SCIENCE CHINA
Information Sciences

• REVIEW •

April 2018, Vol. 61 040302:1–040302:26
https://doi.org/10.1007/s11432-017-9346-1

Special Focus on Deep Space Communications

Solar system interplanetary communication networks: architectures, technologies and developments

Peng WAN, Yafeng ZHAN* & Xiaohan PAN

Space Center, Tsinghua University, Beijing 100084*, China*

Received 14 September 2017/Revised 31 January 2018/Accepted 2 February 2018/Published online 7 March 2018

Abstract With the development of deep space exploration technologies, main space agencies all over the world are working hard to develop the solar system interplanetary communication networks (SSICN). SSICN is a perspective communication networking system characterized by high data rate, high intelligent and perfect interconnection, which could provide the deep-space mission control and scientific application with the convenient, reliable and secure data transmission services. Following the introduction of future deep space exploration prospect, this paper analyzes the similarities and differences for three networks, terrestrial internet, near Earth space networks and SSICN, then discusses the key technologies and research trends of SSICN in details, and finally proposes the suggestions for the construction of future Chinese SSICN.

Keywords deep space exploration, SSICN, system architecture, physical transmission, network access, up-layer application, time synchronization

Citation Wan P, Zhan Y F, Pan X H. Solar system interplanetary communication networks: architectures, technologies and developments. Sci China Inf Sci, 2018, 61(4): 040302, https://doi.org/10.1007/s11432-017-9346-1

1 Introduction

Exploring the unknown universe is the eternal pursuit of human beings. The great success of Chang'E 1 lunar mission could be seen as a milestone in the space project development of China after the man-made satellite and manned space flight project, which opens a new era to further explore the mystery of universe. With the orderly advance of the three-step strategy of 'cycle, descend and return' of China's lunar exploration project, the interplanetary exploration of the solar system, such as the Mars exploration, Jupiter exploration, has also been on the agenda [1].

Similar with most of the international space agencies, such as National Aeronautics and Space Administration (NASA) and European Space Agency (ESA), China has also take the terrestrial telemetry, tracking and commanding (TT&C) system as the primary means for the deep space spacecraft tracking, ranging, monitoring, control and data transmission, utilizing the large diameter antenna, small antenna array or low noise temperature receiver and weak signal demodulation technologies, to establish the large distance, long time delay wireless RF link connection with deep space probe. However, as the space probe flying farther and farther away from earth, the amount of probes becoming more and more, and the data transmission volume growing large and large, the requirement to build the solar system interplanetary communication networks (SSICN) become increasingly urgent. This network could work well for the deep space applications such as communications between earth station and deep space probe, planet

* Corresponding author (email: zhanyf@tsinghua.edu.cn)

© Science China Press and Springer-Verlag GmbH Germany 2018

orbiter and the surface networks, spacecraft and spacecraft, for the mission planning, flight control, data transmission, which would play an important role in the future deep space exploration.

Refs. [2, 3] provide a top-level architecture of the solar system internetwork (SSI), which defines the features, elements, principles, and procedures of the SSI. These articles focus on the model and rules for the inter agencies operation concept, without the detailed analysis of the requirements and technologies on deep space communication networks. Refs. [4, 5] present a space-based network system and its concept on the overall objective, composition, network system architecture, as well as the proposed network protocols and some key technologies. However, these articles focus on the integrated space-ground network topic based on the terrestrial control and management, which would not work well for the SSICN. Ref. [6] provides the current space networking architectures, especially the inter-planetary network (IPN) and delay-/disrupt-tolerant network (DTN) concepts along with the various space networks that are currently deployed, but little wireless communication technologies for deep space explorations to be discussed except the antenna array and laser communications. Refs. [7,8] present comprehensive surveys on the network architectures, protocol stacks, recent developments and persisting challenges on disruption-tolerant network, along with the proposals of network management and security, but also lack the detailed analysis of the key technologies of deep space communication networks, especially the physical transmission. Ref. [9] elaborates the challenges and technologies of the free space optic communications, including the application on deep space communications and future RF/Optical mixed trends. However, this paper only focuses on the optic related topics such as modulation, jitter avoidance, adaptive optics, without the systematic description for the deep space communication networks.

This paper reviews the main aspects of the SSICN based on the previous literatures and our research. The rest of this paper is organized as follows: in Section 2, we introduce the concept of deep space exploration and the development history and future plans of the international deep space exploration activities; in Section 3, we present the major features, present situation and future trends of such three most important communication networks as terrestrial internet, near Earth space networks and SSICN, along with the comparative analysis on their similarities and differences; in Section 4, we provide the key technologies and research trends of the SSICN from several aspects as architecture, physical transmission, network access, up-layer application, time synchronization. Finally, we propose the suggestion for the construction of future Chinese SSICN in Section 5. Section 6 concludes this paper.

2 Overview of deep space exploration

Deep space exploration refers to the exploration activities taking place in the solar system or even further universe space beyond the earth gravitational field. International Telecommunications Union (ITU) provides the definition of deep space with the minimum distance from earth larger than or equal to 2.0×10^6 km [10], and Consultative Committee for Space Data System (CCSDS) also makes such definition as the classification rule of various space missions as type B (deep space mission) [11].

Since August 17, 1958, the launch date of the first lunar explorer 'Pioneer 0', human beings' deep space exploration toward the solar system has lasted nearly 60 years. Deep space exploration activities cover a variety of detection methods as flying-by, impacting, cycling, soft landing, sampling and returning back, including all kinds of celestial bodies of the solar system such as the sun, other seven planets and their satellites besides earth, asteroids, comets. The Pioneer 10/11 [12] and Voyager 1/2 [13] launched by United States in 1970s have flown out of the solar system. Pioneer 10 is heading toward the center of the galaxy, Pioneer 11 is heading in the opposite direction, and Voyagers 1 and 2 are heading in two other directions. In September 12, 2013, NASA announced that Voyager 1 has been flying out of the solar system, entered into the interstellar space dominated by the plasma and ionized gas, becoming the farthest man-made spacecraft, which is also the first man-made object in interstellar space.

In late August 2012, the distance between Chang'E 2 probe and the earth went beyond 2.0×10^6 km, which means that the Chang'E 2 had entered into the 'real' deep space. In December 2012, Chang'E 2 carried out a fly-by mission for the asteroid with No. 4179 and took several photographs of this asteroid at a distance of about 7.0×10^6 km away from the earth, which is the first time that we explored an asteroid as well as the first real deep space exploration activity of China.

Manned Moon and Mars exploration projects are of essential meanings for human beings' solar system exploration activities, because these big space projects would lead the need of inter-planetary network and network access for probes. For manned Moon project, in the last century, the United States have accomplished several successful manned Moon missions, the most famous one is the Apollo 11, whose primary achievement was performing a crewed lunar landing and return to Earth. For Mars exploration, since 1990s the United States have carried out many Mars exploration missions, achieving the soft landing and the Martian rover exploration, including the orbiters such as Mars Odyssey, Mars global surveyor, Mars reconnaissance orbit, and the rovers such as Opportunity, Spirit, Phoenix, Curiosity. In 2016, the ExoMars trace gas orbiter was launched as the first in a series of Mars missions to be undertaken jointly by ESA and Roscosmos (the space agency of Russia), whose key goal is to obtain a better understanding of the Mars atmospheric gases [14], to deliver the lander Schiaparelli and support part of the data transmission during its descent and surface operations, and also to serve as a data relay to support communications for the ExoMars 2020 rover and the surface science platform.

At present, the major space agencies and organizations all over the world have developed the two decades and even more long-term deep space exploration plans. In September 2011, the International Space Exploration Coordination Group (ISECG) composed of 14 space agencies from different countries or organizations such as the NASA, ESA, Roscosmos, Japan Aerospace Exploration Agency (JAXA), released the 'global detection roadmap' [15] for the first time, which was revised in August 2013. The roadmap provides a means for the continued exploration of the Moon, asteroids, and Mars through international cooperation over the next 25 years, with a view of the exploration destinations, mission objectives, mission plans, and preparation activities. The ultimate goal of space exploration activities proposed by ISECG over the next 25 years is to achieve manned Mars exploration. In order to achieve the goal of the future roadmap, the members in ISECG have presented two different schemes, with one preferring the asteroid route as the first step led by NASA but another giving priority to the Moon supported by other countries. The main difference between such two schemes focuses on the manned mission plan after 2020, with the former scheme choosing the sequence from 'Earth-Moon' Lagrange 1 point settlement to manned asteroid landing and finally realizing manned Mars exploration, and the latter scheme choosing the sequence from the manned Moon exploration to manned Mars exploration. The robotic deep space mission, which has been clearly defined by the members in ISECG before 2025, still focuses on Mars exploration, including cycling, landing, sampling and returning back to Earth.

In September 2016, SpaceX CEO Elon Musk on the 67th international astronautical congress (ICA) said that, SpaceX would research and develop the larger rocket and spacecraft for the human Mars travelling, finally realizing the colonization of Mars. He planned to send the first reusable colonial spacecraft capable of carrying 100 people to Mars in 2020, several decades earlier than the plan of NASA. Considering the high requirements for manned spaceflight and unknown effect of the deep space environment for human flight, besides the research and development of the advanced intelligent technology [16], we should enhance the capability of deep space communication network as soon as possible, provide a convenient service for collaborative planning, decision-making, medical cares, and improve the reliability and robustness of the whole system.

With the development of deep space exploration, communication network would gradually extend from the near earth to deep space. Through the connection with the Earth, Moon, Mars and other planets' local networks, we could build the SSICN, so as to provide the flexible and efficient communication methods for the future deep space exploration activities.

3 Features of communication networks

Terrestrial internet, near Earth space networks, and SSICN are significantly different in many aspects, such as technical characteristics, network scales and development levels, which represent three typical

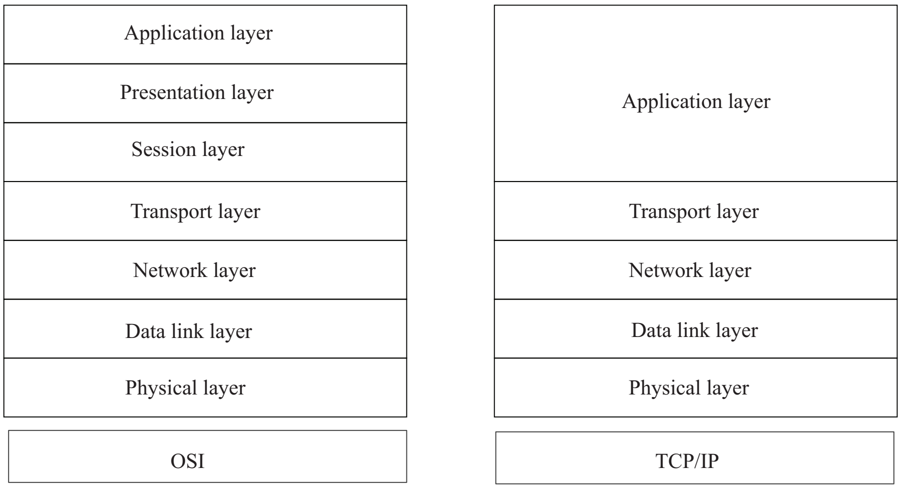

Figure 1 7-layer OSI & 5-layer TCP/IP protocol stacks.

stages of the human civilization gradual expansion on information technology in the space dimension from the inside to the outside. SSICN is the consequent requirement for human civilization to explore the unknown field, which would continue to upgrade with the development of human civilization.

3.1 Terrestrial internet

The terrestrial internet, originated in the ARPANET of the United States in 1969, is now a vast network on Earth composed of different networks connected with each other. This network works on a common set of protocols. Terrestrial internet are characterized by short duration, big bandwidth, multi-user and heavy payload.

