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Networking Architecture and Slicing Technology of Space–Ground Cooperative Network Based on Full-Dimension Definability

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Abstract: Future networks demand ubiquitous and interconnected information services in a full-dimensional space. However, the infrastructure and deriving technology system of the existing satellite Internet still face unprecedented challenges in terms of heterogeneous collaboration, resource efficiency, precision on demand, stability, and reliability. In this article, we analyze the developing demand for satellite Internet in China and discuss the development status and trends of the satellite Internet worldwide. Subsequently, we elaborate on a typical space–ground cooperative networking architecture and full-dimension definable network nodes. Ultimately, we propose key intelligent-slicing technologies for a space–ground cooperative network in terms of network intelligent slicing, data analysis and forwarding, and resource coordination and control mechanisms. Furthermore, a development route is proposed for intelligent slicing technology. Breakthroughs should be made on key technologies such as business on-demand intelligent slicing, data analysis and forwarding with full-dimension definability, and global source coordination and control technologies, which should rely on the space–ground cooperative network architecture and be supported by technologies such as network resource management and control, network intelligence, and full-dimension definability of the network architecture. This will ultimately provide a continuous impetus for the innovation of the global dynamic optimization technology of space–ground cooperative network resources.
Keywords: space–ground cooperative network; intelligent network slicing; full-dimension definable; networking architecture and mechanism

1 Introduction

In recent years, traditional terrestrial wireless communications have shown explosive growth in terms of the number of users and business needs [1], and new network technologies such as 5G and the Internet of Things (IoT) have also emerged. However, owing to the limited network capacity and coverage of these ground-based network technologies, it is difficult to meet the potential communication service needs of ubiquitous cyberspace such as remote terrestrial areas, oceans, sky, and even near-Earth space. New network architectures must be used to adapt to multidimensional integrated information service and application requirements with different quality of service (QoS) requirements [2].

Satellite Internet uses air-, ground-, space-, and sea-based networks to provide efficient and coordinated communication network infrastructure for various information service needs and applications in wide-area spaces

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around the world. At present, American companies such as SpaceX and Amazon are thriving in this field and have entered the substantive construction stage. The application demand for future ultra-large-capacity, wide-area communication networks is extremely high. Therefore, in recent years, China has begun to vigorously strengthen the development of satellite communication technology. In addition, at the national and local government levels, many policies have been formulated to promote the development of the satellite industry.

This study focuses on the space–ground cooperative network architecture with full-dimension definability and slicing technology. First, the development needs of satellite Internet technology in China are analyzed and judged, and the development status and trends of satellite Internet technology worldwide are then discussed. Second, typical space–ground cooperative network architecture and full-dimension definable network nodes are described. The key technologies of business-oriented intelligent slicing in a space–ground cooperative network are then proposed, including intelligent slicing of the network, data analysis and forwarding with full-dimension definability, and a global coordination control mechanism of the resources. Finally, suggestions regarding the development of intelligent slicing technology for a space–ground cooperative network in China are provided.

2 Analysis of development needs of satellite Internet technology in China

2.1 Ubiquitous communication requirements brought about by wide-area cyberspace

In recent years, the demand for ground-based networks, particularly wireless communications, has increased. At the same time, although the scope of human activities has been expanding with the continuous advancements of science and technology, the capacity of traditional ground-based networks is limited. The new wireless network technologies represented by 5G and IoT provide a good solution to the needs of the Internet of Everything. However, as the communication frequency continues to approach the terahertz level, the signal coverage of the base station continuously shrinks. The number and cost of the facility construction are also increasing exponentially, and it is difficult to completely cover geographic spaces such as oceans, near-Earth space, and extremely remote surfaces. Therefore, a single ground-based network is unable to meet the ubiquitous communication needs of a wide-area network space. There is an urgent need for an instant, economical, and efficient integrated three-dimensional network to meet the needs of human society for wide coverage, strong reliability, and high-speed networks [3].

