Research on frontiers of space-ground integration information network

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Abstract: After years of research and development, space-ground integration information network (SGIN) is still in the initial stage. Although the country has yet established a truly global space-based Internet, the development of frontier technology makes the space-based network feasible. In this paper, we proposed a novel system architecture of SGIN adopting the cutting-edge technologies of new communication transmission, plug and play satellite module, flexible configuration effective carrier, modular network system, and multi-satellite launch. The paper further analyses the role of new technologies in promoting space-based networks from the aspects of performance and cost and puts forward the development trend of space-based network technology. Finally, we identified and summarised some common misunderstandings and promising trends of SGIN. With the novel architecture design and demonstration of the promising trends, we believe this paper will guide the future research of high-impact research in SGIN.

Keywords: SGIN; space-ground integration information network; flexible payload of satellite; plug and play; space optical communication; space quantum communication.

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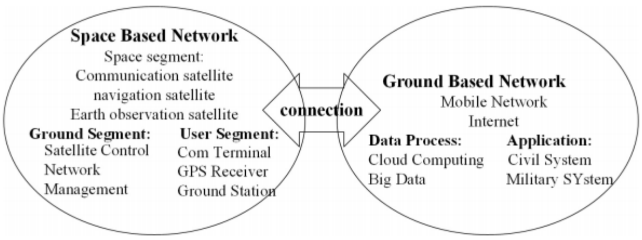
1 Introduction

Shen (2006) first proposed space-ground integration information networks (SGINs), which aim to establish the inter-stellar Internet covering the solar system. Wu et al. (2016) gave a more specific definition of the system architecture for SGIN, which is combined with the application requirements and further started the upsurge of the research of network architecture (Li et al., 2015a; Liu et al., 2018a, 2018b; Jin et al., 2016; Zhang et al., 2015). With the development of research, the definition of SGIN is evolving. At present, it is generally accepted that SGIN includes two parts, i.e., space-based information network and ground-based information network. These two parts are not only interconnected but also integrated together.

In SGIN application scenarios, various communication platforms, e.g., satellites, ground stations, users, and aircrafts, are connected through inter-satellite links. With further adopting intelligent high-speed processing, exchange, and routing technologies, information could be accurately obtained, rapidly processed, and efficiently transmitted to achieve effective and comprehensive utilisation. Such an integrated high-speed broadband information network is composed of space-based and ground-based information networks.

The goal of SGIN is to realise data fusion and information sharing among various functional platforms, integrate different users and application control resources into an organic whole, realise information sharing and overall construction, improve the capacity and timeliness of communication, and enhance the reliability and damage resistance of information network. Figure 1 illustrates the comparison of SGIN with space-based and ground-based networks. On one hand, the space-based network mainly includes space segment, ground segment, and user segment. On the other hand, ground-based network mainly includes mobile network and Internet, in which the data process is achieved using cloud computing (Bhattacharya and Guo, 2020), big data, artificial intelligence (Saavedra-Rivano, 2020), etc. The concept of SGIN is similar to that of space-based integrated information network, but it is broader in terms of the concept, and more attention is paid to the interconnection and integration of space-based information network and ground-based information network.

Figure 1 Composition of SGIN



SGIN consists of space-based and ground-based networks, along with the other infrastructures realising the mutual connection of these two networks. From the perspective of construction and management subjects, we can regard the space-based and ground-based networks on SGIN as two relatively independent systems. The space-based network consists of communication satellites, earth observation, and navigation at the space side; the system for satellite control and network management at the ground side; and various application terminals at the user side. As for the ground-based network, it is a functional system even without the existence of space-based network. The ground-based network includes the commonly used network, such as telephone networks, mobile communication networks, television networks, etc. The interconnection pares in SGIN does not necessarily exist as a stand-alone component. In other words, it could belong to either space-based network or ground-based one.

Currently, there are many researches focusing on SGIN, Such as network protocol design (Li et al., 2016a; Liu et al., 2018b), network security (Yu and Liu, 2015), inter-satellite link, constellation networking, simulation and evaluation system (Li et al., 2016b, 2016c, 2016d), etc. However, most of the existing research is still in the stage of theoretical research or simulation, and lack experiment verification. Especially, most of the proposed theoretical systems are just cultivated according to the requirements or characteristics of the ground-based network (Zhu et al., 2018). Therefore, these systems are not feasible since they have not considered the problems such as environment adaptability in satellite, construction cost, rocket capacity, and satellite platform capacity. Meanwhile, the existing simulation system is normally aimed at physical layer simulation for satellite-ground or inter-satellite links, or top-layer simulation for routing and resource allocation (Xu et al., 2017; Li et al., 2015b). Such a simulation system lacks consideration about satellite ability, which leads to unfeasible for their routing and resource allocation design.

There are few pieces of research for network architecture which could take into account for both space-based load characteristic and the top-level architecture (Wang et al., 2018; Khalighi and Uysal, 2014). In this paper, we propose a novel architecture of SGIN with the main novelty and contributions as follows:

- the proposed SGIN architecture adopts the cutting-edge technologies of space optical communication, space quantum communication, flexible payload of satellite, space plug and play, and multi-satellite launch, making the system advanced to the best of our knowledge
- we adopt the modular, open, and networked architecture design principle for the development, facilitating the satellite function modules
- the development trends of SGIN are identified and summarised, which is of great potential to guide future research.