Terrestrial internet is made up of many computers or mobile terminals, which depends on the communication protocols to ensure reliable data transmission between terminals. In order to reduce the complexity of network design, most networks adopt hierarchical design method [17]. The concept of hierarchical design means that the overall function of the whole network is decomposed into each individual functional layer according to the data flow. The same functional layer of different terminals should utilize the same protocol operating, while the adjacent functional layers on the same terminal could transfer the necessary information through the inter-layer interface.

Ref. [17] gives the 7-layer open system interconnection (OSI) protocol stacks and the 5-layer TCP/IP protocol stacks, as shown in Figure 1. Although the structures of such two protocol stacks are different, the hierarchical idea is the same: the lower three layers (physical layer, data link layer, network layer link) are responsible for establishing a network connection; the four upper layers (transport layer, session layer, presentation layer and application layer under OSI system) or two upper layers (transport layer and application layer under TCP/IP system) are responsible for end-to-end data communication. Each layer performs specific functions and provides necessary services for its upper layer. However, not all of the communication procedures need to work with all layers, some even need only one corresponding layer. The most important feature of such hierarchical structure is that communication occurs only between adjacent layers. Therefore, this hierarchical architecture requires only an accurate description of the interface between adjacent layers with high flexibility and expansibility for the adaption to the characteristics of terrestrial internet, such as massive data volume, diverse user demands, and various business types.

3.2 Near Earth space networks

Near Earth space networks could be seemed as the integrated communication network combined the terrestrial internet technology with near earth space resources. Taking advantages on high data rate and

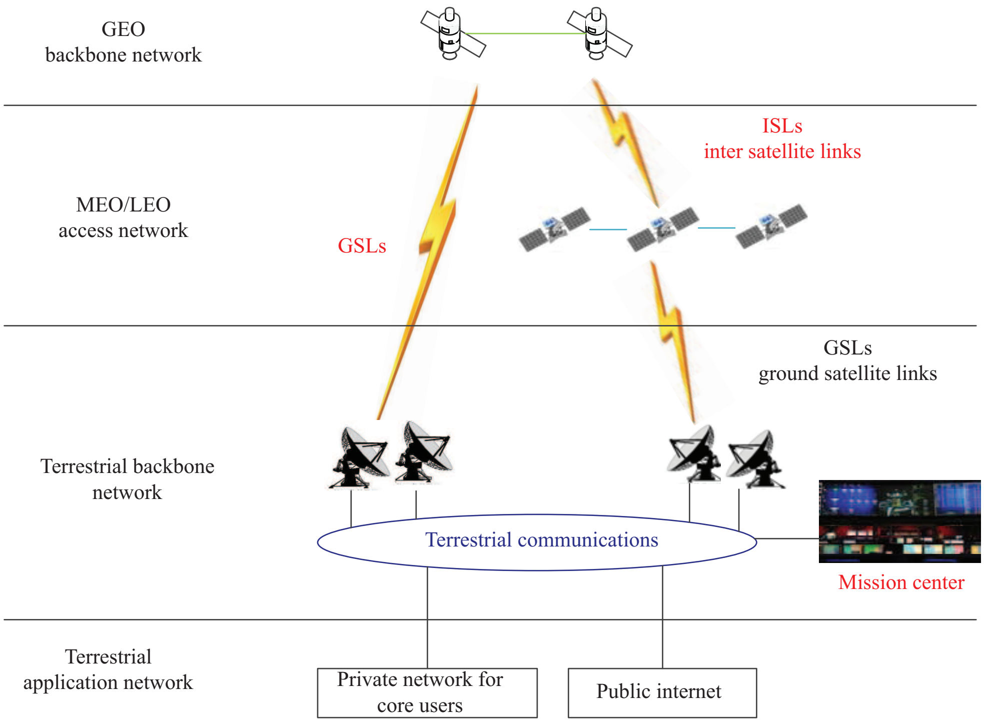

Figure 2 (Color online) Architecture of the integrated space-ground network.

large communication signal coverage, such networks could further improve the efficiency of data transmission. With the rapid development of economy and the continuous progress of science and technology, the near Earth space networks would be widely used in daily life.

3.2.1 *System architecture*

Based on the design of space communication and navigation network (SCaN) from NASA, [18] suggests the integrated space-ground network architecture as 'backbone + access', with the backbone network composed of geosynchronous earth orbit satellites (GEO) and terrestrial network while the access network composed of other spacecraft such as medium/low Earth orbit satellites (MEO/LEO) and user terminals, as shown in Figure 2.

(1) GEO backbone network. GEO backbone network is composed of several GEO satellites to construct the high data rate communication network, which could provide the TT&C and relay data transmission services for LEO satellites, near-space aircrafts, and terrestrial network users.

(2) MEO/LEO access network. MEO/LEO access network is a mesh-like network composed of various space resources distributed in different medium or low earth orbits, such as tele-communication satellites, navigation satellites, space stations, near space aircrafts. Most of these space resources could be reorganized as an individual local network or connect to the GEO satellite for data relay services according to the specific requirements.

(3) Terrestrial backbone network. Terrestrial backbone network is a mesh network composed of many ground stations distributed in different areas on Earth and several mission control & data centers, implementing the satellite flight control, TT&C, data receiving, processing and storage.

(4) Terrestrial application network. Terrestrial application network provides the information services with different security assurance levels according to diverse application requirements. Any fixed or mobile user could get access to the terrestrial backbone network based on some necessary agreements and protocols for specific services.

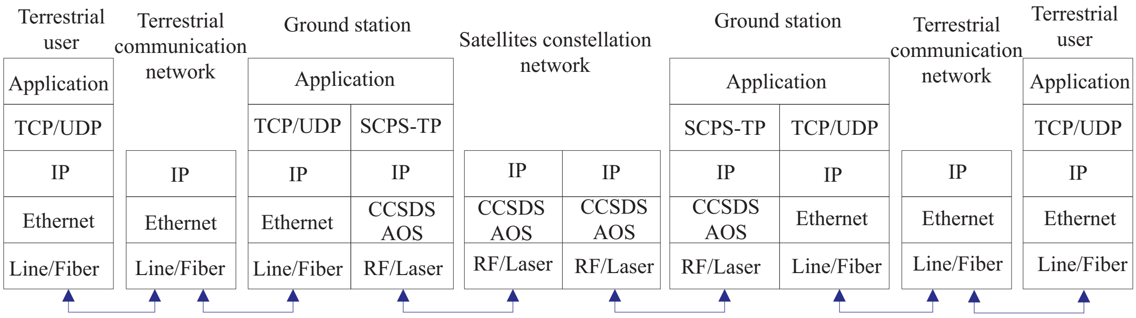

Figure 3 (Color online) Typical near Earth space network protocol stacks and its conversion procedure.

3.2.2 *Network protocols*

The layered network protocol stacks perform well for wired internet and most wireless communication in the terrestrial network, however, the wireless environment in the near earth orbit space is much worse due to such inevitable factors as the power limitation, signal attenuation, RF interference. According to the long-term research and verification, there might be difficult to find a universal network protocol to satisfy any communication requirements. Because the spacecraft would eventually connect to the terrestrial TCP/IP networks, one of the current available methods is to implement IP addressing at the network layer of all the space resources, followed by a specialized protocol at the transport layer [18].

In order to realize the interconnection between space and ground resources, along with the consideration for compatible to protocol stack of existing space system, we should design the gateway to realize the automatic protocol conversion of various protocols. Figure 3 shows a typical near Earth space network protocol stacks and its conversion procedure. In order to achieve the end-to-end transmission, application data should be transferred along the specific communication networks composed of terrestrial users, terrestrial networks, ground stations and satellites constellation network (with inter satellite links), with the ground station as the gateway to transform the terrestrial Ethernet to CCSDS AOS [19].

3.3 Solar system interplanetary communication networks

3.3.1 *Characteristics and challenges in deep space communication*

Wireless radio technology is widely used in current deep space communications. Different from the near earth orbit missions, deep space exploration faces with the large distance and complex space environments, which would influence the radio signals seriously.

(1) Large space attenuation. The radio signal propagation strength accords with the square of the distance attenuation rules, so the large distance between deep space probes and ground stations would cause great path loss, which means that the emission signal with the same intensity would be weaker at the receiver and the effective information would also decline sharply, whereas the cost for the data transmission might be high.

(2) Long time delay. The radio signal propagation time might be several hours for the deep space probes with billions of kilometers distance from earth, which makes it impossible for the real-time (or quasi real-time) flight control and platform health monitoring based on mission control center. Besides, such long time delay also makes it difficult for the continuous tracking by one single deep space station.

(3) Complex electromagnetic environment. Besides the effect of troposphere and ionosphere around the near earth space, deep space radio signal sometimes has to pass through the complicated and uncertain solar plasma zone, suffering from the impact of a solar storm at any moment. Meanwhile, along with the atmosphere attenuation influence in some extraterrestrial celestial planets with an atmosphere, the dramatic attitude changes and blackout problems during the EDL (entry, descend and landing) process of a lander or rover would bring about adverse effects of the wireless communications.

Table 1 shows the distances between the extraterrestrial celestial bodies in the solar system and the earth, as well as the signal attenuation and time delay compared with GEO satellite. Table 2 gives some

Table 1 Comparison of the signal attenuation and time delay [1]

Planet	Max distance from Earth (10^6 km)	Compared with GEO		Maximum time delay (mins)
		Distance times	Path Loss Increase (dB)	
Mercury	221.9	6163.9	75.797	12.336*
Venus	261.0	7250.0	77.207	14.510*
Mars	401.3	11147.2	80.943	22.310*
Jupiter	968.0	26888.9*	88.592*	53.815*
Saturn	1659.1	46086.1*	93.271	92.236*
Uranus	3155.1	87641.7	98.854	175.405*
Neptune	4694.1	130391.7*	102.305	260.964*

Note: According to the situation of [1] such as the furthest distance from earth and GEO altitude, and the light speed in vacuum (c = 299792458 m/s), we recalculate three parameters as times of distance, increase in path loss and maximum unidirectional time delay, with some results (marked as * in this table) revised.

Table 2 Some main parameters during the Mars EDL phase [20]

Probe	MPF	Phoenix	Curiosity
Entry mass (kg)	584	603	3300
Entry velocity (km/s)	7.26	5.6	5.9
Frequency during EDL phase	X-band	UHF	X-band/UHF
Duration of blackout (s)	30	Signal attenuation	< 95

main parameters during the Mars EDL phase.

3.3.2 *Requirements of the future SSICN*

The main purpose of the communication networks is to make the best effort to provide the users with the better information services. As we all known, the users' communication requirements would be endless which could be summed up as three main points: 'high-speed', once able to access the necessary data then asking for more data and quicker transmission; 'interconnection', once able to possess enough data then asking for more convenient high speed channels; 'intelligence', once able to transmit massive data to any user then asking for automatic adaption to any change of any user's requirements in time. All of these come from the human nature, which urges our human beings to explore the unknown world and promote the rapid development of science and technology. Therefore, future SSICN networks will follow the general communication requirements as 'high-speed', 'interconnection' and 'intelligence' with the details as follows.

(1) High-speed. Due to the increasing requirements on the scientific data from remote planet, as well as the future audio and video communication needs for manned moon or mars missions, SSICN should utilize high performance modulation and channel coding technologies at physical layer as well as free space optic communications to achieve high-speed and reliable data transmission between each pair of backbone nodes in solar system, such as:

- Establishing the high-speed wireless channels over long distance between different planetary networks, e.g., Earth networks could communicate with Mars networks at high-speed through direct-to-Earth (DTE) links or large data relay satellites located at Earth-Sun Lagrange points;
- Establishing the high-speed wired and wireless channels over medium distance between different local area networks in the same planetary network, e.g., two local LANs could communicate with each other at high-speed through fibers or on-orbit communication satellites;
- Establishing the high-speed wired and wireless channels over short distance between different terminals in the same local area network, e.g., two computers could communicate with each other at high-speed through Ethernet or WLAN.

