The Space-Terrestrial Integrated Network: An Overview

Haipeng Yao, Luyao Wang, Xiaodong Wang, Zhou Lu, and Yunjie Liu

With the technological advancement and convergence of satellite communications, the Internet, and mobile wireless networking, the STIN has been envisioned. In this article, we introduce a potential architecture of STIN that integrates the extended space network, the Internet, and mobile wireless networks to provide comprehensive services and global anytime anywhere network access.

Abstract

With the technological advancement and convergence of satellite communications, the Internet, and mobile wireless networking, the STIN has been envisioned. In this article, we introduce a potential architecture of STIN that integrates the extended space network, the Internet, and mobile wireless networks to provide comprehensive services and global anytime anywhere network access. The extended space network, being the most complex component of STIN, consists of the space-backbone of several GEO satellites, the terrestrial backbone of data centers and ground access nodes, and the space access network comprised of various satellites at different orbits and other space objects. We present a number of key technical challenges associated with STIN, including physical-layer transmission technologies, network protocols, routing, resource management, security, and test-bed development.

Introduction

Motivation

In the past several decades, the field of telecommunications has witnessed explosive growth in terms of technological advancement, which has a deep impact on many fronts of the human society. By and large, there are three major types of telecommunication infrastructures: satellite systems, the Internet, and mobile wireless systems such as cellular networks and local area networks. Since the launch of the first artificial satellite in 1957, the number of satellites orbiting the Earth has been rapidly increasing. One or several of these satellites form an autonomous system (AS) from other satellites to provide some specific services, such as telecommunications, surveillance, remote sensing, positioning, navigation, and so on. Across different satellite systems, real-time resource and information sharing is typically impossible. Moreover, many satellite systems cannot provide consistent coverage in large areas due to limited illuminating time and region.

On the ground, since its inception in 1969, the Internet has grown into a global network with worldwide coverage and is the main force that revolutionized the information technologies. Moreover, from the first-generation analog systems to the current fourth-generation and the future fifth-generation systems, mobile wireless communication networks have been through a series of major development involving upgrading and redesigning of system architectures, network protocols and transmission technologies.

Currently, mobile wireless networks are well integrated with the Internet. However, the various satellite systems on different earth obits are largely isolated, and they are also isolated from the ground networks such as the Internet and mobile wireless networks. On the other hand, human activities and scientific explorations have expanded to the remote and uninhibited part of the earth, the vast ocean, and deep space. Any one of the above-mentioned networks is not capable of providing such a large-scale coverage. In other words, anytime anywhere seamless access is not supported by current telecommunication networks.

With the continuous integration and expansion of cyberspace, an obvious yet ambitious goal is to integrate satellite networks, the Internet and mobile wireless networks into one network. Such an integrated network can provide comprehensive and efficient services through the collaboration of different subsystems and the utilization of multi-dimensional and multi-modal information.

Related Works

In recent years, the United States and Europe have proposed the Transformational Satellite Communications System [1] and the Integrated Space Infrastructure for Global Communication (ISICOM) [2], respectively, to connect existing isolated satellite systems. The objective of TSAT is to provide a secure communication system covering space, ground and ocean for the military. It is composed of three segments: the space segment, the ground-based management and operations segment, and the terminal segment. The space segment is the most important component, which includes a space backbone network consisting of five GEO satellites and ground gateways. TSAT is able to interconnect with other military communication systems.

Project ISICOM aims to construct an efficient, flexible and reconfigurable satellite infrastructure to provide ubiquitous and secure communications [2]. The architecture includes space and ground components, where the space component is comprised of three core GEO satellites and diverse flying nodes interconnected by optical inter node links, and the ground component contains fixed and relocatable gateways, on-ground relays, dis-

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Haipeng Yao is with Beijing Univ. of Posts and Telecom.; Luyao Wang, Yunjie Liu and Haipeng Yao are with Beijing Univ. of Technology; Xiaodong Wang is with Columbia University; Zhou Lu is with China Electronics Technology Group Corporation.