The remainder of this paper is organised as follows. Section 2 demonstrates the cutting-edge technologies adopted in the proposed SGIN architecture. The misunderstandings by the academia and industry are identified in Section 3. We identify three development trends of SGIN in Section 4. Finally, Section 5 concludes the paper.

2 Frontier technology

With the development of technology, many key technologies, such as space optical communication (Khalighi and Uysal, 2014), quantum communication (Polnik et al., 2020), modular satellite and network framework (Jiang et al., 2016), flexible load technology (Zhu and Li, 2018a, 2018b), multi-satellite launch technology, have made the construction of SGIN feasible.

After years of experiments, space optical communication has gradually possessed the ability of high-speed inter-satellite communication, which provides the essential capacity for satellite networking. Quantum communication can be used to ensure the security of the satellite network. At present, the satellite network lacks effective and perfect security mechanisms, and the security issue has become one of the key problems hindering the development of space-based networks. Through the quantum encryption link, satellite link can be provided. The concept of modular and open network architecture provides a feasible technical route for the heterogeneous integration of space-based networks (Jiang et al., 2019).

Flexible payload technology and multi-satellite launch technology can effectively reduce the cost of space-based network construction and improve network efficiency, which is the key technology to promote the development of space-based networks. Flexible payload technology is conducive to space-based platforms. It can flexibly configure different payloads such as high-resolution imaging, video monitoring, information acquisition, communication transmission, etc. to provide comprehensive information services, which may effectively improve constellation efficiency. One arrow multi-satellite launch technology reduces the cost of a satellite launch multiple times, which is also a hot research topic in various countries. With multi-satellite launch technology, large-scale LEO constellation construction is possible.

2.1 Space optical communication

Space optical communication is a new technology that has been explored for many years in the world and has made breakthrough progress in recent years. It is a high-speed, large-capacity, and high-security space communication using optical as the carrier in outer space, including optical communication between deep space, synchronous orbit, low orbit and medium orbit satellites, including GEO-GEO, GEO-LEO, LEO-Earth, and other forms. It also includes the communication between the satellite and the ground station.

In terms of system composition, an inter-satellite optical communication terminal usually consists of two basic systems, namely an optical communication system and an optical tracking system. The former is used for information transmission between two satellites, and the latter is used for capture, track, and sighting. The optical system as a whole is also divided into two parts, the main telescope and the optical platform. The optical platform is equipped with optical communication and optical tracking components and its optical path arrangement. The design of the terminal must also be suitable for the space environment requirements, consider and overcome the satellite platform environmental interference, and consider the service life. Optical communication often uses two communication methods: incoherent optical direct detection communication method and coherent optical heterodyne reception communication method.

- Incoherent direct detection communication means that the transmitting terminal uses pulsed optical intensity modulation, and the receiving terminal uses a photo detector to directly detect light pulses.
- The receiving principle of coherent optical communication is to use the local oscillator optical and the counterpart signal optical to perform heterodyne in the photo detector, but at present, homodyne coherent optical communication technology is used, that is, the frequency of the local oscillator and the signal is the same.

The optical pulse direct detection method has the advantages of simple structure and mature technology, but the sensitivity of the optical receiver is relatively low. Coherent reception technology can naturally suppress background noise and improve the signal-to-noise ratio, so that the optical power required per bit is about one order of magnitude lower than that of incoherent communication. It is extremely advantageous for long-distance or high-bit-rate data transmission. For example, when the communication rate is more than several Gbps, and the transmission distance reaches tens of thousands of kilometres, the use of incoherent optical communication for the power requirements of the light source has reached an unrealistic level. Therefore, high-rate optical communication terminals for commercial applications have adopted coherence, i.e., the way of optical communication.

USA is one of the earliest countries in the world to carry out optical communication on satellite. In April 2014, LADEE and ESA's optical ground station in Spain successfully carried out the high-speed optical signal transmission. In June 2014, NASA successfully transmitted high-definition video from the International Space Station to the Earth using a new type of optical communication device, which will help to future communication for deep space missions. USA will use a GEO satellite to conduct a two-year GEO-Earth high-speed 2.88 Gbit/s two-way optical communication test to accumulate experience for next-generation relay satellite. In addition, USA also plans to build the world's first space-based commercial optical communication network, which includes 12 MEO satellites. The system can achieve 6T bit/s communication capacity. The inter-satellite link, satellite-ground uplink, and downlink can achieve more than 200 Gbit/s.

Europe has developed a series of optical communication terminals for different orbit satellites and different communication distances. In addition to continuing the LEO-GEO optical communication test at a rate of about 2 Gbit/s, Europe also plans to apply optical communication technology to its first data relay satellite system (EDRS). The EDRS system can use GMES satellites for earth observation. The data is transmitted to ground users at a rate of 1.8 Gbit/s, through 40,000 km.