(2) Interconnection.

- SSICN should utilize access control and route decision technologies at both data link layer and network layer to achieve end-to-end communications between any pair of nodes in solar system, such

Table 3 Differences of such three typical communication networks

Networks	Terrestrial internet	Near Earth space networks	SSICN
Power consumption	Not critical	Critical	Very critical
Time delay	0.01–0.1 s	0.1–1 s	1–10^4 s
Application requirements	Multimedia integrated services	Routine TT&C; observing data download; multimedia integrated services	Deep space TT&C; remote sensing data returned; multimedia integrated services
Network topology	Dense; fixed/low-dynamic	Half sparse; high-dynamic	Sparse; low/high-dynamic
Propagation medium	Copper/Fiber/RF	RF/Laser	RF/Laser
SNR	Wired: high; wireless: low, depending on the power, channel conditions, customer density, etc.	Low, depending on the power, channel conditions, etc.	Very low, depending on power, channel conditions, etc.
Construction cost	Low	High, as a function of mass	Very high, as a function of distance, mass
Maintenance cost	Low	High, as a function of reliability	Very high, as a function of distance, reliability, etc.
Advantages	Short latency, high speed, continuous connection	Low latency, high coverage, reconfigurable easily	Lead the development of space technology, huge investment
Challenges	More data & high intelligent	Easy connect anywhere anytime	High speed data transmission

as: establishing the heterogeneous networks with sparse network topology between different planetary networks, e.g., Earth networks under TCP/IP protocol stacks could connect with Mars networks under CCSDS CFDP/EP/Proximity-1 protocol stacks [21–23] through the proper protocol conversion gateways.

• Establishing the heterogeneous or homogeneous networks with dense network topology between local area networks in the same planetary network, e.g., LANs under Ethernet technology could connect with each other or with other LANs under WLAN technology through the proper routers.

(3) Intelligence. SSICN should provide the cooperation mechanisms among any layer of the whole protocol stacks (from physical layer to application layer) and reconfigure the communication system parameters based on artificial intelligence and cross-layer design to achieve automatic adaption to any change of any user's requirements and diverse electromagnetic environments, such as:

• Providing the high reliable TT&C services for the individual deep space detectors, e.g., adaptive modulation, coding, data rate based on channel conditions;

• Providing the high available information exchanging services between different planetary networks, e.g., dynamical access, communication protocols, routing algorithms based on the time-variant network topology;

• Providing the high concurrent interconnection services between different local area networks, e.g., service priorities adjustment, port rate management based on dynamical changes of the quality of service (QoS) requirements.

3.4 Comparative analysis

Due to the development limitations of the human cognitive level and science and technology, there are significant differences of such three typical communication networks as terrestrial internet, near Earth space networks and SSICN, shown as Table 3.

Above all, the current information developing level and future potential evolution trends for such three networks could be described as follows:

• Terrestrial internet is obviously on the top level of the communication networks, which has already gone through the other two junior stages as high speed and interconnection towards the higher stage as the intelligent networks mainly related to big data and various algorithms;

• Near Earth space networks is in the middle level of the communication networks mainly related to interconnection, with the system architecture and future roadmap generally established and trying best to solve the engineering issues as protocol conversion, on-demand access;

- SSICN is now at the preliminary stage of the communication networks, with some issues concerning the high-speed transmission such as long distance, intermittent connection, bad channel conditions.

4 Key technologies of SSICN

With the development of space technology, deep space exploration activities will be further extended, asking for the better service ability for deep space communications. In order to lay a solid foundation for the future SSICN networks, there are a series of key technologies to be solved including system architecture, physical transmission, network access, up-layer application, time synchronization.

4.1 System architecture

In order to satisfy the future requirements of the SSICN networks, most of the space agencies and international organizations are carrying out the research and verification works of the system architecture.

4.1.1 *Inter-planetary network*

IPN program was launched in 1998 with members from all of the world, whose goal is to build a communication network that could carry out interplanetary communications within different planets in the solar system, shown as Figure 4. In the future, the terrestrial internet could be connected to the IPN backbone network through the edge gateway to realize interoperability with other planetary networks in the solar system. The planetary networks should support different protocols to connect to the backbone network through the proper satellite gateways and implement the protocols conversion seamlessly. IPN advances the basic structure of the interplanetary communication networks as 'local planetary networks + IPN backbone networks' [6], which is currently the most popular and widely studied architecture for the interplanetary communication network, as a baseline for the research on SSICN network topology.

4.1.2 *Delay/Disrupt tolerant networks*

The interplanetary communication network is characterized by long delay, intermittent connection, high bit error rate [24], belonging to the typical intermittently connected network (ICN) [8]. As network protocol architecture for the opportunistic connection network scenarios, DTN [25] could effectively deal with frequent network switching and communication interruption and provide reasonable cross link among heterogeneous networks, which is the most suitable network protocol framework for the interplanetary communication network at present. The design intention of DTN is to solve the challenges which interplanetary networks might face with, so it has good adaptability to deep space communication characteristics mentioned above [26]. Through integrating DTN into the space communication system protocol stacks, even in the extremely difficult environments unique to deep space exploration activities, the communication system could still maintain the quality of services required by diverse users. The main functions of such DTN network are provided by the bundle protocol (BP) layer [27], which means that DTN could fulfill the responsibilities on message 'storage-forwarding' by adding the coverage layer (BP and relative adaptation layer) over the lower layers of diverse heterogeneous networks, including supervised retransmission, dealing with intermittent connections, binding endpoint identifier for overlay network, creating network address.

4.1.3 *Cluster-based IPN networks*

Under the basic architecture given by IPN, some researchers proposed the cluster-based IPN networks [28], in which the whole IPN could be divided into a series of clusters according to the node attributes, link capabilities, mission characteristics and distribution areas, such as IPN backbone network cluster and Mars planetary network cluster, then each cluster might be further divided into several sub-clusters such as Mars orbiters sub-cluster and Mars surface facilities sub-cluster. Through this division, we could establish

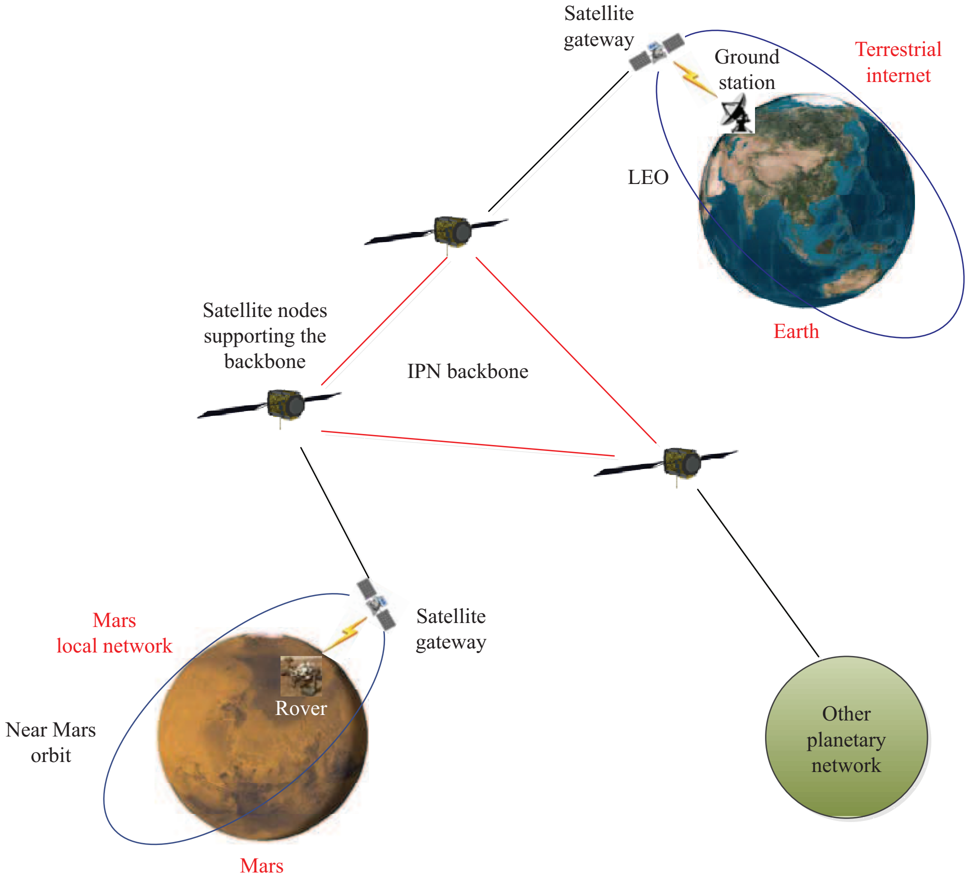

Figure 4 (Color online) IPN architecture diagram.

the communication model and corresponding protocol stack for the interplanetary network, distinctly separate the management plane from application plane, and divide the whole communication network with high dynamical topology changes into each local subnetwork with low dynamical topology changes, which could adopt the relatively independent and unified transmission mechanism. Besides, the cluster-based IPN networks could also realize the decoupling of the dynamical elements in the interplanetary network, make the node's 'plug and play' more convenient and improve the management efficiency of the whole communication network.

The architecture of cluster-based IPN networks is composed of following parts, as shown in Figure 5.

(1) IPN backbone network. IPN backbone network [28] is used to connect individual deep space explorers and various space resources belonged to each celestial bodies in the solar system, such as the Earth, Moon, Mars, outer space planets, characterized by high speed, high reliability and high availability, composed of the links with wide bandwidth and the nodes with powerful processing capacity. This backbone architecture proposes a network formation plan based on Lagrange points, which means that the backbone satellites are placed on the proper Lagrange points between the Earth and the other planets except Mercury, connected together to construct the interplanetary backbone network, as shown in Figure 6. Besides, the whole backbone network could also be classified as large scale IPN backbone network (Figure 6(a)) and small scale IPN backbone network (Figure 6(b)) by the spatial scale rules based on the Mars and Jupiter.

(2) IPN planetary network. IPN planetary network is composed of the planetary on-orbit satellites, science orbiters, communication relay orbiters and surface facilities, such as landers, rovers and sensors [29], as shown in Figure 7, which could be used for the cooperative communication among the above space and ground resources. IPN planetary network could be implemented on any planet to provide interconnections between satellites and planetary surface elements. According to its position in the planet, all

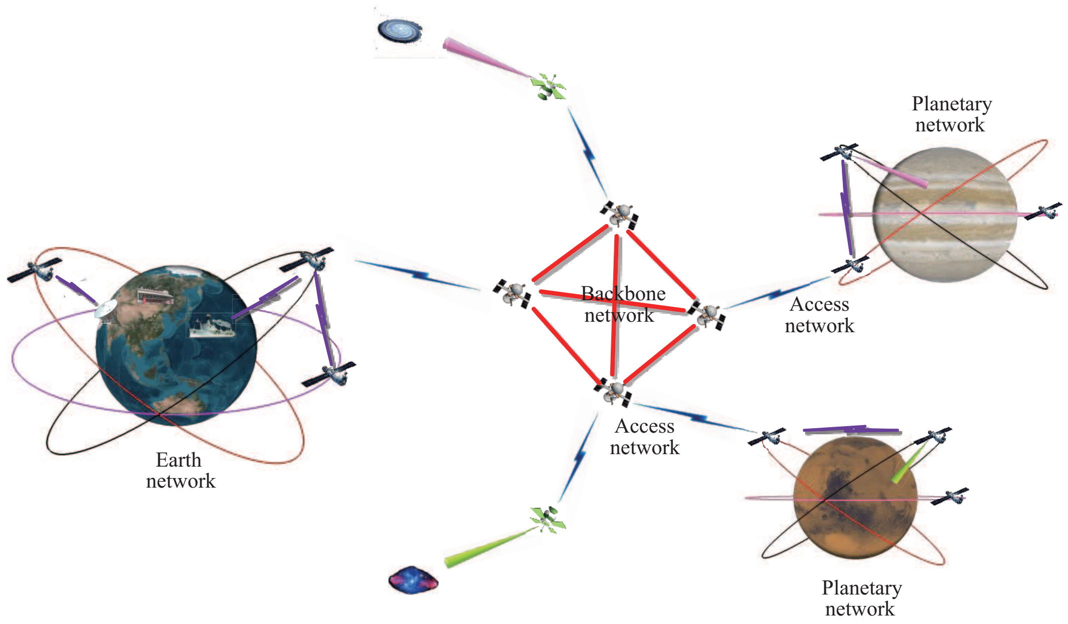

Figure 5 (Color online) Cluster-based IPN networks diagram.