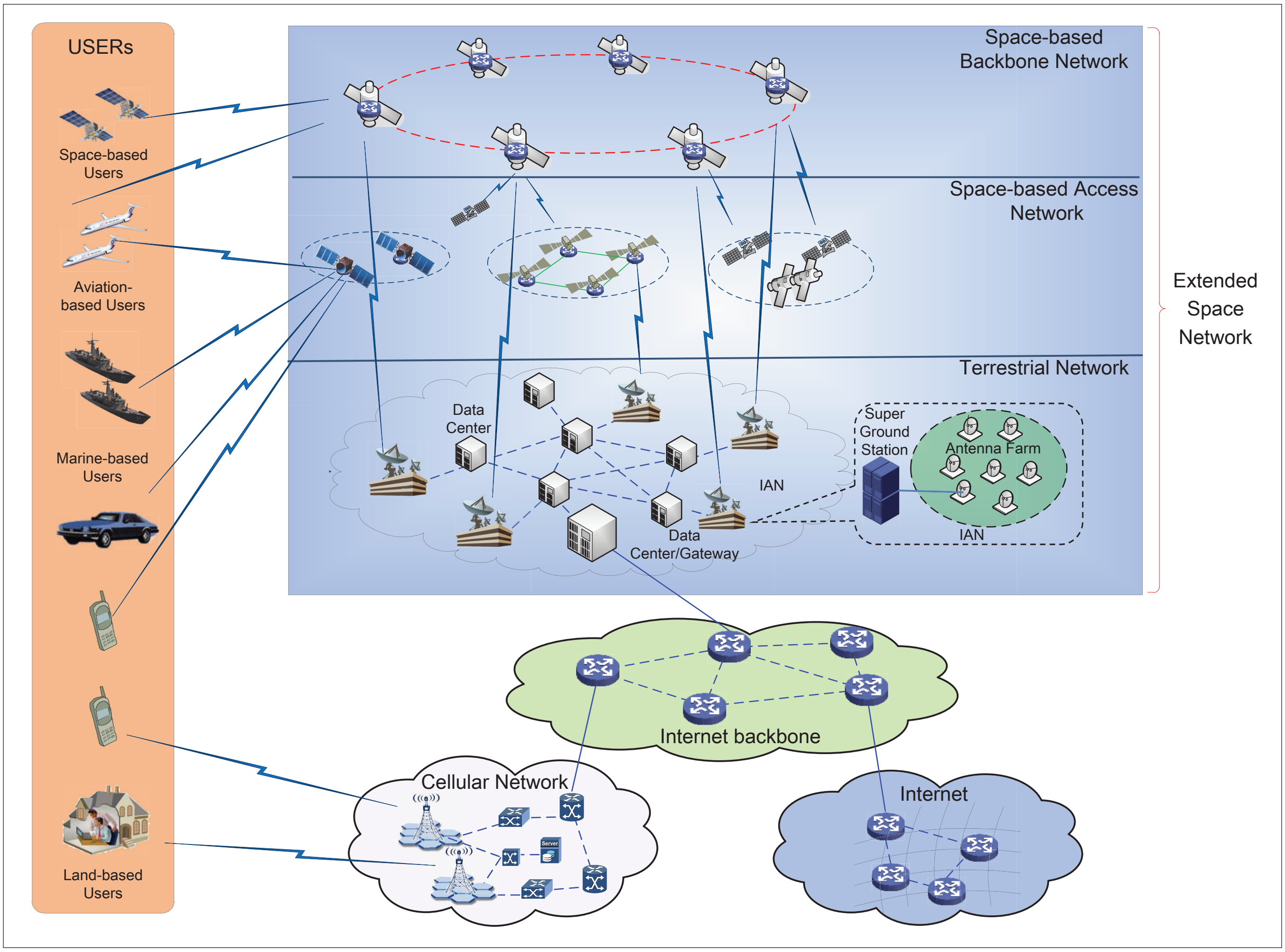

Figure 1. The architecture of the space-terrestrial integrated network (STIN).

tributed antenna systems and terminals. Similar to TSAT, ISICOM mainly focuses on integrating satellite systems rather than integrating all existing networks in space and on the ground.