China has verified high-speed optical communication in-orbit with 'Ocean-1' and 'Ocean-2' satellites. Japan has completed a number of space optical communication research projects. At present, a new generation of the optical communication terminal is being developed for optical data relay satellite, which adopts coherent communication technology, and the communication rate will be as high as 2.5 Gbit/s.

2.2 Space quantum communication

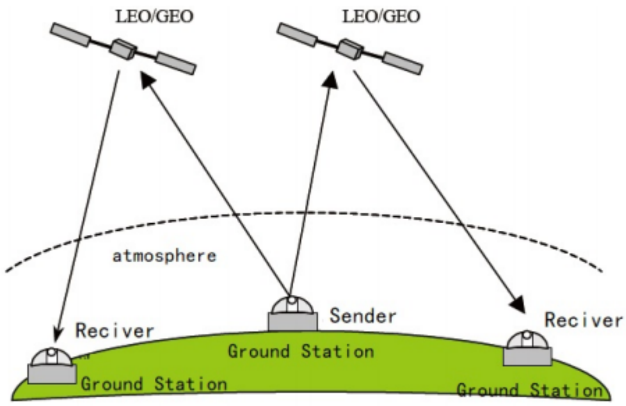
Quantum communication refers to a new type of communication using the quantum entanglement effect for information transmission. Quantum information is information encoded using quantum states, and has different forms and characteristics compared to classical information.

General quantum information can be stored on various microscopic particles, such as atoms, electrons, neutrons, etc. However, because the classical optical communication technology is mature, the relevant hardware is high. The photons are relatively less affected by the external environment, which are more controllable, and have no polarity, so the current general test schemes use photons as carriers for information transmission. Optical quantum communication is mainly based on the theory of entangled quantum states, using quantum teleportation (transmission) to achieve information transfer. According to experimental verification, no matter how far two particles with the entangled state are, as long as one of the changes, the other will also change instantly. The process of using this feature to achieve optical quantum communication is as follows: A pair of particles with entangled states is constructed in advance. Two particles are placed on both sides of the communication, and the particles with unknown quantum state and the particles of the sender are jointly measured (a kind of operation), then the particles of the receiver will collapse (change) instantly, and the collapse (change) will be a certain state This state is symmetrical to the state after the sender's particles collapse (change), and then the joint measurement information is transmitted to the receiver through the classic channel. The receiver performs a unitary transformation on the collapsed particles based on the received information (equivalent to reverse transformation), we can get the unknown quantum state the same as the sender.

Large-scale global quantum communication will uses pace quantum communication as one of the main solutions. There are currently two design options for space quantum communication.

- *Ground-based Quantum Communication Scheme*: The ground-based scheme means that the sender of a single photon or entangled photon pair is on the ground, including a ground-based transmitting terminal, which can distribute a single photon to the ground station or satellite, or distribute entangled photon. In this way, quantum communication can be carried out between these communication terminals. The communication distance of this scheme is far greater than that of terrestrial optical fibre and free-space quantum communication link, which can realise global quantum communication. However, due to the influence of atmospheric turbulence on the satellite to ground uplink optical link, the intensity distortion is large when it reaches the satellite, and the beam dispersion is higher, so additional treatment is needed at the ground terminal, which increases the complexity of the ground terminal. Figure 2 shows the ground-based space quantum communication.

Figure 2 Ground-based quantum communication system (see online version for colours)

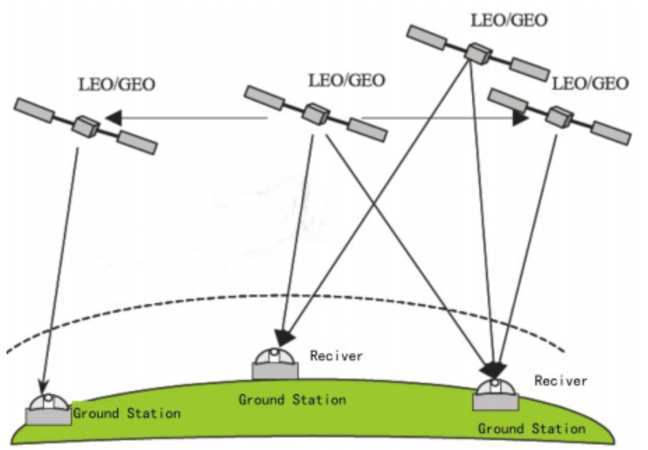


- *Space-based Quantum Communication Scheme*: Space-based quantum communication scheme refers to placing single photon and entangled photon peer light sources on a space platform. At this time, the optical communication link passes through the satellite-to-ground downlink channel or the inter-satellite channel. Compared with the uplink, the downlink is less affected by atmospheric turbulence, and can be reduced by ground terminal compensation, while the inter-satellite optical link is hardly affected by the atmosphere. Therefore, this communication scheme can establish longer-distance links, and it is also a global quantum communication scheme that is easier to accept and implement. As shown in Figure 3, only one downlink can share one photon in an entangled photon pair between two ground terminals; at the same time, a simple downlink can establish a single photon link for a quantum key In addition, the sharing of entangled photon pairs can also be established through two direct downlinks or relayed by another satellite; besides, the distribution of quantum entanglement can also be performed between a satellite terminal and a ground station, or between two satellite terminals. This scheme can be applied to multiple protocols and has multiple application possibilities.