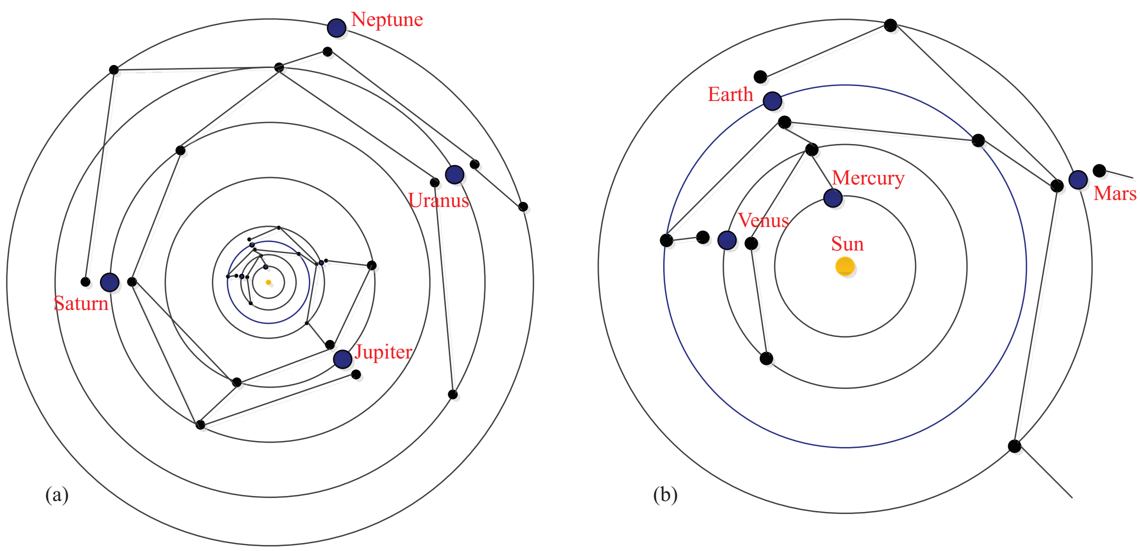

Figure 6 (Color online) (a) Large scale and (b) small scale IPN backbone network diagram.

the elements in the IPN planetary network could be divided into planetary near space subnetwork and planetary surface subnetwork.

(3) IPN access network. IPN access network is composed of IPN backbone network, edge nodes of planetary network and the data relay nodes in outer space, which could be used to provide the communications between any pair of elements in the whole IPN networks such as the links between backbone network and Earth network, the links between backbone network and each planetary network and the links between backbone network and outer space explorers. On the premise of the IPN network formation plan based on Lagrange points, the best access points for IPN planetary network should be the planetary orbiters or satellites nearest the Lagrange points (L_1 and L_2) with directly connective links; the best access points for IPN backbone network should be the backbone nodes nearest the orbiters or satellites; while the best access points for outer space explorers might be any edge node of the backbone network, or the data relay nodes in outer space between the backbone network and the outer space explorers.

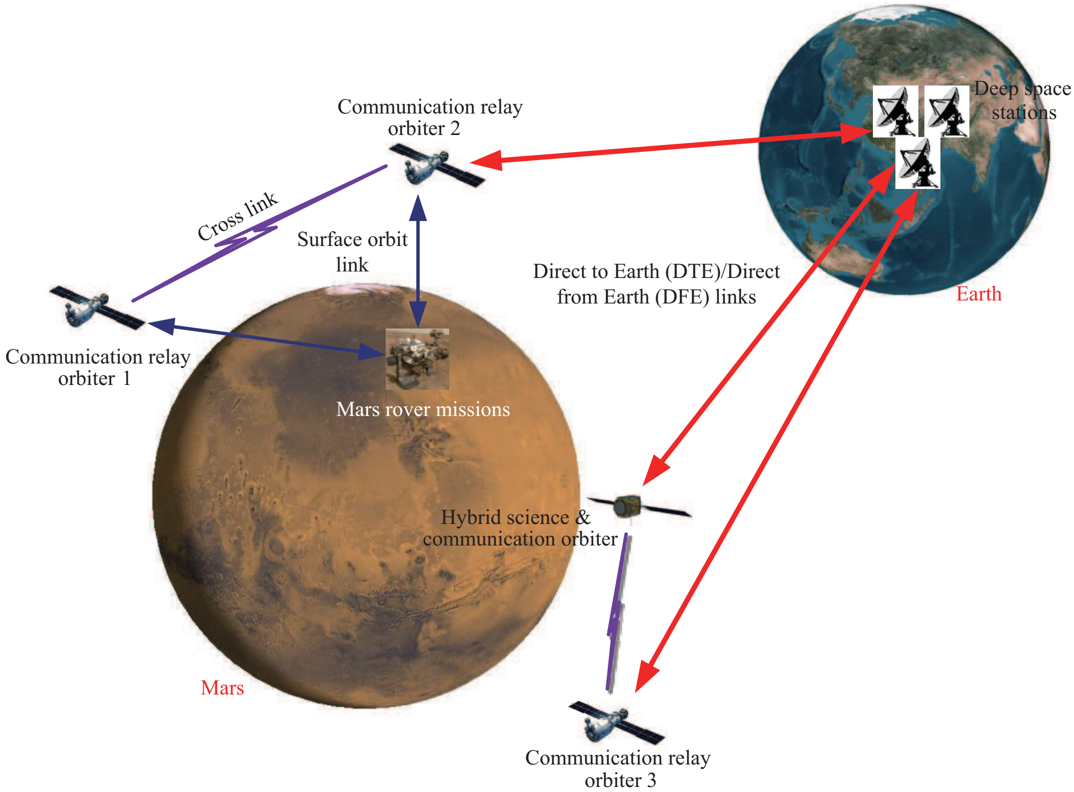

Figure 7 (Color online) Typical IPN planetary network diagram.

4.2 Physical transmission

Compared with terrestrial internet and near Earth space networks, the deep space communications in SSICN networks are characterized by long distance, large space attenuation and very low signal-to-noise ratio (SNR). Concerned with the interplanetary communication networks, system architecture focuses on the top-level design, and network protocol pays attention to customer applications, while physical transmission devotes to the communication fundamentals. Without the efficient and reliable physical transmission methods, the SSICN network based on the physical layer would be castles in the air. Therefore, it is really important for us to carry out the intensive research based on current physical transmission technologies.

4.2.1 *Low SNR reception*

(1) Constant envelope modulation. In deep space communications, NASA Jet Propulsion Laboratory (JPL) has been in a leading position in technology. In 1980s, Feher, Kato and other researchers carried out the research on low signal-to-noise reception, and in 1982 they firstly proposed the constant envelope Feher-patented QPSK modulation (FQPSK) [30] and the related technology system, which was proved to solve the problem of receiving the low signal-to-noise ratio effectively.

In recent years, China has also done some related research on FQPSK modulation, and some scholars put forward an improved constant envelope enhanced FQPSK modulation (CEEFQPSK), which could be used to eliminate the nonlinear effect of power amplifier. In order to overcome the shortcomings of FQPSK such as the fluctuation of signal envelope, CEEFQPSK defines a new group of waveform function. Due to the characteristics of completely constant signal envelope, CEEFQPSK could improve the power conversion efficiency of the power amplifier with wide application prospect in deep space communication.

(2) Antenna array. In order to improve the ability to receive weak signals over long distances, NASA deep space network (DSN) has been using antenna array technology since 1970s, which utilized multiple antennas distributed at different locations to receive radio frequency signals from the same deep space

explorer. With the synthesis of the received signal from each antenna, the antenna array system could obtain a desired high SNR result related to the received signal, which is an important research direction of deep space communication technology in the future. Antenna array technology involves uplink and downlink, with significant differences as follows.

• Downlink antenna array. Regards to the downlink antenna array, the high-frequency signals received by each antenna must be aligned in time and weighted appropriately before the synthesis process. The signal is usually in the microwave band and is processed by down conversion to lower frequency, which requires the precise control of the local oscillator phase and the transmission line delay. Meanwhile, if the antenna array is large scale, the atmospheric delays of the signal received by each antenna would be different.

Ref. [31] points out that, the antenna design, optical fiber transmission, array signal synthesis, phase correction and other technologies of the large scale antenna array would be the future research essentials, especially the array synthesis algorithm for downlink antenna array. According to the future small antenna array and full spectrum synthesis method, NASA JPL proposed several signal synthesis algorithms, including Simple, Sumple, Eigen, least squares, along with the simulation results for such four algorithms based on a 25-antennas array [32].

Based on the theoretical research, some organizations in China have also devoted to the related researches such as the system design of the antenna array, the manufacture of the synthetic baseband equipment prototype and the demonstration test with the deep space satellite. In September 2010, Beijing Institute of Tracking and Telecommunications Technology (BITTT) led to build the first antenna array experimental system [33] composed by 4×12 m dual frequencies antenna in China, and implemented the technical validation test by several deep space explorers such as the Chang'E 2 satellite and ESA's space telescope. Experiment results showed that the synthesis efficiency was better than 91% [34].

• Uplink antenna array. Regards to the uplink antenna array, there is no common reference signal for each antenna of the array to be used for continuous calibration, hence such antenna array system requires the periodically calibrated part. In addition, because the deep space explorer could not align the received signal from different ground antennas, so phase adjustment of the uplink signal must be finished on the ground, with the consideration on the signal instability caused by the electronic equipment and the dynamical troposphere. Ref. [1] points out that the uplink antenna array faces with three major challenges: first, determining the initial calibration value of each antenna, with the clock synchronization for each transmitting signal; second, pointing to the target direction along with the clock synchronization; third, tracking the deep space explorer as maintaining the clock synchronization in a long time period.

In three important antenna array technologies as uplink antenna array, software synthesizer and large-scale antenna array (square kilometer array), the uplink antenna array is the most difficult issue to be solved at present. After ten years efforts, in February 2006 NASA utilized two 34 m BWG antennas of DSN for the first time to realize the uplink antenna array test with the Mars global surveyor (MGS). However, there is still a big gap from the practical engineering, requiring related research in the future.

4.2.2 *High efficient channel coding*

As we all known, the performance of deep space communication has an important effect on the future development of deep space exploration. Channel coding could effectively improve the performance of wireless links in deep space communication, which should be studied thoroughly as a critical technology.

(1) Low density parity check (LDPC). LDPC code is a linear block code with sparse parity check matrix proposed by Gallager [35] in 1962. In 1999, MacKay [36] demonstrated that the performance of LDPC in approximating Shannon bounds under the iterative decoding based on confidence propagation, and then various studies related to LDPC codes developed rapidly. In 2001, Chung et al. [37] worked out an irregular LDPC code using a block length of 10^7 bits for code rate $1/2$, with a threshold within 0.0045 dB of the Shannon limit in the binary-input additive white Gaussian noise (AWGN) channel, which is by far the best channel code found with the closest known performance of the Shannon limit.

