satellite, now the primary satellite in China, can carry a payload of 700 kilograms and provide up to 8 000 watts of power. However, there is still a large gap between the DFH-4 and the Alphabus platform in Europe, which has a payload of 1 500 kilograms and 18 000 watts of power.

3 Overall architecture

Space information network platforms mainly include synchronous satellites, low-orbit satellites and stratospheric airships, and UAVs. It is necessary to take these platforms' advantages and disadvantages into account in the overall architecture design.

The advantages of geosynchronous communication systems, such as extensive geographical coverage, are obvious. In theory, a geosynchronous satellite can cover one-third of Earth's surface. A satellite is able to operate in orbit for more than 10 years. Synchronous satellite communication systems utilize a star network topology, which enables simple and convenient connection with ground networks. Very high information distribution efficiency can be achieved because of its inherent broadcast property. However, geosynchronous communication systems have disadvantages, such as failure to cover the region of polar latitudes and long signal delays resulting from extremely long distances. Further, the capacity of geosynchronous communication systems to counter interference and destruction is so weak that the entire network is paralyzed if the center of the system is damaged. The broadcast characteristic of the system can result in weak signal seclusion performance and other problems. At present, most communication satellites operate in geosynchronous orbit, such as the Thuraya satellite and the Inmarsat-4 maritime satellite, which belongs to the International Maritime Satellite Organization (Inmarsat). Both of these satellites are used for mobile satellite communication. Ka-Sat of ViaSat and the Inmarsat-5 maritime satellite of the European Telecommunications Satellite Organization (EutelSat) are also used for broadband transmission.

Low earth orbit satellites have advantages such as coverage of the polar regions and less delay. However, worldwide coverage by these satellites requires construction of enormous constellations, which can also result in problems such as low cost-effectiveness ratio and network complexity. IRIDIUM system, created by Motorola in an ambitious plan, is a representative case. The system, developed in the early 1990s, was put into operation in 1998. Unfortunately, ground mobile communication networks were also developing rapidly at the same time. Consequently, in 1999, Iridium, the operator of the Iridium system, declared bankruptcy. In 2000, the assets of the company, which had spent more than five billion dollars, were acquired by the U.S. military for 25 million dollars. From a business perspective, the Iridium system was very unsuccessful, but from a technical point of view, the design of the system was also quite advanced beyond a few decades, even today. Although its network, which consists of 66 satellites, may seem complex, its topology is actually relatively static. Each satellite has 48 point beams, each of which can support several users, and more than 4 000 multiplex communication links are supported by each satellite. Although the IRIDIUM system currently has tens of thousands of users, making it really profitable is very difficult. There are plans to integrate functions such as mobile communication, data transmission, earth observation, electromagnetic spectrum monitoring, and GPS navigation enhancing in the next generation Iridium system. These non-communication space services will be integrated to improve the cost-effectiveness of the system. At the WRC 2015 (2015 World Radio Conference), the United States proposed to use the frequency spectrum monitoring system of Iridium satellites to receive secondary surveillance radar signals from commercial aircraft for the purpose of real-time monitoring of airplane flight path, and to build a so-called “flighthero tracking system” to ensure flight safety. From the development of the Iridium system, a global system comprising a low earth-orbiting constellation that is only used for communication would not be profitable. In order to achieve sustainable development, the efficiency needs to be improved through integration of spectrum sensing, space observation, navigation enhancing, and aviation management into the system.

A stratospheric platform has many advantages, the most prominent of which is that it is compatible with ground communication terminals. In addition, the altitude of the platform is much higher than that of ordinary civilian aircraft, which makes airspace management much easier. The main disadvantages of stratospheric platforms are limited coverage (hundreds of kilometers) and payload. In space information networks, stratospheric platforms can be used as an important means of coverage enhancement in key areas and as an effective complement for satellite platforms in terms of positioning and precise timing. At present, although there are no actual commercial stratospheric platforms, such platforms would have broad application prospects once the technology matures.