Key Features of STIN

Recently China has initiated a key national research project for the development of a space-terrestrial integrated network (STIN) [3]. Different from TSAT and ISICOM, the goal of STIN is to integrate the space-based information network, future Internet and mobile wireless networks and serve as an infrastructure to provide global coverage and information support for a variety of types of services. It is a large-scale heterogeneous network with complex structure, high flexibility and dynamic topology. Moreover, as an essential part of STIN, various existing satellite systems are isolated, each providing specific services. How to abstract the heterogeneous large-scale STIN into a well-organized, scalable network architecture is a key challenge. Under this architecture, network components and inter-connections can be easily configured so that the network is able to adapt not only to the new telecommunication technologies but also emerging applications. In this article, we introduce a new STIN architecture with global network management and high system flexibility. Moreover, we also discuss some key research issues in this area. We summarize some of the distinct features of STIN as compared with TSAT [1] and ISICOM [2], as follows.

Integrated: Different from TSAT and ISICOM, STIN integrates the extended space network, the Internet and mobile wireless networks by using an innovative architecture and an IP-based protocol translation system.

Heterogeneous: Through the 'backbone-access' network architecture, STIN incorporates the various existing satellite systems in space, as well as networks on the ground. Thus, STIN is composed of a plethora of heterogeneous nodes, links and networks with diverse functionalities.

Efficient: The double-backbone structure consisting of a space-based backbone network (SBN) and a terrestrial network (TN), enables immediate data processing, data storage and real-time information sharing, which significantly reduces the transmission delay.

Intelligent: Thanks to the utilization of data centers, STIN is able to aggregate, store, analyze, process and distribute data. Hence, the system is transformed from a data transmission channel to an intelligent, content-aware network.

The remainder of this article is organized as follows. The following section introduces the architecture of the extended space network and discusses how to integrate it with the Internet and mobile wireless networks at both the physical and protocol levels. After that, several technical

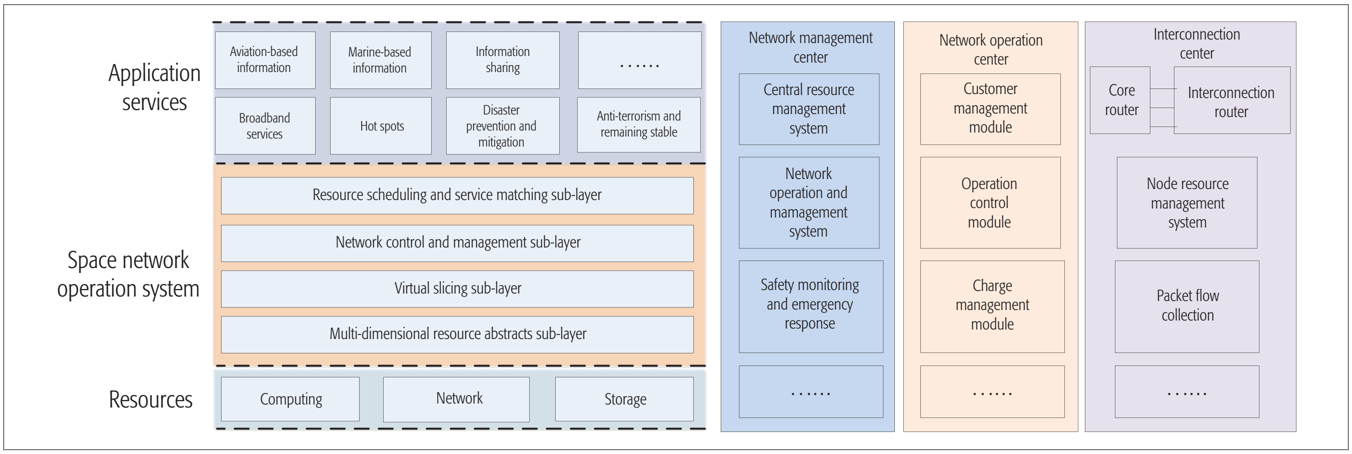

Figure 2. The inner structure of a terrestrial data center.

challenges including physical-layer technologies, routing algorithms, resource allocation methods, security mechanisms and test-bed design are discussed. The conclusion is presented in the final section.