Some main international organizations for standardization are also attracted by the excellent performance of LDPC. Since 2004 CCSDS has published a series of recommendations for space communication of LDPC codes in deep space, such as the initial orange books CCSDS 131.1-O-1 [38] (released in 2006) and CCSDS 131.1-O-2 [39] (released in 2007). After further study and discussion, in 2011 CCSDS officially made the LDPC codes into the blue book CCSDS 131.0-B-2 [40] as the recommended channel coding standard, and then proposed the recommended LDPC encoding parameter settings (e.g., code rate 1/2, 2/3, 4/5.) used in deep space communication within the magenta book CCSDS 131.4-M-1 [41]. In 2012, CCSDS published the green book CCSDS 130.1-G-2 [42] with the LDPC performance results and recommendations for space missions.

In recent years, the theoretical researches and engineering applications for LDPC codes have made great progress. LDPC codes are widely used in satellite communications, deep space communications, mobile communications, optical fiber communication, optical magnetic recording and other fields. In Chinese space missions, LDPC code has become a preferred coding scheme to provide high quality of wireless communication services, especially in such circumstance as long propagation distance, large volume data, high data rate. It is worth mentioning that, LDPC codes play an important role in Chinese Chang'E 2 and future Mars exploration missions, and provides the high gain reliable data relay links for the data relay satellites system (DRSS) of China.

(2) Polar codes. Polar codes were proposed firstly in 2008 by professor Erdal Arikan [43] from Bilkent University in Turkey, proved to achieve the Shannon limit of any given binary-input discrete memoryless channel in theory, with low encoding and decoding complexities. Currently, polar codes are the only channel coding techniques which could reach the Shannon limit theoretically and have practical linear complexity in coding and decoding capabilities. Besides the low encoding and decoding complexities, polar codes also have the uniform structure decoding rules [44]. Therefore, polar codes could support different length of input and output information with 1 bits step changing ability based on the same structure of the encoder and decoder, so as to get higher encoding gain.

At present, polar code has been adopted by 3GPP as the standard scheme of 5G eMBB control channel, and it is expected to play an important role in deep space communication in the future.

(3) Rateless codes. Rateless codes could be used to improve the data transmission efficiency under the time-variant wireless channel conditions. The source could send the encoding data blocks to the destination continuously at appropriate rate until the destination returns back the acknowledgement message of the successful decoding event. At present, in most of the widely studied rateless codes, some schemes could achieve favorable encoding and decoding effects, even able to get close to the Shannon limit under certain conditions, such as LT codes [45], Raptor codes [46], Spinal codes [47].

Above rateless codes have proved to be perform well for the terrestrial wireless mobile channel conditions, similar in the circumstance of proximity wireless links. However, for the long time delay in deep space wireless links, the source might be continuously transmitting the redundant coding blocks even if the destination had already successfully decoded the effective information and sent the acknowledgement message due to the long time delay for the arrival of such necessary acknowledgement, which would reduce the system performance too seriously to restrict the application of rateless codes in deep space communications. One possible solution is to replace the feedback mechanisms with the automatic coding rate according to channel conditions, whose performance is to be validated further.

4.2.3 *Free space laser communications*

Compared with the RF link, the frequency of laser link is higher, which means that the diffraction efficiency loss is smaller and transmission of signal energy is higher. Therefore, even if the laser communication system works at a lower power with smaller size, it could still achieve a high data rate. In addition, compared with the RF system with large diameter antenna and heavy feed device, laser communication system could provide the equivalent function with smaller size and less weight, further reducing the engineering difficulties with the same data rate as RF system. With the increase of the data volume relating to the diversity of the future deep space exploration, as well as the trend of miniaturization and lightweight for the deep space explorers, it is more and more urgent for us to do some research on laser communication technology.

In the long term, laser communication technology should be the key technology to solve the problem of high-speed data transmission in the future deep space exploration mission, which would play an important role in the future physical transmission of interplanetary communication network. Nevertheless, due to the long distance of deep space communications, optical collimation and tracking of narrow beam signals are very difficult, as well as various operating conditions and orbit constraints for the deep space exploration missions to deal with. Therefore, in order to make the laser communication system available for future SSICN networks, there are still some problems to overcome, such as high sensitivity, small source detector quality stable and efficient (amplifier and laser), large-scale space telescope, beam pointing control system of optical electromechanical device. The challenges and solutions of free space laser communication technology are systematically reviewed in [9], with main contents as follows.

(1) Aperture averaging. Aperture averaging is used to mitigate the effects of atmospheric turbulence. Through increasing the size of the aperture, the small eddies caused by relatively fast fluctuation could be averaged which helps to reduce channel fading. Ref. [48] compares the ground and satellite laser links based on various coherent modulation schemes, and considers that the performance improvement of aperture averaging is effective only in ground communications and satellite downlink. It should be pointed out that the increase in the received aperture area also increases the receiver's background noise. Therefore, the best choice of the aperture size is to improve the power efficiency of the whole system.

(2) Diversity reception. The use of diversity reception in time, frequency and space could further mitigate the effects of atmospheric turbulence. In this case, a large aperture telescope could be replaced by an array system composed of several small aperture telescopes to achieve diversity reception of related signals in time, frequency, or space. This technology has been fully validated in RF links, which could improve the availability and bit error rate (BER) performance of the system, while also reduce the requirements of the tracking accuracy for the optical system. Some study [49] pointed out that, in the case of time diversity, convolutional codes are a good choice for weak atmospheric turbulence, and Turbo codes could provide enough coding gains in strong turbulence.

(3) Data relay. Data relay is an effective technology to deal with the turbulence effect [50]. As a form of distributed spatial diversity reception, data relay allows multiple terminals to share resources through cooperative communication, so as to establish a virtual antenna array in a distributed mode, rather than other diversity methods such as antenna array or large aperture telescope. Data relay usually performs well at a high SNR situation, so that the received signal strength could be better than the signal suffering from scattered particle noise, atmospheric fading and other interference.

(4) Adaptive optics. Adaptive Optics could be used to mitigate the effects of atmospheric turbulence and to reduce the distortion effects of laser beams passing through the atmosphere. The adaptive optics system is basically a closed loop control system, whose principle is to transfer the conjugate of atmospheric turbulence to the atmosphere before the signal transmitted, so as to realize the pre-correction of the laser beam [51]. The performance of laser systems might be improved through the power increase or diversity reception, but adaptive optics could be a very useful technique for further SNR improvement in low power conditions.

(5) Modulation/demodulation. The most widely used binary modulation schemes for laser communications are on-off keying (OOK) and pulse position modulation (PPM). OOK modulation [52] requires adaptive adjustment of threshold in turbulent atmospheric conditions to achieve the best effects, but due to the simplicity of its implementation, OOK modulation has been widely used in laser communication systems. For M-PPM, it has been widely used in long distance deep space communication because of its higher peak to average power ratio [53]. As a kind of coherent modulation scheme, differential phase shift keying (DPSK) has attracted more attention with its high power efficiency, which could get much more link gains with 3 dB compared with the OOK modulation [54]. The receiver sensitivity of DPSK is close to the quantum limit in theory, but the higher complexity has still limited its widely application.

(6) Channel coding. There are various channel coding schemes that could be used to improve the performance of laser communication system, such as Reed Solomon (RS) codes, turbo codes, convolutional

code, trellis coded modulation (TCM), LDPC. Both schemes of the PPM modulation based on LDPC encoding and PPM serial cascaded modulation are compared in [55], and the results show that the former has better performance in free space laser communications.

(7) Jitter isolation/elimination. In order to achieve the precision of the micro arc magnitude in the case of platform jitter, a dedicated pointing control subsystem should be arranged to ensure the isolation and elimination of platform jitter or satellite vibration. Because the pointing loss caused by platform jitter might be around 10 micro arc, either an isolator or a compensating control loop should be used to accomplish the isolation and elimination [56].

(8) Sunlight noise rejection. Sunlight is one of the major background noise sources, while the sunlight effect mainly depends on the light wavelength, i.e., the longer the light wavelength, the weaker the background noise. The spatial filter is a good alleviation choice, with most filter parameters based on the signal's angle of arrival, Doppler shift of laser linewidth and the number of laser transient modes [57]. Besides, Ref. [58] points out that the narrow-band intermediate frequency (IF) system could reject the sunlight noise well, enabling the laser communication system to operate normally in the sunlight field of view without functional degradation.

(9) RF/Laser hybrid system. The performance of laser communication system is seriously influenced by meteorological conditions and atmospheric turbulence, more likely resulting in link failures or communication performance degradation. Therefore, in order to further improve the reliability and availability of the laser communication system, it could be mixed with the higher reliable radio frequency system, known as the RF/Laser hybrid system [59], which would provide high link availability under bad weather conditions. The major attenuation factors of RF signals is rainfall and laser is seriously influenced by the cloud, therefore the utility of low data rate RF system as the backup for laser communication could improve the availability of the whole system.

4.3 Network access

In order to provide the network access services for any customers anywhere at any time, based on the system architecture described in Subsection 4.1, SSICN should keep on with the high-speed data transmission capabilities over the deep space links between the IPN backbone networks and service relative planetary networks in physical layer, as well as the high efficient and flexible network access capabilities over the near space or proximity links between the planetary on-orbit networks and surface networks in data link layer and network layer. Considering that the network access techniques in terrestrial internet has been so mature to extend the application to the other planetary surface networks, the network access technologies within the planetary surface networks are not included in this paper.

4.3.1 *Backbone network access*

With regards to the backbone network, the L_1 and L_2 Lagrange points between the planets and sun could be used as the edge nodes of backbone network to provide access services for the planetary networks. And for the planetary networks, there are usually two methods to access into the backbone networks, as ground stations and relay satellites in planetary on-orbit networks.

(1) Ground stations. The ground stations' method refers to the access strategy with the connections between TT&C stations on planet surface and backbone nodes, in which such ground stations are separated by the uniform distribution of their longitudes to compensate for the wireless links interruption caused by rotation of the earth, e.g., the deep space stations in NASA DSN networks are deployed in this way. However, this method requires perfect ground infrastructures to interconnect ground stations, which brings many difficulties and challenges for other planets except Earth.

(2) Relay satellites in planetary on-orbit networks. The relay satellites in planetary on-orbit networks' method refers to the access strategy with the connections between relay satellites in planetary near space orbits and backbone nodes, such as tracking and data relay satellite system (TDRSS) on Earth and Mars orbiters for data relay services. The relay satellites in outer space are characterized with large coverage rates, therefore only a few satellites could provide with uninterrupted communication services and amplify

the signal strength to improve the transmission reliability. However, there are still some shortcomings for this method. As a relay node, the mobility and the planet's rotation makes the relay satellite a little difficult to access into the adjacent backbone edge nodes with seamless coverage for the planetary surface, which might be mitigated by the optimal design of satellite constellation configuration.

4.3.2 *Near space network access*

With regards to the elements on the planet surface, as described in Subsection 4.3.1, the relay satellites in planetary on-orbit networks' method should be a better choice, which could be classified as low orbit global satellites constellation, geostationary orbit data relay satellites and hybrid orbit satellites constellation.

(1) Low orbit global satellites constellation. Global star system is typical of low orbit global satellites constellation. This system is composed of 48 satellites orbiting low earth orbit (no polar areas) to provide users with seamless mobile satellite communications coverage and cheap business services, such as voice, data, fax, message, location, which could provide anyone with the communication to any others anywhere at any time, so-called global personal communications.

(2) Geostationary orbit data relay satellites. TDRSS is typical of geostationary orbit data relay satellites. This system is mainly used to support the manned space flight mission of NASA, whose major design objective is to increase the communication time between spacecraft and ground, as well as to improve the transmission data rate. At present, there are four operational geostationary earth orbit satellites of Tianlian-1 data relay satellite system in China, which is mainly used to provide manned spacecraft with data relay and TT&C services, along with the data relay services for other medium and low earth orbit satellites.