Quantum communication technology as a whole is in the stage of technology pre-research and experimental verification. It is currently developing rapidly in the direction of high-speed, long-distance, and network.

European research on quantum communication technology is in a leading global position, and released the "Quantum Information Processing and Communication Strategy Report", which proposes the staged development goals of European quantum communication, including the realisation of terrestrial quantum communication networks, satellite-ground quantum communication, and air-ground integration. Thousand kilometres quantum communication network. At the same time, ESA collaborates with a team of scientists from Europe, USA, Australia, and Japan to conduct space quantum experiments, and plans to achieve long-distance quantum communication between the International Space Station and the ground station.

Figure 3 Space-based quantum communication system (see online version for colours)



The "Advanced Research and Development Activities" (ARDA) plan supported by the US Department of Defence extends quantum communications applications to satellite communications, metropolitan areas, and long-distance fibre-optic networks. NASA is planning to establish a long-distance fibre-optic quantum communication trunk line containing ten backbone nodes between its headquarters and the Jet Propulsion Laboratory (JPL) with a straight distance of 600km and a fibre sheath length of about 1000 km. Currently, China has launched the first quantum communication test satellite 'Mozi' in 2018, and for the first time, verified the feasibility of ultra-long-range quantum communication on space-based scale. Japan has also proposed a long-term research strategy for quantum information technology, investing 200 million dollars, and plans to build a nationwide high-speed quantum communication network within 5–10 years. Japan's National Institute of Information and Communication plans to realise quantum relay in 2020, and build a wide-area optical fibre and free-space quantum communication network with extreme capacity and unconditional security by 2040.

2.3 *Flexible payload of satellite*

In recent years, research on the flexibility of communication satellites has arisen. The Flexible Satellite mainly refers to a satellite that uses Flexible Payload technology. The key lies in the flexibility of the payload.

After the traditional transparent communication satellite is put into orbit, its technical status is basically fixed, and it is difficult to make dynamic adjustments in time for market changes. Therefore, the industry has sprouted the concept of 'flexible satellites', that is, satellites can dynamically adjust on-board resources in response to changes in business models or market demands during the service period of satellites, and continuously provide satellite communication services to achieve satellite flexibility. 'Flexible payload' is a general concept that includes many connotations. According to Thales Alenia's definition, flexibility includes seven areas:

- *Orbital flexibility*: Orbital flexibility does not mean that the orbital position of the satellite can be moved at will, but that it can provide the same coverage and complete the same tasks in multiple orbital positions.
- *Coverage flexibility*: Mainly for antenna beams, which means that the shape of the beam, the contour of the EIRP, the centre of the beam, the number and size of the beams can be changed according to demand.
- *Frequency planning flexibility*: Mainly refers to the variable number of channels, bandwidth, and guard interval. It also means that the frequency conversion and local crystal design are also flexible.
- *Transmit power flexibility*: Refers to the transmission power allocated by changing the channel or beam according to the needs of service transmission.
- *Routing flexibility*: Including routing granularity and routing definition are closely related to the flexibility of satellite coverage and frequency planning. Satellites can change the filtering characteristics of channels or sub-channels to route all or part of the channels.
- *Flexibility of waveform and MAC layer protocols*: For regenerative transponders, it can include the flexibility of modulation and demodulation schemes and coding schemes. It is required that the on-board modulator-demodulator has the ability to adapt to new waveforms, such as from DVB -S upgrade to DVB-S2.
- *Flexibility at the switching level*: More advanced flexibility switch above the physical layer, including flexibility in the data structure (data packet size, header) and communication protocols.

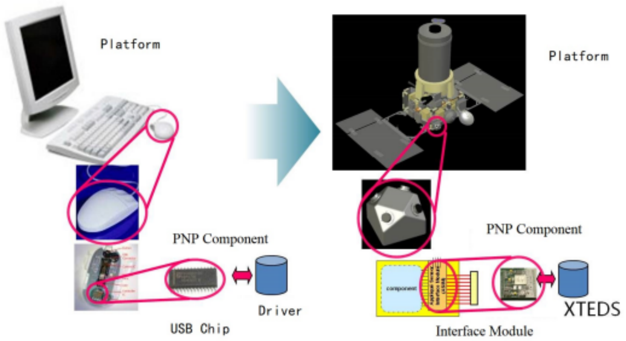
There are many technologies that support flexible payloads at different levels, such as digital beam forming antennas, flexible TWTA, and multi-port amplifiers (MPA), digital translucent payloads, regenerative payloads, and more. From the perspective of the composition of the communication payload, it can be divided into two parts, the antenna, and the transponder. Among them, the typical representative technology of the antenna part is the reconfigurable antenna technology, which is divided into two categories, passive and active, and passive antennas include mechanical and electronic passive antennas. The transponder field technologies include optical interconnection, intermediate frequency processors, transparent digital processors, and many other technologies.