Architecture

In this section, we introduce a potential architecture of the STIN. As we mentioned above, STIN integrates the extended space network, the Internet and mobile wireless networks where the extended space network is the most complex component. We first introduce the architecture of the extended space network as shown in Fig. 1, and then discuss how to integrate the three networks at the physical architecture level and the protocol level.

Extended Space Network

The extended space network aims to integrate all existing satellite systems and to provide various satellite services in a seamless way. Based on the architectures of the space segments of TSAT [1] and ISICOM [2], it is clear that having a core backbone helps extending coverage and ensuring reliable space-ground connectivity. Moreover, different existing satellite systems can connect to the backbone network to achieve integration. Thus as shown in Fig. 1, the extended space network adopts the "backbone-access" architecture and is composed of a space-based backbone network (SBN), a terrestrial network (TN) and a number of space-based access networks (SANs), where SBN and TN are considered as a "double-backbone." Different from other satellite systems like ISICOM [2], the extended space network contains a terrestrial backbone that can be considered as the extension of SBN, and thus the term 'extended' is used to distinguish from the conventional space network of satellites only.

Space-Based Backbone Network (SBN): As part of the double-backbone network, the SBN is comprised of several GEO satellites and the inter-satellite links (ISLs) connecting them. Although all GEO satellites have large coverages and high-speed space-terrestrial connections, it is worth mentioning that these GEO satellites have more powerful on-board computing capability and storage capacity than other GEO satellites. One or more GEO satellites in SBN can function as a data center with the capabilities of data storage, processing, routing and network management. Space-based data centers can process users' data immediately and therefore reduce the delay caused by space-terrestrial communication while reducing link load. For example, if a low-orbit satellite cannot establish a reliable communication link to the ground, it can send its data to a space-based data center that can process and forward its data to avoid the long delay caused by waiting for the next illuminating time.

Terrestrial Network (TN): The other part of the double-backbone network is the TN, which can be viewed as the extension of SBN to further process data given the limited power and processing capability of satellites. As shown in Fig. 1, the TN is formed through the interconnection of data centers via fiber optic links, and a number of integrated access nodes (IANs) are connected to data centers. In this structure, fiber connections provide low-cost high-speed transmissions. Data centers are responsible for data storage, data processing and network management. IANs are responsible for communicating with SBN as shown in Fig. 1. In order to support the increasing network scale, the large amount of data streaming and comprehensive services, the network needs to be capable of aggregating and processing data instead of only transmitting data. Thus, the TN is designed as a data center network. Figure 2 shows the inner architecture of a terrestrial data center that contains not only network operation and management components but also an interconnection center that is responsible for connecting with the Internet backbone. The main components of an IAN consist of an antenna farm and a super ground station. These nodes are called "integrated" because the antenna farm collects all types of radio signals in all spectrum bands from different satellites in different orbits. Moreover, the super ground station is able to demodulate all received signals by using a large-scale programmable digital signal processing array, resource pooling and virtualization technologies. The functionalities of the IANs mainly include signal reception, fast signal pre-processing and forwarding packets to data centers for further analysis and real-time sharing.

Space-Based Access Networks (SANs): As shown in Fig. 1, SANs contain existing dedicated satellite systems that provide specific services serving as subsystems in the extended space network. Note that within each such subsystem, a custom designed physical link transmission technique and protocol can be employed. Each subsystem can communicate with the SBN via ISLs or directly communicate with the TN. This connection diversity helps achieve real-time communication between subsystems and facilitates the integration of various satellite resources.