(3) Hybrid orbit satellites constellation. Mars orbiters constellation is typical of Hybrid orbit satellites constellation, with the satellite parameters from reference [60]. This constellation is composed of four Mars orbiters, such as MGS [61], ODY (Mars Odyssey) [62], MRO (Mars reconnaissance orbit) [63], and MEX (Mars express) [64] to provide the data relay services between the earth and Mars surface facilities (e.g., landers, rovers), which could be reconfigured and upgraded in future.

4.3.3 *Network routing*

Network routing is one of the basic technologies of SSICN networks. At present, the communication routing techniques in space networks focus on the routing of satellite networks. As the current research hotspot, the development of inter satellite routing technology also provides the research foundation for deep space communication network routing. Different from the terrestrial internet and near Earth space networks, SSICN is characterized by long time delay, resource constrained, sparse network topology, intermittent connection, asymmetry data rate and high bit error rate, suffering from the challenges of channel coding and the failures of end-to-end acknowledgement mechanism.

In recent years, various routing algorithms concerned with space networks based on the features of interplanetary communication networks are proposed with good performance [65, 66], with their characteristics described as follows.

- DataMULEs [67], based on active movement and characterized by the message forwarded through controlling the movement of a particular class of nodes, with the shortcomings as only controlled mobile nodes available with the strong storage capacity requirements.
- Contact graph routing (CGR) [68], based on deterministic connection and characterized by the message forwarded through the network's future status, with the shortcomings as only available with the future topological information known or partially known.
- Epidemic [69], based on flood routing and characterized by the message copies forwarded during the nodes' contact time period, with the shortcomings as large buffer and bandwidth.
- Spray and wait [70], based on quota and characterized by fixing the number of message copies before routing and transmitting each copy independent, with the shortcomings as the difficulty on choosing the appropriate copies quota along with some performance degeneration.

• Network coding [71], based on coding and characterized by the message encoded and forwarded at the source and decoded at the destination to get the original information, with the shortcomings as the complexity and redundancy from the coding requirements for nodes.

• Seek and focus [72], based on efficiency and characterized by the message forwarding decision originated from the historical information or other status from the whole network to predict the future movement or nodes' contacts, with the shortcomings as long time loss to collect the historical information which increases the wait time of the message forwarding and the serious influence on network performance based on the prediction accuracy.

• PRoPHET [73], based on hybrid redundancy and efficiency and characterized by the integration of parallel transmission and efficiency-based forwarding decisions to improve transmission performance, with the shortcomings as spray and wait and seek and focus.

4.3.4 *DTN protocols*

DTN is an important network model suitable to the space communications situations, especially for the SSICN networks with long time delays and link disturbance, which derived from one of the NASA sponsored project conducted by the united research group of NASA JPL and the Maryland University. Recently, DTN has been accepted by many international standard organizations such as CCSDS and Internet Engineering Task Force (IETF). In order to match well to the extreme space communication environment, DTN protocols introduce two important aspects as follows.

• First, insert a middleware called BP [74–76] between the application layer and transport layer, in order to provide hop-by-hop acknowledgement. BP works as the critical protocol for the whole DTN protocol stacks. If there is not complete end-to-end routes in the DTN networks, BP would provide the data forwarding service with the characteristics of delay tolerant, as well as the dynamic routing, which have been described in Subsection 4.3.3.

• Second, supplement a protocol called Licklider transmission protocol (LTP) [77, 78] in the transport layer, in order to minimize the number of communication handshake between the end users. LTP is a point to point communication protocol, which could not be care about the issues such as routing and congestion control. Furthermore, LTP tries to solve the problems such as time delay and link disturbance in the point to point communication situation, especially the long time delay transmission difficulty.

4.4 Up-layer application

Various deep space missions might have the potential commonality from the view of communication networks despite of the different scientific goals. At least in the near future, the major purpose for deep space exploration is mainly relevant to the unknown celestial bodies sensing with relative scientific data returning back to the users located on Earth, therefore the tele-command & telemetry, application data transmission and navigation should still be the most important applications for SSICN. However, the development of future SSICN networks would gradually transfer from constant data rate transmission to dynamic access network services, with the requirements on reconfiguration and cognitive capacity.

4.4.1 *Tele-command & telemetry*

The tele-command & telemetry service is most important to ensure the reliability for deep space missions, so it is usually set with the highest priority as well as enough communication resources, whose essential factor is network connectivity. However, the data volume for such service is not very large, with little design constraints for communication network throughputs.

4.4.2 *Application data transmission*

(1) Link asymmetry. For data transmission, a significant feature is that the amount of data sent to earth would be far greater than the amount of data sent to the deep space, so the wireless links of backbone network is characterized by high asymmetric, i.e., data flow asymmetry. Terrestrial internet is designed

under the assumptions that the physical links are symmetry, whose communication protocol might not be suitable for SSICN networks, so it is necessary to abandon the symmetry assumptions to deal with the data flow asymmetry in SSICN.

(2) Time asymmetry. Space missions usually have different phases, such as EDL, planetary surface activities, which brings about dynamic changes in data transmission flow. For terrestrial internet, the network traffic could be predicted by long-term statistics (e.g., the night download peak, the massive Spring Festival blessing messages) so the network service providers could adopt the necessary measures to maintain the whole network with stable operating status. Similarly, the communication capacity for deep space exploration missions could be better improved through reasonable analysis and planning, meanwhile the software radio technology to reconfigure communication parameters at each phase could also improve the whole system performance efficiency.

(3) Massive application data. The application data from deep space explorers usually describe the unknown phenomenon for human beings. Scientists on Earth eager to get the raw data without processing by the communication network and these data are always massive, because they worry that the compressed data might lose some critical information to discover the unknown world. Although some proper data compressing algorithms could significantly improve the transmission efficiency and reduce the bandwidth requirement and power consumption, these algorithms (such as lossless source compression) might increase the amount of dynamic data volumes with some unpredictability. However, with the basic scientific objectives, scientists could also optimize the acquisition methods of raw data (such as various sampling rates, hybrid sensors).

(4) Cooperative communication. The 'network scientific experiment' has been attracted by some researchers recently, which means that the space distributed sensors could be used to observe the same phenomenon or event in different views. Distributed sensing has some application advantages such that in earthquake monitoring scene the sensor array could calculate earthquake magnitude and locate epicenter more accurately than single sensor. In certain sensing area, multiple detectors or sensors could achieve cooperative signal processing through the local network such as beamforming, relative ranging, cooperative communications, and then return the processed data back to Earth through the backbone network. As a result, the data traffic with the local subnetwork might be much larger than the traffic over the DTE links.

4.4.3 *Navigation service*

Both the deep space exploration and the deployment of nodes in future SSICN networks require complex and accurate navigation capabilities. Navigation subsystem and communication subsystem in the same spacecraft are highly related but with different requirements. For example, the navigation subsystem usually requires a broadband front-end to improve the signal resolution, while the communication subsystem requires the narrowband front-end to reduce noise interference. Therefore, it is necessary to do some research on the merging design of such two subsystems. Besides, considering the reliability of the whole system, the navigation information might also be transmitted through the communication subsystem, which would bring some constraints to the design of communication protocols. Therefore, the navigation service might not only increase the traffic flow of application data, but also influence the availability of RF wireless links.

4.4.4 *Autonomous cognitive*

With more deep space explorers in the future and the development of space technology, it is likely impossible for the orbiters and surface facilities such as landers or rovers to use the same data rate, protocol, channel codes, modulation, therefore it is necessary to develop a general wireless communication device located on the planetary orbits to provide the automatic data relay services. With the theoretical researches and engineering applications, in 2006 NASA released a technical report about the autonomous software-defined radio systems for deep space applications in [79], which introduced the wireless transceiver system Electra radio based on autonomous software-defined radio, including the modulation index estimation, frequency correction for residual carrier, data format and pulse shape classification, SNR estimation, data rate estimation, carrier synchronization, symbol synchronization, which had been successfully used in several Mars exploration missions for the adaptive data relay services between Mars orbiters and landers.

Concerned with the requirements of flexible adaptability to future deep space exploration missions, the cognitive radio and cognitive radio network technology originated from the terrestrial mobile communications might also be gradually applied in future interplanetary communication networks [1]. Cognitive radio is developed based on software radio with a series of intelligent radio technologies, which could detect surrounding electromagnetic environment, communicate intelligently within the networks by the radio knowledge representation language, and adjust the communication parameters such as frequency, power, modulation, channel codes. Cognitive radio could improve reliability and spectrum efficiency of the communication system, as well as the adaptability of software and hardware. Cognitive radio network [80] is the network form based on the cognitive radio technology, with highly intelligent abilities to obtain the environment information of various communication networks and distinguish them, which could significantly raise the operating efficiency of future SSICN networks.

4.5 Time synchronization

4.5.1 *Demands*

With the development of SSICN networks, the overall communication demands assume the growth tendency. In order to ensure cooperative communications, it is necessary for both users to be time synchronized within the uniform time frame. Meanwhile, time information is an important kind of data in most space missions, for example, the meteorological observation and data analysis for some exoplanets within the uniform time frame would help the flight controller in making reasonable and effective plans for future missions. Besides, DTN protocols also require time synchronization of each node in the SSICN networks with following considerations [26].

- Most space applications are time sensitive and the resource allocation are constrained by time and space, therefore a node without timing capacity is useless in DTN architecture to some extent;
- Most DTN routing algorithms are prior knowledge decision making plans based on links status tightly coupled with time, with the requirements for a uniform time frame;
- BP protocol requires uniform time information, including node registration, time to life, fragmentation and recompose;
- According to the plan and test of DTN networks, there are already some mechanisms with the ability to provide online time information, and the time synchronization of the whole network is also in favor of network operation, management and maintenance.

4.5.2 *Challenges*

Ref. [81] lists some challenges for time synchronization in SSICN networks as follows.

- Time delay. The deep space backbone network links are characterized by the long and variable time delay features, which results in timing fluctuations;
- Data rate. The change in the deep space channel condition determines the dynamic adjustment of the data rate, for example, during the solar storm the data rate would be decreased to improve the communication reliability, which also results in timing fluctuations;
- Temperature situation. Different planets and locations in the universe have different temperature situation, which might bring differences in the timing drift rates;
- Electromagnetic interference. This might also result in timing drift, even the crystal damages in severe cases;
- Intermittent connection. This might result in timing fluctuations or time-hopping;
- Retransmission invalid. Because the distance between two end nodes in SSICN networks might be so far away that time synchronization protocol could not rely on the message retransmission mechanism to realize time synchronization;

• Distributed time server. Based on the architecture described in Subsection 4.1, there would be one or more time servers in each planetary network to provide the local time synchronization services. Furthermore, various planetary networks should achieve time synchronization to build the uniform time frame all over the SSICN networks.

4.5.3 *Time frame*

At present, the time framework in astronomical observation and deep space exploration is mainly divided into three categories [82] as terrestrial time standards (TT), parameterized post-Newtonian frame (PPN), and solar system barycenter frame (SSB).

(1) TT. Terrestrial astronomical observation stations and deep space TT&C stations always utilize the TT time frame to obtain observation data or measurement data with time scale, such as the international atomic time (TAI) or coordinated universal time (UTC), in order to facilitate the further statistical analysis. Such time frame is usually converted to other earth time frames as desired, such as TT or geocentric coordinate time (TCG).

(2) PPN. PPN [83] performs well on the general relativity analysis and determination of reference time and inertial position in the solar system, as well as the uniform framework for celestial navigation.