Google is currently beginning a project called Project Loon that is aimed at providing fast and reliable broadband network services for specific areas. The project involves the preparation of thousands of stratospheric balloons to constitute a space network around Earth. In 2013, Google released 30 stratospheric balloons in New Zealand and conducted a ground wireless network coverage experiment. Meanwhile, solar-powered stratospheric UAVs are also being rapidly developed by Google and Facebook. These UAVs can hover 20 000 meters above the ground for an extended time, using solar energy during the day and batteries at night. Their hang time can be up to five years, according to the limited times of charge cycles in theory. The mobility of UAV platforms in the stratosphere is better than that of floats; however, the payload of UAV platforms is slightly lower. Therefore, the characteristics of these platforms should be fully taken into consideration in the design of space information networks and need to be used properly.

In accordance with the requirements and challenges of space information networks, the following preliminary space information network is being considered. In terms of the overall network, a simple architecture is the basic starting point in complex systems design. Moreover, space information networks require a backbone that is stable and reliable as the national infrastructure. Thus, fundamental ideas underlying the design of the top-level architecture of space information networks include constructing a backbone network to provide global coverage, building the backbone in the stratosphere to enhance regional coverage, and integrating ground backbone networks with the space-ground Internet[8]. A schematic of the proposed architecture for space information networks is shown in Fig.1.

By constructing such a space information network, huge amounts of data captured by low-orbit earth observation satellites or remote sensing satellites can be transmitted back to Earth in real time via the backbone, without having to wait dozens of minutes until the satellite is in a suitable location. A continuous and uninterrupted interconnection can be formed for measurement and control of space stations and deep space platforms for lunar exploration and Mars exploration. In addition, in areas where the coverage capacity or the satellite coverage is insufficient, emergency communication networks can be rapidly constructed by accessing the stratosphere platform and interconnecting the space-based backbone network with ground networks. For civilian aircraft, real-time flight data can be transmitted back to management centers on the ground over the space information networks, rather than relying on ground radar to detect and monitor flight paths. In short, the purpose of constructing space information networks is not to replace ground optical fiber networks or mobile networks, but to help complete missions that terrestrial networks cannot (such as spatial and oceanic coverage) or have implementation difficulties (such as coverage for sparsely populated areas).

In such a comprehensive network architecture, the space-based backbone network is critical. To