2.2 Demand for multi-dimensional integrated information services brought about by the development of the economy and society

Information services have gradually increased the demand for multidimensional integrated information resources. The efficient operation of services in the fields of national strategic security, disaster prevention and mitigation, aerospace and navigation, education and medical care, environmental monitoring, and traffic management all rely on a comprehensive application of multidimensional information such as air, space, and ground data [4].

The space–ground cooperative network [5] is a future-oriented new network architecture. The traditional terrestrial mobile communication network is based on the cellular network structure used to achieve wide area coverage, which has the problem of a huge investment and unsustainability. A space–ground cooperative network aims to achieve the complementary advantages of the breadth of satellite network coverage and the strength of terrestrial network coverage, which can eliminate of the limitations of their independent development, and form a safe and reliable on-demand space–ground cooperative network system with anytime access. The system integrates a definable structure through all layers of the network, adopts collaborative processing of the software and hardware, and uses a combination of dynamic resources, among other means, to establish a flexible network architecture that is definable in all dimensions from the lower to the upper layers under the requirements of function, performance, efficiency, and security, among other factors, to achieve a new dynamically focused business-based scheme.

From the perspective of social, economic, and ecologically sustainable development, research on the space–ground cooperative network is conducive to the rapid formation of social benefits and equipment advantages, thereby establishing and consolidating related theoretical research and technology to achieve an internationally leading position in this field. The space–ground cooperative network is oriented for use in wide-area mobile communication scenarios, such as ocean and aviation and can support continuous coordinated coverage of space and ground, as well as the mobile deployment of infrastructure, and realize the on-demand provisioning of information service capabilities, which has important significance for promoting the development of national informatization and national strategies such as the Belt and Road initiative. In addition, the space–ground cooperative network can promote the development of B5G and 6G wireless mobile communication technologies and standards in China,

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create a complete technological collaborative innovation system, and provide key support for the implementation of the national Cyberpower and Internet Plus initiatives.

2.3 Development requirements for flexible networking of space–ground cooperative network

Compared with the traditional ground network and satellite network, the space–ground cooperative network has outstanding features such as continuous changes in network resources over time and space, a wide business coverage, complex and uncertain business types, and multiple heterogeneous network equipment. It cannot directly apply mature network resource coordination and control technology on the Internet, resulting in an extremely complex coordination and control of network resources, and making it difficult to provide customized and personalized resources for businesses.

The contradiction between resource supply and business load demand in the space–ground cooperative network is mainly reflected in two aspects. One aspect is the uneven development of space- and ground-based nodes, which are difficult to manage in a unified manner. The space–ground cooperative network includes a large number of space-, air-, and sea-based nodes. Owing to their special geographic location, it is difficult to update the infrastructure of these nodes frequently. However, ground nodes can support a rapid update of the device functions. There is an urgent need to coordinate the sky and Earth nodes in a coordinated manner to achieve the flexible expansion of equipment functions, given the tight coupling of traditional space–Earth network devices with transmission protocols, matching rules, and processing logic. Second, although the services of the space–ground cooperative network are diversified, the resources are limited, and it is difficult to update the network architecture on demand. A traditional satellite network mainly undertakes the relay task of the information transmission process, whereas the space–ground cooperative network has a variety of business requirements and a wide coverage; business delay, bandwidth, and security requirements change in real time; on-demand access, imbalance between busy and idle times, and difficult management exist regarding network resources. There is therefore an urgent need to dynamically divide the service subnets in the network and achieve a refined service response.

Based on network virtualization technology, slicing technology abstracts multiple end-to-end and isolated virtual networks in a single network in response to differentiated network business requirements that provide different functions and performance characteristics as well as customized network services for different users under the premise of an independent operation and maintenance. This technology provides a good solution to the contradiction between resource supply and business load requirements in a space–ground cooperative network. The space–ground cooperative network virtualizes multiple network slices in the entire physical network, distinguishes the service types to flexibly organize the network for different needs, and combines various network capabilities to meet the performance requirements of different services, maximize the utilization of network resources, and reach a high adaption between the network and business.