We have introduced the three main components of the extended space network. As noted earlier, in contrast to "peer-to-peer," the "backbone-access" architecture is more suitable for integrating existing space networks. Between the two backbone networks, nodes in SBN and TN are connected by reliable high-speed space-terrestrial links, for example, microwave or laser channels. SANs can use ISLs to access the SBN or satellite-terrestrial links to access the TN.

Physical Integration Architecture

The requirements of global coverage and anywhere anytime access for space, ocean and ground users motivate the research and development of the STIN. Next, we will introduce the architecture for interconnecting the extended space network, the Internet and mobile wireless networks to achieve the effective integration of these heterogeneous networks while reducing any possible negative impacts.

The STIN is highly complex because different components with various nodes, links and functions are distinct in network scale and various other properties. Thus, in the design of physical STIN architecture, the interconnection schemes and the corresponding overall system architecture will have a great impact on different performance aspects of the global network. For instance, if any space node is allowed to directly communicate with the Internet and initiate routing, the highly dynamic space network topology will cause routing oscillation in the Internet backbone, which will in turn lead to system instability.

While the main goal is to achieve integration of space and terrestrial networks, proper insulation of system components is important. Considering the interconnection schemes for hybrid networks on the ground, both mobile wireless networks and Internet access networks are connected to the Internet backbone via gateways for low-cost high-speed packet routing. In order to effectively integrate the extended space network with existing terrestrial networks, a potential solution is to connect some of the data centers that also function as gateways to the Internet backbone as shown in Fig. 1. A main reason for this design is that both the TN and the Internet backbone are interconnected by high speed fiber, and therefore it is convenient to connect the two networks directly. Moreover, data centers are responsible for data storage and processing, and hence it is natural to designate them to exchange information with other networks. Direct communications between satellites and the Internet backbone are forbidden to avoid routing oscillation. In this architecture, the extended space network can be considered as an independent system to provide various non-ground services to users and the extension or enhancement to the ground network to increase the coverage range and improve the service quality.

Integration Protocol

Based on the physical integration architecture discussed above, nodes that belong to different networks need a communication protocol to exchange information without having to know the detailed transmission mechanism at the physical layer. In other words, we need to interconnect the different components of the STIN at the network layer. Due to the high complexity and heterogeneity of STIN, a universal protocol that enables cross-network data transmission, though highly desirable, becomes a major challenge.

To facilitate information sharing among different satellites and strengthen the interconnectivity among different systems, the CCSDS protocol system is designed for space links with long transmission distance, highly dynamic nodes, time-varying connections and intermittent communications [4]. It follows the layered structure of Open System Interconnect (OSI).

Given the distinct architectures of the extended space network, the Internet and mobile wireless networks, they employ different protocols. Before a universal protocol can be developed and adopted, one potential solution is to translate protocols at gateways to interconnect different networks. The objective is to enable packet transmission across different types of networks at low cost. The design is based on the IP technique and follows the layered structure to simplify the translation process. An interconnection example is shown in Fig. 3 where IP over CCSDS provides the support for IP addresses in space networks. For example, a user on an ocean liner intends to communicate with a user in the land mobile network. The source user first communicates with a GEO satellite by translating its protocol from TCP/IP to CCSDS at its gateway. Then the satellite will relay its packet to an IAN in the terrestrial network where the protocol is translated from CCSDS to TCP/IP. The packet is then relayed by the Internet backbone and nodes in the mobile network to the destination user. Note that such a sequence of protocol translations, although straightforward, is not efficient. Hence it is of great interest to design a universal protocol for efficient packet transmission over different components of the STIN. We envision that this protocol may maintain the layered structure but with different naming rules, addressing methods and routing algorithms, and can be based on new network and protocol architectures such as Multi path TCP (MPTCP) and Information Centric Networking(ICN) as discussed in [5].