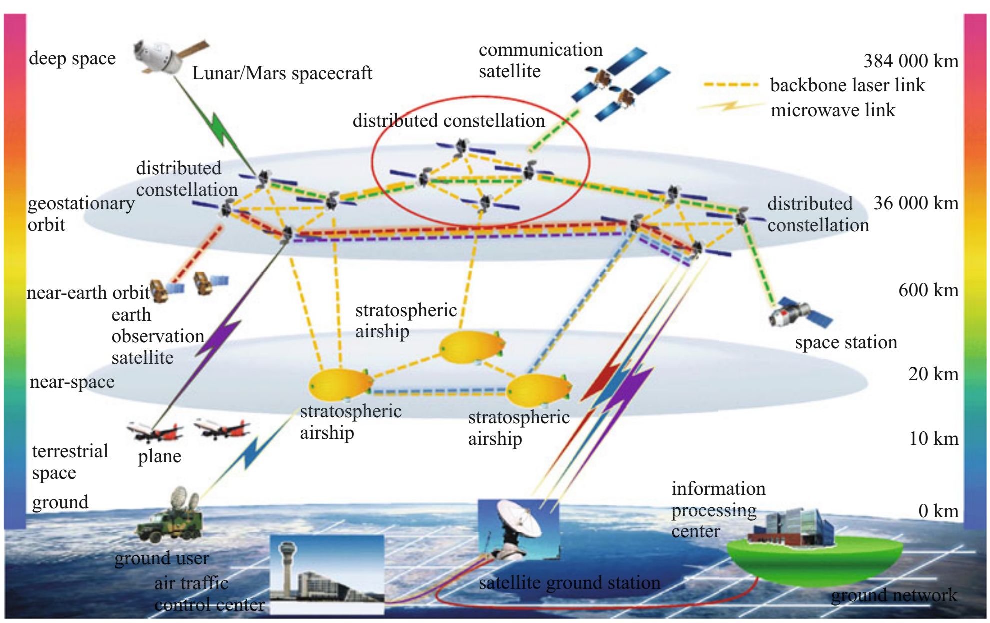

Figure 1 Proposed architecture for space information networks

overcome the challenges of the backbone nodes lacking orbital frequency and the weak payload of satellites, we propose the concept of distributed constellation networks. In this type of network, a satellite cluster is constructed using multiple satellites distributed in the same orbital location through high-speed interconnected inter-satellite links. Further, the synergy of the satellites facilitates functions that cannot be achieved by a single satellite[9]. As a result, the constructed satellite cluster can realize rapid self-recovery in cases where any of its component satellites are experiencing problems. The orbital frequency of distributed constellation networks can be promoted through the combination of multiple satellites in the same orbit, and the capacity of platforms can be improved by cooperative transmission by the satellite constellation. Distributed constellation networks also support orbital self-healing and reconstruction and rapid response.

4 Critical technologies

In the research plan, "basic theory and critical technology of space information network" of NSFC (the Natural Science Foundation of China), the fundamental theory underlying the construction of space information network includes three aspects: network architecture, high-speed wireless transmission, and information processing in orbit[10].

In terms of network architecture, a space information network has the following characteristics: network heterogeneity, business heterogeneity, multi-dimensional resources, and links diversity. The topology structures vary considerably between backbone networks. For example, a space-based backbone is a grid network, while a ground backbone is often a tree distribution network. As a high-capacity and multi-level heterogeneous network, a space information network needs to accommodate various activities, such as remote sensing, measurement, control, air traffic control, and communication. These activities require quality of service that differs completely in terms of bandwidth, delay, and error coding. A space information network is a complex giant system that contains various kinds of resources for transmission, storage, and calculation. Its links include microwave, millimeter wave, and laser. Its communication distance can range from dozens of kilometers to tens of thousands of kilometers.

For such a complex network, the first scientific problems that need to be resolved include determination of the most appropriate model and the mechanism to enable high efficiency. These areas of research focus are explained below.

The network topology model should be constructed with changing space-time scales and should facilitate construction of a dynamic payload mechanism for heterogeneous business and network capacity theory based on transmission, storage, and dynamic computing.

To achieve network topology breakthrough from static state to task-oriented dynamic reconfiguration, network protocols that can develop from fixed delay constraint to adaptive delay constraint and technological approaches that increase network capacity from link models to transmission, storage, and dynamic computing models should be developed.

The network dynamic application-oriented or task-oriented capacity needs to be expanded and the stability and high efficiency of networks maintained. The problem of cooperation communication in the overall network architecture and the problem of service flexibility in open environments with multitask constraints for distributed heterogeneous autonomous networks need to be solved. A discontinuous, extensible, highly efficient, and safe basic network should be provided for high-value applications such as space exploration. The core issues involved are the network architecture and information payload fusion.

As regards wireless transmission, the first problem is dynamic access. The spatial backbone network is relatively static, whereas the space-ground heterogeneous access platform is highly dynamic. Thus, network access capability challenges exist. The second problem is service quality. The service quality requirements for various kinds of heterogeneous services, such as remote sensing, measurement and control, air traffic control, and communication, are completely different. Therefore, facilitating different businesses on the same network while ensuring quality of service is a major problem to be solved. The third problem is efficient scheduling of multidimensional resources. Because of the specialty of the space environment, problems that can be easily solved on the ground present major constraints in space. Given the oriented tasks, the question of how to realize efficient integrated scheduling of communication resources such as power, frequency, timeslot, storage, and computing is a challenge in space information networks[11]. The scientific problem underlying these challenges is the theory and method for dynamic network transmission in space. Consequently, important problems to be solved include allocation of resources through real-time concurrent task scheduling instead of static preplanning, use of dynamic space-ground routing instead of static routing, and adoption of transmission models that can be expected to develop from point-to-point link to collaborative transmission in multidimensional wide areas. The main research focus include real-time network planning that satisfies multitask requirements, virtualization, efficient scheduling of network resources, and collaborative transmission methods in dynamic time-varying networks. Dynamic resource scheduling and efficient cooperative transmission of space information network are critical problems.