3 Development of satellite Internet technology worldwide

3.1 Existing satellite Internet system

During the past few decades, a variety of space–ground integrated systems have been proposed in the field of communication networks and have been applied to wireless communications. For example, the Global Information Grid (GIG) is a representative space–air–ground integrated network. The space–ground integrated network mainly has two network architectures: a geostationary orbit (GEO) satellite system, such as the Transformational Satellite System (TSAT), and a non-geostationary orbit system, such as the Other 3 Billion (O3b) and Starlink.

3.1.1 GIG

GIG is a full-dimensional communication project developed by the US Department of Defense that integrates communication, sensor, and operational networks. GIG structures are divided into ground, aviation, near-space, and satellite layers, including communication equipment and nodes needed to support the seamless coverage of global communication [6].

3.1.2 TSAT

The TSAT system is a next-generation GEO satellite system for military purposes, which is jointly constructed by the National Aeronautics and Space Administration (NASA), the US Department of Defense, and the intelligence department [7]. It is composed of five GEO satellites that communicate with each other through laser links to form a backbone network with a bandwidth of 10 Gbps and cooperate with the ground network to support ground terminals to access the optical and radar images of UAVs and satellites in real time.

3.1.3 O3b

The O3b satellite system is a medium orbit (MEO) constellation deployed by O3b Networks [8]. O3b aims to support approximately 3 billion residents in Africa, Asia, and South America to access the Internet through satellite networks. The O3b plan is composed of a constellation of 12–20 MEO satellites with an orbital height of approximately 8000 km.

3.1.4 Starlink

Starlink is an ultra-low-orbit constellation project developed by SpaceX in the United States. It has successfully launched approximately 420 satellites into orbit, indicating that the low-cost, high-performance satellite Internet communication system has entered the substantive construction stage. Owing to the relatively mature and easy deployment of a global ground-based network, the current differences between satellite Internet systems mainly lie in the type of constellation and the operating frequency band of the satellite used in the space-based network. Table 1 briefly compares the differences between the representative satellite Internet systems. With the maturity of technology and the development of application requirements, satellite Internet has gradually transitioned from military-oriented to civilian and commercial use. To meet the low-cost and large-scale deployment requirements, MEO and LEO constellation modes are mainly used, and the operating frequency bands of satellites also converge. Starlink is currently a state-of-the-art and mature project. It develops a globally uniform coverage based on the premise of an even distribution of services, ignoring the status quo of an uneven distribution of global communications services, resulting in a huge constellation scale and low cost-effectiveness.

Table 1. Comparison of existing satellite Internet systems.

System name	Constellation type	Working frequency band	Application range	Application time
GIG	GEO, MEO, and LEO constellation	EHF, UHF, X, C, Ku, Ka	Military	2000
TSAT	GEO constellation	EHF	Military	2003
O3b	MEO constellation	Ka	Civil and commercial	2007
Starlink	LEO constellation	Ku, Ka, V	Civil and commercial	2019

Note: EHF stands for extremely high frequency; UHF stands for ultra-high frequency; X stands for radio wave band with a frequency between 8 and 12 GHz; C represents the frequency of the radio wave within the frequency band of 4–8 GHz; Ku stands for a lower frequency band than the K wave band under the IEEE521–2002 standard; Ka represents the 27–40 GHz band; and V represents the 136–174 MHz band.

3.2 General networking architecture of satellite Internet

Satellite Internet mainly includes three parts: space-based networks, ground-based networks, and air-based networks. Because the distance between ground-based networks and air-based networks is mostly negligible compared to space-based networks, air-based networks can also be incorporated into the category of ground-based networks; that is, satellite Internet becomes a wide-area network that includes the two dimensions of space- and ground-based networks.