(3) SSB. Compared with the PPN frame, the SSB frame is more suitable as the space-time framework for interplanetary communications in the solar system, especially for interplanetary navigation and positioning. SSB is based on the international celestial reference frame (ICRF), whose axis points to the equator and vernal equinox of J2000 [84]. The origin of the ICRF frame locates in the barycenter of the entire solar system. In the solar system, the most contribution to the barycenter is the Sun and Jupiter, while other planets, satellites, asteroids and other celestial bodies contribute relatively little. Because the sun has an absolute mass advantage, the barycenter of the entire solar system is near the sun's surface.

The widely used time frame for interplanetary navigation and communication is barycentric coordinate time (TCB) and barycentric dynamical time (TDB) [85]. TCB is the reference time frame in SSB, which could be used to determine the motion equation of the celestial bodies (or spacecraft) relative to solar system barycenter. TDB is an abstract and smooth time variant to determine the motion relative to solar system barycenter, which is widely used as the almanac for the moon, the sun and each planet in the solar system. Therefore, the future SSICN network in China could choose TDB as the uniform time frame for the whole networks, with the consideration of the relativistic effects in the solar system [86].

4.5.4 *Synchronization methods*

In order to provide the time synchronization services in the distribution networks, IEEE Instrumentation and Measurement Society released the IEEE1588 standard in July 2008 [87]. This standard is to upgrade the network performance of time synchronization with the reference on Ethernet, which is mainly utilize the network time protocol (NTP) to make the local time of each device (client) in a distributed communication network to keep on the strict time synchronization with the time of server. Compared the network with IEEE1588 with traditional Ethernets, the time delay reduces from 1000 to 10 μs, therefore the time synchronization performance of the whole network is significantly improved.

Recently, some improvements based on the NTP in the space network environment [88, 89] have been proposed, which mainly focus on enhancing the security of IEEE1588, including key negotiation, key management, information integrity protection and rejection of replay attack. These methods assume NTP with high time precision, without the analysis whether NTP available in deep space long time delay links or not. Besides, some experts of ESA advanced the time synchronization method for deep space explorers based on terrestrial TT&C stations [90] which were used to provide the highly accurate time reference. This reference provided two methods to achieve the time synchronization between the deep space explorers and earth stations, such as 'space-ground frequency lock' and 'close loop'. However, the former is only suitable for the application scenes with high precision orbit prediction results obtained to calculate the Doppler frequency offset, and the latter might results in the synchronization precision deterioration with the increase in signal propagation distance.

With the above analysis, the current time synchronization methods in deep space communication networks are still in the primary stage without the systematic general design. For SSICN networks, the traditional time synchronization methods based on terrestrial accurate clock would not perform well due to the long time delay and other unfavorable channel conditions, which call for other more effective solutions. The rotation periods of X-ray pulsars are extremely stable especially for millisecond pulsars, whose long term stability is even better than atomic clocks. X-ray pulsar is all known as 'natural perfect clock', so it could be used as a time reference [85]. This paper proposes an available time synchronization solution for future SSICN networks, i.e., the uniform X-ray pulsar time frame (XPT) based on TDB and high stability satellite clocks based on X-ray pulsar time giving, with general thoughts as follows:

(1) Deploying the X-ray detectors on the satellites to periodically measure the time of X-ray pulse arrivals (TOA) $\tilde{t}_{\rm SC}$;

(2) Based on the time transformation model (introduced by [85], including various necessary corrections), utilizing the TOA value $\tilde{t}_{\rm SC}$ to get the extrapolation result $\tilde{t}_{\rm SSB}$ on the fixed point SSB;

(3) Based on the pulsar phase time model (introduced by [85]), calculating the actual TOA value on the fixed point SSB $t_{\rm SSB}$;

(4) The difference between $t_{\rm SSB}$ and $\tilde{t}_{\rm SSB}$ reflects the clock correction value, which could be used to adjust the satellite clock and keep the time synchronization within XPT frame;

(5) Besides, deploying the X-ray detectors only on some large satellites such as the deep space information hubs located at Lagrange points [91] or geostationary satellites on planetary orbits, which could calculate the accurate TDB time and broadcast such time information to any adjacent satellites through the RF links or laser links, in order to achieve the time synchronization within the local networks and the whole SSICN networks.

5 Suggestions for further development

5.1 Development trends

Concerned with the current science and technology development, there are still many technical limitations for SSICN networks, such as the scarce deep space resources, imperfect network protocols. Therefore, in addition to further improvement of the interplanetary communication network technologies, three main development trends henceforth are listed as follows, in order to optimize the system architecture, improve the network performance, strengthen the operation management and enhance the communication security.

5.1.1 *Enhance resource capacity*

In the SSICN networks, man-made satellites are the most important parts of the whole system architecture. Due to the satellite movement at all the time, the network topology would be changing at any time. Meanwhile, the communication subsystem on satellite is the most critical element to achieve the network interconnection, but such subsystem might not perform well due to the severe deep space electromagnetic environment and time-variant wireless channel conditions, which would result in the performance degradation of the whole system.

The increase in numbers of satellites and performance improvement of each node are the foundation to ensure the transmission capacity of the SSICN networks. Therefore, subsequent research should concentrate on the R&D of the core components for each communication element, gradually increasing the number of satellites, optimizing the network topology, as well as the international cooperation, in order to enhance the overall performance of the whole network.

5.1.2 *Optimize network protocols*

Space communication network protocols are usually divided into three categories as CCSDS standards, space IP and DTN protocol, while according to various service requirements and network environments, some layers of such three protocol stacks could also combine with each other through the adapter interfaces in order to provide the specific customer services. Nevertheless, there are still problems in these protocols, such as smaller scale of the application network instance, worse compatibility of the protocol options, and lack of the effective integration with the terrestrial TCP/IP internet, which requires the further scientific, professional and systematic demonstration.

Network protocols are the core elements related to the overall performance of the SSICN networks, which would be the most important technology in the near future. Therefore, subsequent research should concentrate on the analysis of the protocol architectures, study on the relationship within the external constraints, communication requirements and protocol options, and devote to the manufacturing and validation of the protocol stacks available to SSICN networks, in order to achieve the global optimization of the entire network protocol stacks.

5.1.3 *Improve management system*

Different from terrestrial internet, the SSICN networks are characterized by complex network topology and long propagation distance, which might bring in the uncertainty factors for network management. Once the network managers were distracted from concentrating on their works, then they might distribute the space resources unreasonably, resulting in the quality of service decline even serious electromagnetic interference, hence damaging the security and integrity of the data transmission.

Network management is the necessary mechanism for the successful and effective operation of the SSICN networks, which has not yet attracted sufficient attention at present. Therefore, subsequent research should demonstrate the appropriate network management technologies based on the analysis of space resources and network protocols, in order to form the scientific, reasonable and systemic management system for the SSICN networks.

5.2 Potential roadmaps

In the sum of the above analysis, the potential roadmaps for the construction of Chinese SSICN could adopt three steps strategies with the detailed concepts as follows.

First, establishing the full-sparse dynamic networks according to the deep space exploration mission requirements, with all of the satellites undertaking exploration tasks and some of them related to the data relay services. At this stage, the typical application scene is robotic Mars exploration missions, and the typical network architecture could be described as the model 'terrestrial deep space stations, Mars orbiters, Landers/Rovers'.

Second, establishing the half-sparse cooperative networks according to the deep space mission extension and international cooperation requirements, with all of the satellites enhancing communication capacities and some of them only related to the data relay services. At this stage, the typical application scene is robotic solar system exploration missions, and the typical network architecture could be described as the model 'terrestrial deep space stations, Lagrange points satellites, Mars on-orbit satellites constellation, Landers/Rovers'.

Third, establishing the distributed heterogeneous interconnected networks according to the integrated multimedia services requirements for SSICN networks, with all of the space resources sorted into different local area sub-networks and some large nodes connected with each other as the backbone networks. At this stage, the typical application scene is manned Mars exploration missions, and the typical network architecture could be described as the model 'terrestrial deep space stations, Lagrange points satellites, Planetary networks'.

6 Conclusion

Following the introduction on the concept, development history and future plans of the international deep space exploration activities, this paper reviews the main aspects of the SSICN, as well as its major features, present situation and future trends compared with the other two important communication networks as terrestrial internet, near Earth space networks. In addition, the key technologies and research trends of the SSICN from several aspects as architecture, physical transmission, network access, up-layer application, time synchronization are introduced in details. It can be seen from the analysis results that although the deep space communication technologies have advanced at a breathless pace, there is still a lot more to be done for the construction of future Chinese SSICN.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 61671263, 61271265), and Tsinghua University Independent Scientific Research Project (Grant No. 20161080057). The authors thank professor Gengxin ZHANG with the Army Engineering University of PLA for his helpful discussions and insights.

References

1 Li H T. Principles and Design Methods of Deep Space TT&C System. Beijing: Tsinghua University Press, 2014
2 Edwards C D, Denis M, Braatz L, et al. Operations concept for a solar system internetwork. In: Proceedings of IEEE Aerospace Conference, Big Sky, 2011. 1–9
3 CCSDS. Solar System Internetwork (SSI) Architecture. CCSDS 730.1-G-1, 2014
4 Shen R J. Some thoughts of Chinese integrated space-ground network system. Eng Sci, 2006, 10: 19–30
5 Huang H M, Chang C W. Architecture research on space-based backbone network of space-ground integrated networks. J CAEIT, 2015, 5: 460–467
6 Mukherjee J, Ramamurthy B. Communication technologies and architectures for space network and interplanetary internet. IEEE Commun Surv Tut, 2013, 15: 881–897
7 Fall K, Farrell S. DTN: an architectural retrospective. IEEE J Sel Area Commun, 2008, 26: 828–836
8 Khabbaz M J, Assi C M, Fawaz W F. Disruption-tolerant networking: a comprehensive survey on recent developments and persisting challenges. IEEE Commu Surv Tut, 2012, 14: 607–640
9 Kaushal H, Kaddoum G. Optical communication in space: challenges and mitigation techniques. IEEE Commun Sur Tut, 2017, 19: 57–96
10 ITU-R. Radio Regulations. 2008 ed. 2008. http://www.itu.int/pub/R-REG-RR
11 CCSDS. Radio Frequency and Modulation Systems. CCSDS 401.0-B, 2016
12 Anderson J D, Philip A L, Eunice L L, et al. Indication, from Pioneer 10/11, Galileo, and Ulysses data, of an apparent anomalous, weak, long-range acceleration. Phys Rev Lett, 1998, 14: 2858–2861
13 Ludwig R, Taylor J. DESCANSO Design and Performance Summary Series Article 4: Voyager Telecommunications. Washington: NASA, 2002. 1–6
14 Korablev O, Trokhimovsky A, Grigoriev A V, et al. Three infrared spectrometers, an atmospheric chemistry suite for the ExoMars 2016 trace gas orbiter. J Appl Remote Sens, 2014, 8: 084983
15 International Space Exploration Coordination Group. The Global Exploration Roadmap. Washington: NASA, 2013
16 Lu K F, Qi Z Q, Liu J R, et al. Analyses and reflection of intelligent autonomous technology for Chinese manned deep space exploration. In: Proceedings of 2016 IEEE Chinese Guidance, Navigation and Control Conference, Nanjing, 2016. 1033–1038
17 Zhang H X, Yuan D F, Ma Y B. Cross-layer Design for Wireless Communications — From Principle to Application. Beijing: Posts and Telecom Press, 2010
18 Wang M Z, Lei B, Ding C B, et al. Technical considerations of construction space-ground integration network. In: Proceedings of the 2nd Space Information Networks Academic Forum, Yinchuan, 2017. 193–198
19 CCSDS. AOS Space Data Link Protocol. CCSDS 732.0-B-3, 2006
20 Cui P Y, Dou Q, Gao A. Review of communication blackout problems encountered during mars entry phase. J Astronautics, 2014, 35: 1–12
21 CCSDS. CCSDS File Delivery Protocol (CFDP). CCSDS 727.0-B-4, 2007
22 CCSDS. Encapsulation Service. CCSDS 133.1-B-2, 2009
23 CCSDS. Proximity-1 Space Link Protocol-Data Link Layer. CCSDS 211.0-B-5, 2013
24 Marchese M. Interplanetary and pervasive communications. IEEE Aerosp Electron Syst Mag, 2011, 2: 12–18
25 Psaras I, Wood L, Tafazolli R. Delay-/Disruption-Tolerant Networking: State of the Art and Future Challenges. Technical Report, 2010
26 Cerf V, Burleigh S, Hooke A, et al. Delay-Tolerant Networking Architecture. Network Working Group IETF, 2007. https://tools.ietf.org/html/rfc4838
27 CCSDS. CCSDS Bundle Protocol Specification. CCSDS 734.2-B-1, 2015
28 Jiang Y, Li G X, Zhang G X, et al. The hierarchical-cluster topology control strategy of interPlaNetary internet backbone based on libration points. Przegląd Elektrotechniczny, 2012, 4A: 271–276
29 Younes B, Perko K, Shier J. Space Communications and Navigation (SCaN) Network Architecture Definition Document (ADD) Volume 1: Executive Summary. Washington: NASA, 2014. 2–17
30 Kato S, Feher K. Correlated Signal Processor. US Patent, 4567602, 1986-01-28
31 Shi X S, Dang H J, Hong J C, et al. Research on large scale small antenna array for deep space TT&C. In: Proceedings of the 9th Annual Conference of Deep Space Exploration Technology Committee of Chinese Astronautical Society, Hangzhou, 2012. 581–588