In general, research in this field is still in its infancy, and several research projects are still underway in Europe. Known projects include ESA 'Europe's Flexible Payload Roadmap', Eutelsat Quantum. US satellite manufacturers have also conducted flexible payload attempts through advanced digital processing technology, such as Thales Alenia's Agile/Flexible Payload Component Research.

2.4 *Space plug and play technology*

Plug and Play Technology (PnP) was originally an industry standard for automatically handling the installation of PC hardware equipment, which greatly simplified the installation of hardware equipment without the need for jumpers and software configuration programs. AFRL, ESA, etc. extended the concept of plug and play to the spacecraft field. Based on the layered spacecraft model, they proposed 'space plug architecture' (SPA). Its purpose is to realise the rapid discovery of equipment and the self-configuration of services provided by the equipment through this system. This research directly led to the development of plug-and-play technology in the field of integrated electronic systems for spacecraft. It provided a technical guarantee for the rapid assembly and rapid replacement of spacecraft electronic equipment, as shown in Figure 4.

Figure 4 SPA is similar to USB equipment interface of PC (see online version for colours)



SPA technology is a hot research technology at present. The core idea is to extend the land plug and play technology based on intelligent machine negotiation interface and integrated bus to spacecraft. Plug and play satellite is a modular satellite with open standards and interfaces, which can self describe the components and automatically configure the system. System integration can be simplified and tested automatically. Plug and play pay loads are the core of plug and play satellites, and their specific concepts have not been defined clearly, but the basic idea is to use the space plug and play technology payloads.

The supporting technologies ofSPA mainly include system-level packaging technology, MEMS technology, multi-functional structure technology, software radio technology, reconfigurable system technology, reconfigurable computing principle based on FPGA, adaptive multi wiring, self-organising network technology, FPGA public front-end processor of the high-performance sensor, and the realisation of high-performance on-orbit meters. The fusion processor grid array network is calculated.

SPA technology has been widely concerned since it was proposed. After several years of research, the US military has made remarkable progress, found a solution to realise the spacecraft plug and play, established relevant standards, and completed the development of demonstration verification satellite. This series of progress shows the broad prospect and development potential of plug and play spacecraft to the world, which will have a revolutionary impact on the development of global space technology.

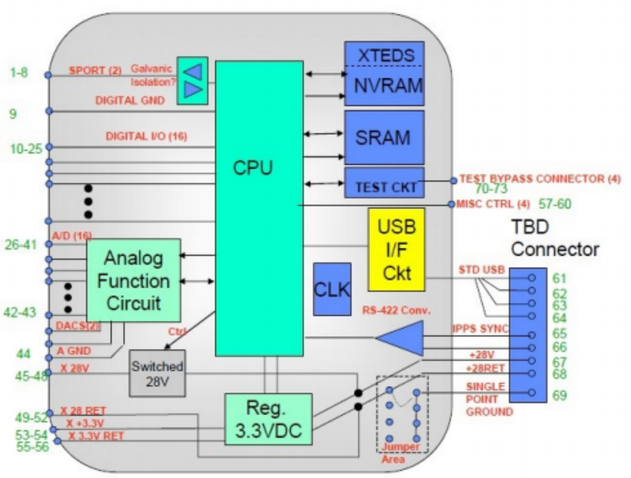
In terms of hardware, NASA has formulated the SPA interface standard and related hardware architecture; the European Space Agency (ESA) has designed a high-speed, scalable, low-power, low-cost plug-and-play. The serial bus SPA-SpaceWire is used, and related routers and interface conversion modules are designed.

In terms of software, AFRL has designed a set of SDM software architecture based on SPA plug-and-play technology, and designed the corresponding electronic data table xTEDS, which has been applied to actual satellites. In terms of standards, the US AFRL has proposed the SPA standard, which specifies the physical interface, power supply, clock synchronisation, middleware software SDM, electronic data table xTEDS, and corresponding testing technologies; the European ESA has proposed a PUS standard close to the underlying hardware. It improves the reusability of the software and reduces the R & D cost and the cycle of plug-and-play satellites.

In terms of interfaces, AFRL proposed the PnPSat satellite concept, which implements the spacecraft architecture based on the SPA-U and SPA-S interfaces (SPA-Spaceware); the European SOIS standard interface shields the differences in the underlying hardware interfaces through technical means, and supports applications. The layer provides users with five well-defined interface services that regulate how upper-layer applications call lower-level hardware, and applications can access the underlying hardware.

SPA-U, as shown in Figure 5 is a plug-and-play interface standard based on the existing USB interface standard. It supports 12Mbps data transmission and is suitable for most spacecraft equipment interfaces. The SPA-U connection uses an 8-wire cable connection. In addition to the same 4-wire as the USB, two of the additional 4-wires provide power, and the two support synchronisation. This design allows the intelligent features of the existing USB standard to be used. At the same time, it provides additional support, that is, it can provide 28V, 3A power, and 1Hz synchronisation pulse. Mechanically, on the premise of ensuring that the shape of the interconnection module is consistent, the device does not distinguish between uplink and downlink connections, and any host or terminal can be connected to any SPA-U port. The multi-beam signal transceiver on the KUTESAT-2 satellite in the USA has adopted the SPA-U plug-and-play interface standard.