3.2.1 Space-based network

Space-based networks consist of satellites, constellations, and their corresponding ground infrastructure (such as ground stations and network operation control centers). These satellites and constellations are in different orbits and have different characteristics. According to different orbital heights, satellites can be divided into GEO, MEO, and LEO; they can also be divided into narrowband and broadband satellite networks according to the channel bandwidth. Narrowband satellite networks refer to MEO and LEO satellite systems, such as Iridium and Globalstar, which mainly provide voice and low-rate data services for global users. Broadband satellite networks can use a wide frequency band to transmit large numbers of data, with high-speed data transmission rates of up to 10 Gbps.

As a practical architecture of a next-generation satellite network, a multi-layer satellite network (MLSN) integrates multiple satellite networks and has a hierarchical structure [9]. MLSNs are composed of several types of links, such as inter-satellite links and inter-layer links.

3.2.2 Ground-based network

Ground-based networks are mainly composed of ground communication systems, such as cellular networks,

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mobile ad-hoc networks (MANETs) [10], world interoperability for microwave access (WiMAX) [11], and wireless local area networks (WLANs). Cellular networks have evolved to the fourth generation (4G) or advanced long-term evolution (LTE-A) and are evolving to 5G wireless networks to support various service types. Although ground-based networks can provide users with higher data rates, the network coverage in rural and remote areas is limited.

3.2.3 Wide-area mobile network

Wide-area mobile networks are different from ground mobile communication networks, such as 5G, but are a type of air or water mobile system. They use airplanes and ships as carriers for information acquisition, transmission, and processing. In addition, UAVs, airships, and balloons are the main types of infrastructure that constitute high-altitude platforms (HAPs) and low-altitude platforms (LAPs) [12]. Ocean-going ships and military vessels are the main infrastructure that constitute sea-based platforms (SSPs), providing mobile broadband wireless communication to supplement ground-based network service capabilities [13]. Compared with a base station (BS) used in a ground-based network, a mobile network has the characteristics of low cost, easy deployment, and large coverage area, and can provide wireless access services within a local area.

Although satellite networks can provide global coverage for the Earth, their propagation delay is long. In addition, although a ground-based network has the lowest transmission delay, the related infrastructure is susceptible to natural disasters or man-made damage. Wide-area mobile networks have advantages in terms of delay and coverage, but capacity limitations and link stability must be fully considered during deployment [14].

3.3 Key performance analysis of satellite Internet

Compared with traditional terrestrial communications, satellite Internet is greatly affected by on-star resource constraints and has problems such as a limited spectrum, limited bandwidth, and unreliable wireless links. To provide a good network performance, network operators must establish wide-area communication networks with high bandwidth, high reliability, and high throughput.

3.3.1 Bandwidth allocation

To obtain a specific network performance, such as a certain packet loss rate, delay, and energy consumption, it is necessary to allocate a reasonable bandwidth to the target network. In satellite Internet, bandwidth is a scarce resource with multiple uses, and the bandwidth consumes more power. When implementing bandwidth allocation strategies, a trade-off should be made between power and information transmission performance. High-frequency reused multibeam satellite systems are not only limited by aggregate interference, they also have a low fixed bandwidth allocation efficiency owing to an uneven user distribution and different content requirements, making it difficult to meet the differentiated needs of a large number of users.

3.3.2 Reliability

Satellites, airplanes, ships, and other nodes in the satellite Internet are always moving, and the network topology is also dynamically changing [15], resulting in little to no complete end-to-end path between the source and destination, and the end-to-end transmission delay is much greater than that of a terrestrial network. When network reliability needs to be maximized, the performance indicators cannot be optimized simultaneously, and the waiting time or data rate must be sacrificed. It is therefore a significant technical challenge to successfully set up an end-to-end transmission path and ensure a reliable message delivery.