32 Fort D. Array Preliminary Design Review. Pasadena: NASA JPL, 1998
33 Xu M G, Chai L. Technical status and development suggestion of China's deep space antenna arraying. Telecommun Eng, 2014, 1: 109–114
34 Hong J C, Yang W G, Hou X M, et al. Study on downlink antenna array technology and its test verifying. J Acad Eq Command Technol, 2011, 1: 58–62
35 Gallager R G. Low-density parity-check codes. IRE Trans Inf Theory, 1962, 1: 21–28
36 MacKay J C D. Good error-correcting codes based on very sparse matrices. IEEE Trans Inf Theory, 1999, 2: 399–431
37 Chung S Y, Forney G D, Richardson T J, et al. On the design of low-density parity-check codes within 0.0045 dB of the shannon limit. IEEE Commun Lett, 2001, 2: 58–60
38 CCSDS. Low Density Parity Check Codes for Use in Near-Earth and Deep Space Applications. CCSDS 131.1-O-1, 2006
39 CCSDS. Low Density Parity Check Codes for Use in Near-Earth and Deep Space Applications. CCSDS 131.1-O-2, 2007
40 CCSDS. TM Synchronization and Channel Coding. CCSDS 131.0-B-2, 2011
41 CCSDS. TM Channel Coding Profiles. CCSDS 131.4-M-1, 2011
42 CCSDS. TM Synchronization and Channel Coding-Summary of Concept and Rationale. CCSDS 130.1-G-2, 2012
43 Arikan E. Channel polarization: a method for constructing capacity-achieving codes for symmetric binary-input memoryless channels. IEEE Trans Inf Theory, 2009, 55: 3051–3073
44 Yang W Z, Liu T. Research status and prospect of polar codes. Inf Commun, 2016, 4: 218–219
45 Luby M. LT Codes. In: Proceedings of the 43rd Annual IEEE Symposium on Foundations of Computer Science (FOCS'02), Vancouver, 2002. 271–280
46 Shokrollahi A. Raptor codes. IEEE Trans Inf Theory, 2006, 52: 2551–2567
47 Perry J, Iannucci P A, Fleming K E, et al. Spinal codes. In: Proceedings of the ACM SIGCOMM 2012 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communication, Helsinki, 2012. 49–60
48 Viswanath A, Gopal P, Jain V K, et al. Performance enhancement by aperture averaging in terrestrial and satellite free space optical links. IET Optoelectron, 2016, 10: 111–117
49 Xu F, Khalighi M A, Causse P, et al. Performance of coded time-diversity free-space optical links. In: Proceedings of the 24th Biennial Symposium on Communications, Kingston, 2008. 146–149
50 Safari M, Uysal M. Relay-assisted free-space optical communication. IEEE Trans Wirel Commun, 2008, 7: 5441–5449
51 Barbier P R, Rush D W, Plett M L, et al. Performance improvement of a laser communication link incorporating adaptive optics. In: Proceedings of Conference on Artificial Turbulence for Imaging and Wave Propagation, San Diego, 1998. 93–102
52 Viswanath A, Kaushal H, Jain V K, et al. Evaluation of performance of ground to satellite free space optical link under turbulence conditions for different intensity. Proc SPIE, 2014, 8971: 897106
53 Moision B, Hamkins J. Deep-Space Optical Communications Downlink Budget: Modulation and Coding. IPN Progress Report 42-154, 2003
54 Wree C, Collier C P, Lane S, et al. Ten Gb/s optically pre-amplified RZ-DPSK for FSO communications systems with very large link losses. Proc SPIE, 2008, 7091: 709103
55 Barsoum M F, Moision B, Fitz M. Iterative coded pulse-position-modulation for deep-space optical communications. In: Proceedings of IEEE Information Theory Workshop, Tahoe City, 2007. 66–71
56 Chen H J, Bishop R, Agrawal B. Payload pointing and active vibration isolation using hexapod platforms. In: Proceedings of the 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Norfolk, 2003. 1643–1661
57 Gagliardi R M, Karp S. Optical Communications. New York: Wiley, 1976
58 Chan V W S. Intersatellite optical heterodyne communication systems. Opt Space Commun, 1989, 1: 169–186
59 Stotts L B, Andrews L C, Cherry P C, et al. Hybrid optical RF airborne communications. Proc IEEE, 2009, 97: 1109–1127
60 Edwards C D. Relay communications for Mars exploration. Int J Satell Commun Netw, 2007, 25: 111–145
61 Taylor J, Cheung K, Wong C. DESCANSO Design and Performance Summary Series Article 1: Mars Global Surveyor Telecommunications. Pasadena: NASA JPL, 2001
62 Makovsky A, Barbieri A, Tung R. DESCANSO Design and Performance Summary Series Article 6: Odyssey Telecommunications. Pasadena: NASA JPL, 2002
63 Taylor J, Lee D K, Shambayati S. DESCANSO Design and Performance Summary Series: Mars Reconnaissance Orbiter Telecommunications. Pasadena: NASA JPL, 2006
64 Chicarro A, Martin P, Trautner R. The Mars express mission: an overview. Mars Express Sci Payload, 2004, 1240: 3–13
65 Wan P, Zhang S L, Song S J. Study on the enhancement of contact graph routing in space DTN networks based on the network coding. J Spacecr TT&C Technol, 2016, 5: 400–408
66 Wan P, Chen S, Yu T, et al. A hybrid multiple copy routing algorithm in space delay-tolerant networks. Sci China Inf Sci, 2017, 60: 042301
67 Shah R C, Roy S, Jain S, et al. Data mules: modeling and analysis of a three-tier architecture for sparse sensor networks. Ad Hoc Netw, 2003, 1: 215–233
68 Birrane E, Burleigh S, Kasch N. Analysis of the contact graph routing algorithm: bounding interplanetary paths. Acta Astronaut, 2012, 75: 108–119

69 Mundur P, Seligman M, Lee G. Epidemic routing with immunity in delay tolerant networks. In: Proceedings of IEEE Military Communications Conference, San Diego, 2008. 1–7

70 Spyropoulos T, Psounis K, Raghavendra C S. Spray and wait: an efficient routing scheme for intermittently connected mobile networks. In: Proceedings of the 2005 ACM SIGCOMM Workshop on Delay-Tolerant Networking, Philadelphia, 2005. 252–259

71 Widmer J, Le Boudec J Y. Network coding for efficient communication in extreme networks. In: Proceedings of the 2005 ACM SIGCOMM Workshop on Delay-Tolerant Networking, Philadelphia, 2005. 284–291

72 Spyropoulos T, Psounis K, Raghavendra C S. Efficient routing in intermittently connected mobile networks: the single-copy case. IEEE/ACM Trans Netw, 2008, 16: 63–76

73 Lindgren A, Doria A, Schelen O. Probabilistic routing in intermittently connected networks. In: Service Assurance with Partial and Intermittent Resources. Berlin: Springer, 2004. 239–254

74 Sabbagh A, Wang R H, Zhao K L, et al. Bundle protocol over highly asymmetric deep-space channels. IEEE Trans Wirel Commun, 2017, 16: 2478–2489

75 Zhao K L, Wang R H, Burleigh S C, et al. Performance of bundle protocol for deep-space communications. IEEE Trans Aerosp Electron Syst, 2016, 52: 2347–2361

76 Jiao J, Wang R H, Burleigh S C, et al. Reliable deep-space file transfers: how data transfer can be ensured within a single round-trip interval. IEEE Veh Technol Mag, 2017, 12: 86–94

77 Shi L L, Jiao J, Sabbagh A, et al. Integration of Reed-Solomon codes to Licklider transmission protocol (LTP) for space DTN. IEEE Aerosp Electron Syst Mag, 2017, 32: 48–55

78 Zhao K L, Wang R H, Burleigh S C, et al. Modeling memory-variation dynamics for the licklider transmission protocol in deep-space communications. IEEE Trans Aerosp Electron Syst, 2015, 51: 2510–2524

79 Hamkins J, Simon M K. Autonomous Software-Defined Radio Receivers for Deep Space Applications. Hoboken: John Wiley & Sons, 2006

80 Zhang P, Feng Z Y. Cognitive Radio Network. Beijing: Science Press, 2010. 2–12

81 Akyildiz I F, Akan O B, Chen C, et al. InterPlaNetary internet: state-of-the-art and research challenges. Comput Netw, 2003, 43: 75–112

82 Sheikh S I. The use of variable celestial X-ray sources for spacecraft navigation. Dissertation for Ph.D. Degree. Washington: University of Maryland, College Park, 2005

83 Richter G W, Matzner R A. Second-order contributions to gravitational deflection of light in the parametrized post-Newtonian formalism. Phys Rev D, 1982, 26: 1219–1224

84 Seidelmann P K. Explanatory Supplement to the Astronomical Almanac. Sausalito: University Science Books, 1992. 95–198

85 Sun S M. Study on autonomous navigation method of spacecraft based on X-ray pulsars. Dissertation for Ph.D. Degree. Changsha: National University of Defense Technology, 2011

86 Brumberg V A, Kopejkin S M. Relativistic time scales in the solar system. Celestial Mech Dyn Astronomy, 1990, 48: 23–44

87 IEEE Instrumentation and Measurement Society. IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems. NY 10016-5997, 2008

88 Yang J, Guo Y, Cheng Z, et al. Space time protocol based on IEEE1588. In: Proceedings of the 10th International Conference on Broadband and Wireless Computing, Communication and Applications (BWCCA), Krakow, 2015. 359–363

89 Cheng Z, He L, Zhao J, et al. A security enhanced IEEE1588 protocol for deep-space environment. In: Proceedings of the 9th International Conference on P2P, Parallel, Grid, Cloud and Internet Computing (3PGCIC), Guangdong, 2014. 9–13

90 Re E, Di Cintio A, Busca G, et al. Novel time synchronization techniques for deep space probes. In: Proceedings of International Frequency Control Symposium, Joint with the 22nd European Frequency and Time Forum, Besancon, 2009. 205–210

91 Zhan Y F, Wan P. Thoughts of chinese development strategy for deep space exploration. In: Chinese Development Strategy for Deep Space Exploration Workshop. Beijing: Tsinghua University, Space Center, 2016. 7–14