Figure 5 Architecture of SPA-U ASIM (see online version for colours)



In order to meet the rapid response to space requirements, AFRL launched the 'plug and play satellite' (PnPSat) project with the support of the Ministry of Defence, and adopted the SPA-S interface for the requirements of the operational response space (ORS) mission. Standards that verify the feasibility of rapid development, integration, and testing at a low cost. During the construction of the ORS system, USA has conducted a large number of ground and flight verifications for space plug and play technology, including RESE PnPtests, SAE, PnPSat-1, APT, PnPSat-2, TechEdSat, and ORS-2 satellites. These works verify and improve the effectiveness of space plug and play technology in ORS hardware and software implementation.

2.5 *Modular, open and networked architecture*

'Modular, open, networked architecture' (MONA) technology is a new concept proposed by the US AirForce Space and Missile System Center (SMC) in 2012. The essence is to use modular and standardised technology to build an open, networked Aerospace equipment system.

MONA is not a specific engineering and technology research method and implementation approach, but a top-level idea that guides the development of the aerospace equipment construction and aerospace industry in the USA. Space equipment system with interoperability, interconnection and interoperability.

SMC believes that the logical relationship of MONA is M→O→N, that is, to achieve openness based on software and hardware modularity, and to achieve system network based on openness. Specifically, the requirements of software modularity are as follows:

- software is completely independent of hardware
- adapting to changes in ICD
- interface standardisation
- modules can be completely reused
- software application (APP) supports different tasks and loads.

In terms of the hardware, it should be of high modularity with requirements as follows:

- scalable
- support new technology insertion
- can deal with supply chain risk management.

Open requirements:

- standard is free and open
- adapt to task tailoring
- enhance interchangeability.

Finally, there are certain requirements for the network as follows:

- decouple the software from the physical layer
- realise information packet transmission between nodes in the transmission layer
- ensure security
- have a multi-layer security foundation.

Modularisation and standardisation can strengthen the stereotyped design of satellite function modules and the generalised design of payload modules, forming a multi-series product profile and specifications, realising pre-processing and batch production, achieving shelf-type storage and rapid assembly as required. Respond to the launch purpose. Adopting public or industry-accepted standards to achieve open design, at the system level, component or stand-alone 'Plug and Play' (PnP) can be achieved, and at the system level, the entire star equipment can be 'Plug and Fight' (PnF). Opening up is conducive to the reconstruction, expansion, modification, and maintenance of the aerospace system. It can support the insertion of new technologies without modification. It can greatly improve the availability of aerospace equipment, rapidly upgrade and enhance system capabilities, and reduce the life cycle cost of the aerospace equipment system.

Networking refers to the use of Bluetooth and optical communications to build inter-satellite links to enhance the interoperability and interoperability of aerospace equipment, to achieve a doubling of the system's capabilities, and to transform space equipment from satellite-centric to networked actual combat effectiveness.

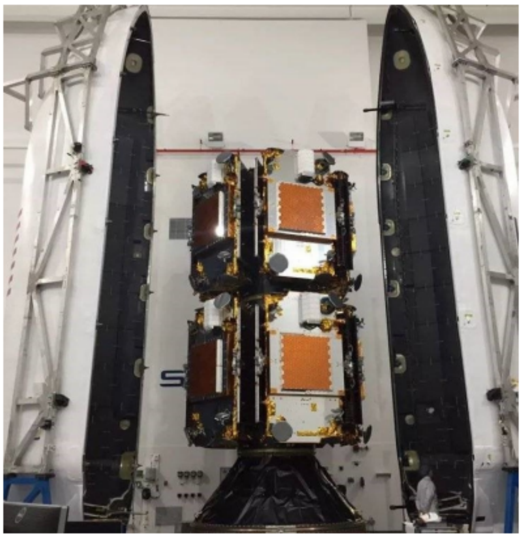
In recent years, ORS program, DARPA 'F6' plan, 'Seeme' plan, 'Phoenix' plan, and NRO 'Colony' plan all studied satellite standardisation and modularisation technology, and formed a series of achievements, including: development and delivery of modular open platform; verification of space plug and play integrated electronic technology, release of 10 plug and play standards; establishment of 'satellite data model' (SDM), standardisation software services and interfaces are provided on the hardware platform to realise hardware identification and resource sharing (Jiang et al., 2018); software function unit module library is established; cell satellite technology is developed to complete the modular design of integration of mechanical, electrical and thermal. NASA launched 'small satellite technology program' (SSTP), developed optical communication and inter satellite interconnection technology, and technology for open and networked space equipment system. US industry has also actively participated in Mona concept practice and developed a series of modular, open and networked architecture platforms to support rapid response tasks, including the 'Phantom Phoenix' platform developed by Boeing, the 'Eagle-1M' platform developed by Nuoger and the Altair platform developed by Millennium space systems for 'Seeme'.