3.3.3 Throughput

There are many wireless communication scenarios in satellite Internet, with strict delay constraints and high data throughput content delivery requirements. Analyzing and improving the information transmission rate and saving bandwidth to increase the network throughput are outstanding challenges.

3.4 Research progress of satellite Internet technology in China

The construction of satellite Internet is significant to the high-quality development of China. In addition to the international strategy of the nation and the livelihood strategy of the Chinese people for global coverage of information services, the current rapid increase in the number of satellites has caused congested orbital positions and an extremely scarce space communication spectrum. China urgently needs to rapidly develop a satellite Internet system to maintain its proper position in the process of competition for space resources.

In September 2019, the 5G network in China took the lead in entering the full commercial stage, indicating that the nation's ground-based communication network, particularly in terms of the domestic research and application of wireless communication networks, has taken the lead position globally. In terms of space-based network construction, China successfully launched the first satellite of the Tiantong-01 mobile telecommunications satellite system in 2016, which was deployed in GED orbit and can simultaneously serve millions of mobile users such as individuals, vehicles, aircraft, and sea ships with data, voice, short messages, and other services. China also successfully sent the first HongYan satellite into a predetermined non-stationary orbit in 2018. It has been estimated that the system will fully deploy more than 300 satellites by 2025, and can provide users with full-time and full-domain two-way data communication services and integrated information services.

With the increasing maturity of space- and ground-based network technology research, China included the space information network in its 13th Five-Year Plan as a major scientific and technological innovation-2030 project. The space information network takes the space-based network as the backbone and the ground Internet as the foundation and integrates the global information network to realize the interconnection of everything. In 2020, China incorporated low-orbit satellite Internet into the implementation plan of the New Infrastructure, and will build toward the ability of providing services that have seamless global coverage, high security and credibility, high-mobility on-demand access, and regional large-capacity transmission [4].

4 Overall architecture of space–ground cooperative network

With the implementation of national initiatives such as the Belt and Road, China is becoming increasingly open to the outside world, and the application demand for ultra-large-capacity wide-area communication networks is extremely urgent. The existing terrestrial cellular architecture is scaled for capacity, and the investment is huge and unsustainable. It is urgent to start from the overall system design to find the entry point for the future development of the space–ground cooperative network. For land services in wide-area communication networks, 90% of the world's population is concentrated on 10% of the land, and the distribution of services is uniform and clustered. For maritime services, although the ocean area occupies approximately 71% of the Earth's surface area, and the geographical scope is vast, the business distribution is extremely sparse. It can be considered that, for high-density areas of terrestrial services, a uniform coverage can achieve a higher efficiency. A non-uniform coverage can be more efficient for wide-area satellite service areas.

4.1 Space-ground cooperative networking architecture with full-dimension definability

A typical space–ground cooperative networking architecture is shown in Fig. 1. MEO satellites are used as the central node of the network to build a wide-area information backbone network. Ground communication base stations provide global ground access capabilities for access requirements from various ground terminal users. The access capability of satellites in the network and the switching and routing capability of the space-based core backbone network can realize the information transmission and interaction between ground users and any other locations around the world. The network architecture further leverages the space-based interconnection capabilities of the MEO constellation to interconnect a variety of LEO constellation application systems in space, achieve system coordination, on-demand networking, and on-demand coverage of space-based applications, and finally complete high-speed global information transmission and interaction. This architecture supports innovative breakthroughs in China's future communication network architecture, leading to the 5G evolution path and 6G basic network planning, and revolutionizing the ability and efficiency of network services [16].