As regards information processing in orbit, the critical problems that need to be addressed include the question of how to convert the mass data of different features and resolutions into usable information and knowledge and how to provide support for decision-making by system applications. The mass data mentioned above are obtained by multiple platforms with heterogeneous sensors. The resulting problems include sparse representation and fusion processing of space information. Several major breakthroughs are needed: information representation methodology should be developed from directly obtaining the data to sensing data and making sparse representation; a time-space benchmark should be developed, from single time-space benchmark to vectors of multiple time-space benchmarks; and information fusion should be developed from single-source processing to time-space correlation and multi-source fusion. The associated research contents include unified representation of the time-space benchmark in space information networks, time-space assimilation and fusion processing of multidimensional information, and rapid extraction and knowledge discovery of spatial information. Orbital processing and sparse representation of mass data are the core problems.

5 Integrated authentication

To validate the feasibility and application of critical technologies in space information networks, small-scale demonstrations and evaluations need to be conducted before constructing and developing the actual space information networks. The followings are the primary considerations. Firstly, we consider typical scenes based on backbone satellites, several earth observation satellites, stratosphere airships, HALE UAVs (High Altitude and Long Endurance UAVs), and ground stations. By implementing typical scenarios that enable rapid response to emergent events and focusing on demonstration of cooperative sensing acquisition, dynamic networking transmission, and orbital fusion processing, key technologies such as spatial three-dimensional

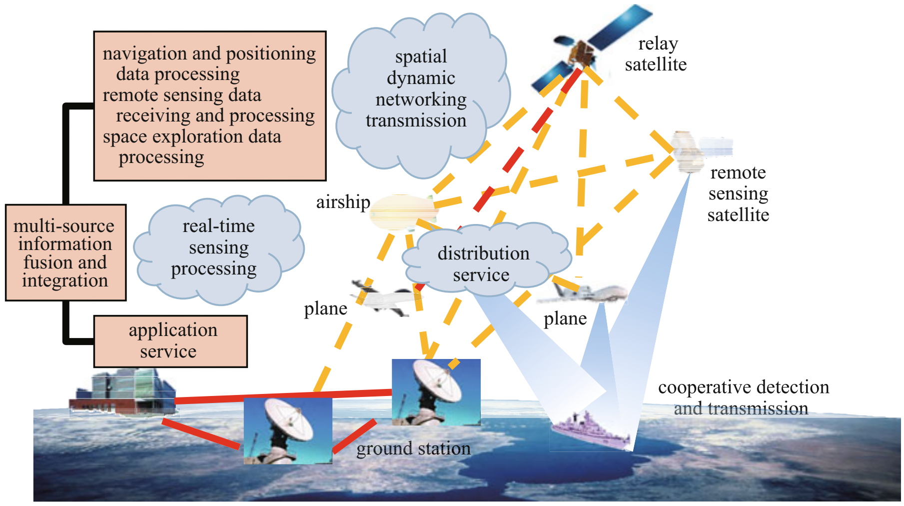

Figure 2 Integrated demonstration and evaluation environment for space information networks

routing, high-speed collaborative transmission, dynamic access, task real-time planning, and information fusion processing can be validated. The resulting system architecture of the integrated demonstration and evaluation environment is shown in Fig.2.

At present, China is putting significant effort into promoting the rapid development of space technology. Related departments have developed and promulgated strategic documents such as the Medium and Long-term Development Plan of the National Civilian Space Infrastructure from 2015 to 2025 and other strategic documents. However, the plan was implemented independently by different departments. These departments created, demonstrated, and implemented their plans independently, which inevitably results in repeated construction. Therefore, an overall top-level design is urgently needed in civil-military integration and civil-commerce coordination to realize standardization and healthy development of plans in different industries and systems. The space information network in China should be promoted in accordance with existing systems. The technology path includes technical research and demonstration of integration and implementation. With our proposed innovations and characteristics, space information networks can be constructed, integrated, and evolved with existing systems under a unified top-level architecture.

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