2.6 Multi-satellite launch technology

The progress of multi-satellite launch can greatly reduce the launch cost, making large-scale LEO constellation possible. On June 20, 2014, Russia successfully put 37 satellites into the scheduled orbit with a rocket. On May 24, 2019, the falcon-9 carrier rocket successfully put the first 60 satellites of the 'StarLink' into orbit. On February 17, 2020, the falcon-9 rocket of SpaceX company put the fifth batch of 60 stars chain satellites into space. So far, the total number of satellites in orbit has reached 300.

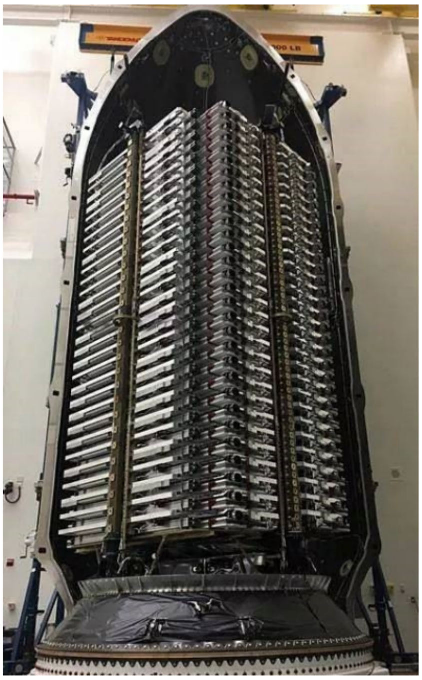
The traditional satellite loading is shown in Figure 6. Most of the satellites in China, USA, Japan, etc. are cube shaped, while the Russian satellites are generally round. Because the satellite design and rocket design belong to different manufacturers, it is difficult to achieve conformal. SpaceX adopts the integrated design of rocket, satellite and payload, so that the number of satellites will increase dramatically under the condition of space invariability.

Figure 6 Launch object of iridium on board (see online version for colours)



The SpaceX company divides a large number of satellites into two stacks of 30 flat satellites, as shown in Figure 7. A single satellite is 227 kg. The satellite and the rocket are optimised as a whole, on the comprehensive analysis of satellite's shape and the rocket's fairing. A scheme that can maximise the carrier rocket's transport capacity and the inner envelope of the fairing is formed. Five Iridium satellites are arranged in petal shape with symmetrical centre around separation and adapter to form one group.

Figure 7 SpaceX 60 stars loading structure (see online version for colours)



It can be seen that in the future, the satellite shape should be comprehensively optimised according to the number of satellites in the constellation, the satellite load and the fairing envelope of the rocket. The optimisation approach can be based on simulated annealing and particle swarm optimisation (Brezinski et al., 2020). The era of cube is gone, and the era of load platform transportation is coming.

3 Misunderstandings in frontier technology

In many researches, some technologies are not suitable for space-based networks. Researchers either do not understand the space-based environment and characteristics, or do not think deeply about them. Here are a few seemingly beautiful technologies that are not suitable for space-based networks.

3.1 Multi-layer satellite network

The research on the protocol, route and structure of multi-layer satellite network (Li et al., 2006; Qi et al., 2015; Huang et al., 2018) has been continuous, and the feasibility of multi-layer satellite network (Huang and Jo, 2010; Jiang et al., 2015) is low in the actual construction, the main reasons are as follows:

- High construction complexity. The multi-layer satellite structure means that, in order to interconnect the high, middle and low-level networks, a large number of diverse satellite antenna and transceiver equipment are needed, which makes the satellite nodes, network management and other complex, which is not conducive to engineering realisation. At the current technical level, the space-based network design is simplified.

- The resources of satellite frequency and orbit are scarce. Satellite frequency orbit needs to be approved by ITU, following the principle of first come, first served. At the same time, it is very difficult to obtain high and medium orbit satellite frequency orbit resources, which does not have the feasibility of engineering construction.
- The combination of high, middle and low rails did not improve significantly. High, middle and low orbit satellites have their own advantages and disadvantages, GEO satellite has the advantages of wide coverage and stable coverage, LEO has the advantages of low cost. GEO mixed with LEO can improve user access and routing performance. But we cannot find obvious advantage in the networking of high, middle and low orbit multi-layer satellites, neither capacity nor performance can be improved, nor cost can be reduced. Among the existing satellite networks, there is no mixed multi-orbit network.

3.2 DTN protocol

Delay tolerant networking (DTN) originated in 1998 by NASA's Jet Propulsion Lab (JPL) research on the InterPlaNetary Internet (IPN). Originally designed for interstellar communication services such as Mars data backhaul. In the research of space-based network protocols, the DTN protocol has been used as one of the alternative protocols (Chuang et al., 2014). DTN is an intermittent transmission protocol and is not suitable for SGIN applications. There are several reasons for this:

- Large transmission delay. The space-based network is instant transmission and communication system. The Large delay of information transmission is meaningless for the network and does not have availability.
- High complexity of network protocol. The space-based network generally adopts the synchronous orbit or low orbit constellation group network, which is equipped with inter satellite link and real-time return network link, without storage conversion. The application reaction of storage and forwarding will increase the complexity of network protocol design.
- Waste of storage resources. The on-board storage resources are digital devices. The cost of building and using storage resources is the same as that of computing resources. The use efficiency of the whole system is affected and the cost-effectiveness ratio of the system is reduced by using store and forward mode.