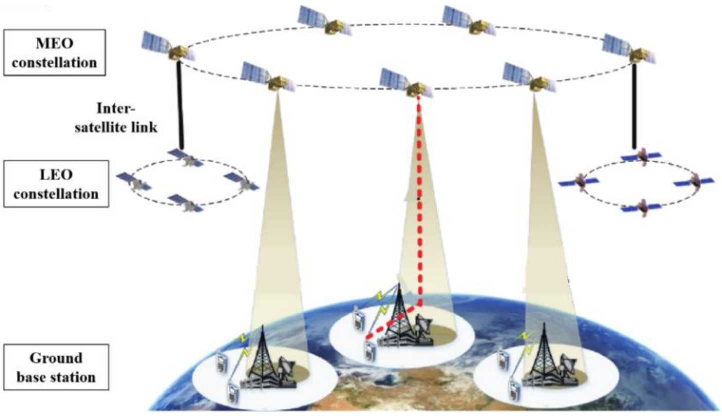

Fig. 1. Space–ground cooperative mobile communication system architecture.

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Based on the theoretical idea that the structure determines the function, performance, efficiency, and security, the space–ground cooperative network breaks the traditional rigid network architecture (Fig. 2), integrating a "definable structure" through all layers of the network. Co-processing hardware and software and dynamic resource combinations are used to achieve a full-dimensional flexible and definable network structure from bottom to top, such as supporting the definition of a network structure under the requirements of function, performance, efficiency, and security.

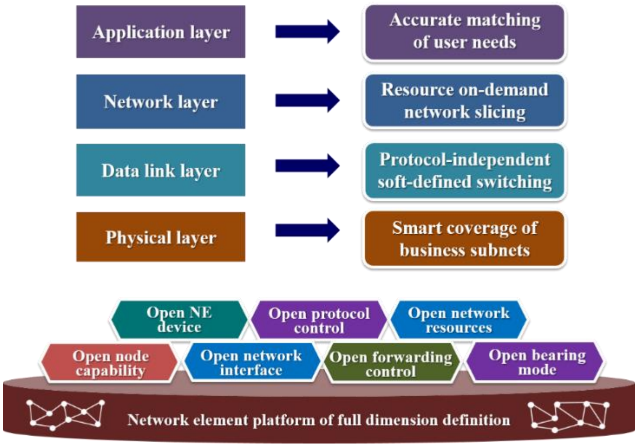

Fig. 2. Full-dimension definable network nodes.

The space–ground cooperative network architecture with full-dimension definability has such capabilities as openness, scalability, an incremental deployment, and heterogeneous integration. It supports a network on-demand reconstruction and a rapid response to new services, where the network layer realizes the integrated carrying of diversified services through on-demand slicing, effectively solves the problems of unified management of space-/ground-based nodes and limited node resources, and drives the establishment of core mechanisms such as a precise adaptation of resources and services.

4.2 Application scenarios of intelligent slicing of space–ground cooperative network

In the application scenario of intelligent slicing of the space–ground cooperative network (Fig. 3), nodes such as mobile access terminals, satellite communication base stations, satellites, and gateways form a network topology, which is managed and scheduled by the operation control center. When a user sends a service request for data transmission, remote control, or other application, the operation control center generates delay-sensitive slices and bandwidth-sensitive slices according to the type of service, combines a typical space–ground cooperative networking architecture to perform multi-domain control of network resources, and allocates the required resources for different services. In addition, it deploys a programmable forwarding platform on each node, defines forwarding rules on-demand, and ultimately completes service request responses for different businesses.

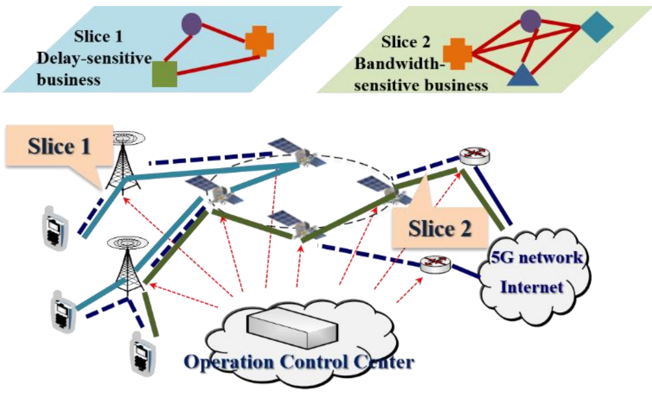

Fig. 3. Application scenario of intelligent slicing of space–ground cooperative network.

5 Business-oriented intelligent slicing technology of space–ground cooperative network

Aiming at the strongly changing space–time scale characteristics of the space–ground collaborative network resources and the complex and uncertain characteristics of diversified services, the intelligent slicing technology of the space–ground collaborative network aims to overcome the integrated slicing management difficulty caused by the differentiated forwarding plane of space-based and terrestrial network hardware facilities. Such technology also aims to meet the diversified time-varying network services and the limited network resources of space-based nodes, put forward higher requirements for the on-demand update of business slicing, and provide high-reliability and high-quality services for ultra-large-capacity wide-area coverage network applications.

5.1 Intelligent slicing technology for the resources of the space–ground cooperative network with business on demand

In response to the needs of differentiated wide-area information network applications, differentiated network slices involving different business characteristics are dynamically constructed to accurately match the resource requirements of different business data and realize multi-service integration applications. The realization of this technology can be divided into two key aspects:

The network resource slice generation technology based on virtual network mapping rapidly generates slices of network resources through weighted matching of the virtual and physical networks. Based on the principle of eigenvector decomposition of the adjacency matrix, this technology performs a fast matching of network-weighted graphs to reduce the computational complexity of network resource slicing. It then uses the adjacency matrix element replacement mechanism to reduce the minimum bandwidth requirement of network resource slicing. Finally, a virtual network mapping optimization method based on a hill-climbing algorithm is adopted to optimize the balance of load and bandwidth.

The network resource slice scheduling mechanism based on a flexible function orchestration achieves the adaptive adjustment of network resource slices with service requirements through an online flexible orchestration strategy of network functions based on a perception of the traffic evolution. One approach is to use online learning algorithms to perceive changes in network traffic and analyze the time-varying laws of business requirements to support real-time updates of network resource slicing requirements. The second is to realize a network function migration and traffic path adjustment through online elastic orchestration algorithms to support the precise matching of virtual resources and business loads and reduce the scheduling overhead of network resource slicing.

5.2 Flexible packet analysis and forwarding technology with full-dimension definability

Aiming at the wide-area flexibility and full-area coverage characteristics of a typical space–ground cooperative networking architecture, this technology constructs a full-dimensional perception, independent decision-making, and real-time adaptation mechanism between large-scale network resources and dynamic service requirements, and implements rapid perception and migration schedules for traffic services in the network. The realization of this technology can be divided into two key aspects:

A full-dimension definable packet parser is used to identify the type field of the data packet according to the user configuration and extract the corresponding matching field at the same time according to the type field. Specifically, the parser uses a configurable header parser and a combinable fine-grained meta-processing unit to implement a fully programmable data packet processing pipeline hardware design and optimization mechanism, effectively improves the data packet processing rate, and supports updates of the underlying hardware to significantly improve the flexibility and adaptability of the forwarding plane.

The flexible and programmable data packet processing method handles protocol-independent data packets through a combination of software and hardware, flexibly supports standard protocols, private protocols, and custom protocols, and supports users to directly describe network protocols and data packet processing behaviors. It can complete the programming description of the data packet processing mode without considering the details of the underlying hardware, realizing the real-time configuration of the programmable components of the forwarding plane, and achieve the dynamic loading of network functions according to the automatic perception of the state of the network operation.