3.3 Terahertz communication technology

Terahertz high link communication speed, small antenna aperture, energy concentration, wide band capacity, large capacity, high-speed return. It seems to have very good properties (Wang et al., 2019), but it is not ideal in practical use. Terahertz communication rate is lower than optical, and it has all defects of optical in engineering realisation:

- The beam width is too narrow, so special tracking and aiming equipment is needed. The terahertz frequency is high and the beam is very narrow. According to the antenna radiation theory, the beam width is calculated as follows:

$$\theta = 70\lambda/D \tag{1}$$

  λ is the wavelength, D is the antenna aperture, θ is the radiation beam width, the current frequency used for terahertz communication is generally 0.3–3 THz, calculated by the longest wavelength, the antenna aperture is calculated as 0.5 m, the beam width is 0.14O, the tracking accuracy required by space communication is generally 1/10 of the beam width, so its aiming accuracy is 0.014O, such a high accuracy has exceeded the closed-loop or open-loop tracking ability of traditional antenna. It must be equipped with tracking and aiming mechanism, which is same as optical communication.
- The performance of THz LNA is poor. The loss of THz LNA is generally more than 5dB, which is almost the same as that of optical EDA. The low-noise amplifier using InP material is better, but the low-noise amplifier of this material has higher voltage stability requirements, and the space-borne products are still immature (Wang et al., 2019).

Except for the above two points, terahertz is similar to optical. There are also problems such as solar windows and rain and fog. Space high-speed communication has risen early crossed the terahertz stage and directly entered optical communication.

4 Development trends of SGIN

In this section, we identified and summarised three development trends of SGIN. In the following, we will introduce them one by one.

4.1 Space architecture is changing

With the increasing demand for potential applications, the traditional highly integrated military aerospace architecture and design concepts of in-flight construction and post-ground applications have fallen behind, and the original model must be changed to meet future development needs. Satellite design has become more focused on capacity development, and SGIN has gradually become the mainstream idea. The construction of the military aerospace system has begun to shift from the traditional performance-oriented index to the service-oriented capability, from the separation of satellite-ground to the integration of satellite-ground. At the height of the system, from the perspective of users, applications, and operations, through the coordinated planning and overall design of the space segment satellite system, the ground segment application system, and the user segment terminal system, it can achieve a reasonable decomposition of SGIN, a balanced capacity, and system construction. At the same time as minimising operating costs, it maximises system application capabilities.

4.2 Application of frontier technology is accelerated

Attach importance to the construction of an innovative environment, strengthen original innovation capabilities, actively explore major frontier directions that may change the future military and aerospace paradigm, vigorously cultivate subversive innovation concepts and technologies, and become a breakthrough in the development of satellite payload technologies. USA, Europe, Russia, Japan and other countries or regions attach great importance to the development of cutting-edge satellite payload technology. They have noticeably increased their attention to basic research and cross-cutting technologies such as quantum communication, optical communication, and large-aperture optics. They continue to introduce innovative concepts and basic, highly innovative cutting-edge technologies will gradually achieve in-orbit verification and application, and will become a key player in promoting the rapid improvement of their respective military and aerospace capabilities. In the field of communication, optical communication and quantum communication technologies have continuously made breakthroughs. In the future, they will develop in the direction of further increasing bandwidth, communication capacity, communication rate, improving availability, and improving anti-interference ability.

4.3 Meet different application with integrated payload of satellite

Driven by the integration of actual combat effectiveness and technological development, the requirements of military operations for aerospace equipment capabilities have become more diversified. The development of aerospace payload development has shown an integrated development trend, and more attention has been paid to task-oriented function integration and redundancy. Foreign countries attach great importance to the integration of different technology systems, focusing on the integration and integration of different functional loads. In terms of the technical system, satellites are developing towards the integrated detection of imaging and surveying. Radar signal intelligence and communication signal intelligence are integrated with high-orbit signal intelligence satellites and low-orbit signal intelligence satellites. In terms of functional tasks, complex integrated tasks are completed through the integration of multiple systems and information fusion. NASA comprehensively uses signal intelligence, imaging reconnaissance and other methods, adopts the idea of simplifying the function of single star, focusing on system design, through coordination of high and low orbit satellites, electronic and imaging multi-source information fusion, Optimise the configuration and form comprehensive surveillance capabilities in key areas.

5 Conclusion

The SGIN is an inevitable product of the development of satellite communications. In recent years, new technologies such as new transmission, network security, space networking, and new satellite payloads have developed rapidly. Large-scale space networking has initially met the requirements. This paper analyses the Modularisation Open Networking system, optical communication, quantum communication, space plug-and-play, multi-satellite and other cutting-edge technologies, discussed technical misunderstandings such as DTN protocol and multi-layer satellite networks, and finally combined technology and international development to propose the development trend of SGIN technologies. In the future, the frequent changing of the space architecture will demands new technologies so as to minimise the operating costs and maximise system application capabilities of SGIN. Moreover, the great advances of SGIN technologies, we believe there will be high-impact emerging applications shortly.

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