5.3 Global coordinated control technology for resources in space–ground cooperative network

This technology addresses the definable forwarding requirements of the space–ground cooperative network at the

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network control level, breaks the limitations of network equipment on service and function deployment, realizes the full-dimensional definability of data packet parsing-matching-execution processing procedures, and enhances the adaptability and scalability of network resources provided to services. The realization of this technology can be divided into two key aspects:

The multi-domain adaptive planning algorithm oriented toward intelligent domain management is used as an improved unsupervised nearest-neighbor clustering algorithm for adaptive fitting of network control capabilities and network scale. The design idea is to conduct clustering operations on network nodes based on attractiveness and ownership, aiming at network QoS guarantee and reliable operation, outputting the corresponding multi-domain planning schemes, and realizing an intelligent adaptation of network division and network control capabilities.

The multi-domain network resource matching mechanism oriented to space–ground collaboration integrates and reorganizes limited control resources based on intelligent traffic scheduling and resource elastic control, which is conducive to the establishment of matching, mapping, and unified management mechanisms of the identification space. Based on user and service requirements, this mechanism intelligently selects and collaboratively schedules spatial network resources, performs rapid sensing and migration scheduling of network traffic services through the coordinated matching of control functions, and achieves coordinated management and control of multi-domain networks with fine-grained awareness of dynamic changes in resources.

6 Suggestions and countermeasures

6.1 Building an overall architecture with full-dimension definability for the space–ground cooperative network

It is recommended that, based on promoting the incremental deployment and evolutionary development of satellite Internet, basic changes to the satellite Internet architecture and technology system be carried out to promote the transformation of technology research and development from plug-ins to endogenous, and to build a space–ground cooperative network with full-dimension definability.

The key to constructing the overall architecture of the space–ground cooperative network is to establish a full-dimension definable network core operating logic: Based on the theoretical basis in which structure determines function, performance, efficiency, and security, the network coverage, services, and heterogeneous resources in the space–ground cooperative network are carried out for a unified management and flexible scheduling according to business needs through cooperative processing of the software and hardware and a dynamic combination of resources, among other factors. A “definable structure” runs throughout the physical, link, network, and application layers of the network to realize the on-demand definition of the network structure in terms of function, performance, efficiency, and security, and thus the space–ground cooperative networking architecture is open and scalable, incrementally deployable, and has a heterogeneous integration, supporting on-demand network reconstruction and quickly responding to new services.

6.2 Deepening the research on intelligent slicing technology of the space–ground cooperative network

Through on-demand slicing, the network layer can realize the integrated bearing of diversified services, effectively solving the problems of unified management of space- and ground-based nodes and limited node resources. Network slicing is the core mechanism of a space–ground cooperative network used to achieve an accurate adaptation of resources and services.

The development route of intelligent slicing technology of the space–ground cooperative network in China should be based on the space–ground cooperative networking architecture, supported by technologies such as network resource management and control, network intelligence, and network structure with full-dimensional definability. Key breakthrough technologies are also required, such as the intelligent slicing of network resources of a business-on-demand space–ground cooperative network, a flexible analysis and forwarding of data packets with full-dimension definability, and global coordinated control of resources in the space–ground cooperative network. Moreover, the key scientific issues and technologies faced by the space–ground cooperative network must be comprehensively solved from the level of network resource optimization, providing a continuous impetus for the innovation and development of the overall dynamic optimization technology of space–ground cooperative network resources.

6.3 Provisioning of policy support to space–ground cooperative network at the national level

Satellite communication networks are expected to become one of the fastest-growing industries in the high-tech fields of China. It is recommended that policies should be given to both theoretical research and application demonstrations to promote the high-quality development of space–ground cooperative network technology and industry.

In terms of theoretical research, it is recommended that the National Key R&D Program, the National Natural Science Foundation, and other channels reasonably add projects related to the space–ground cooperative network and focus on the development of related basic theories and engineering technologies to achieve an internationally leading position in this field. In terms of an application demonstration, it is recommended to carry out a special layout of an application demonstration for wide-area mobile communication scenarios such as navigation and aviation to significantly improve the level of informatization of the national economy, such as the marine industry, and to promote the industrialization of China's satellite network systems and terminal equipment, and ultimately improve the application level of satellite communication networks and value creation ability.

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