Technical Challenges of STIN

In this section we discuss a number of technical challenges associated with STIN, including physical-layer techniques, routing, resource management, security, and testbed development.

Physical-Layer Techniques

Given the heterogeneity of STIN, efficient physical-layer transmission techniques are essential in maintaining high-speed links between different subsystems. In particular, we mention the following techniques.

In contrast to "peer-to-peer," the "backbone-access" architecture is more suitable for integrating existing space networks. Between the two backbone networks, nodes in SBN and TN are connected by reliable high-speed space-terrestrial links, for example, microwave or laser channels. SANs can use ISLs to access the SBN or satellite-terrestrial links to access TN.

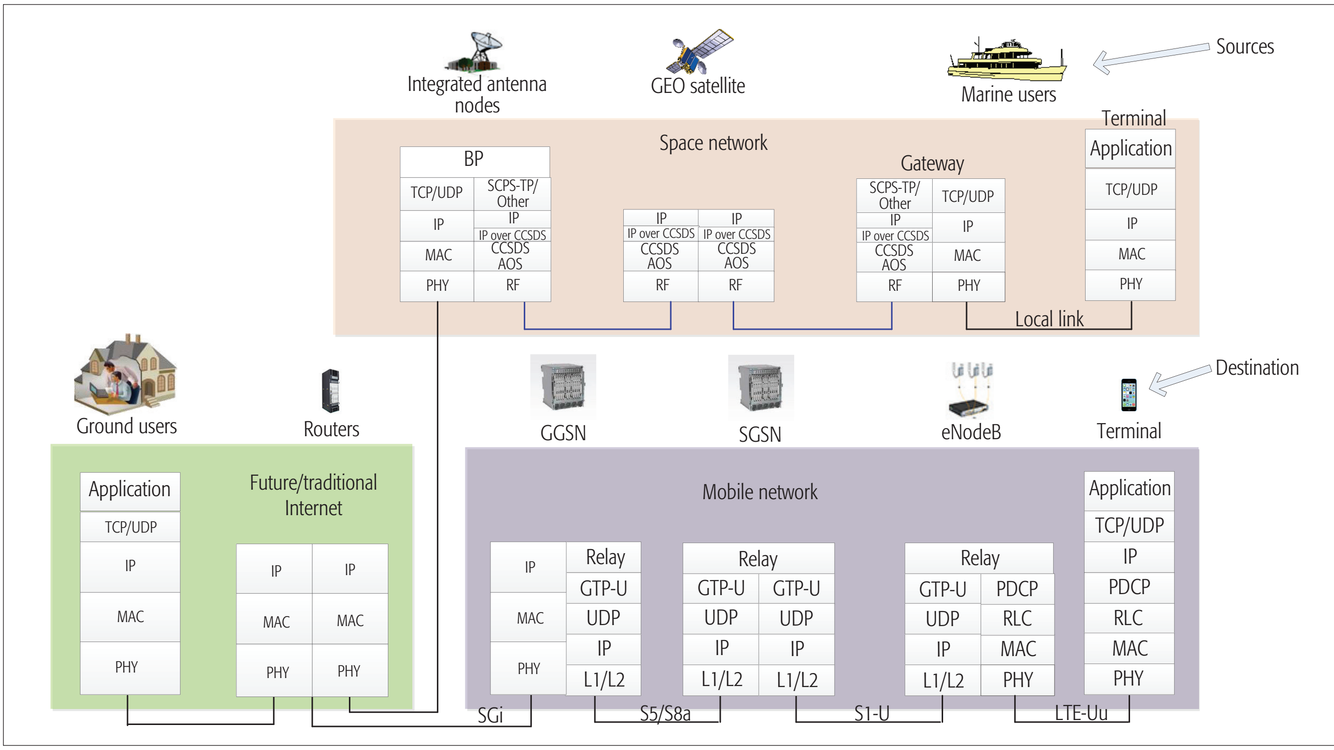

Figure 3. An interconnection example of protocol translating system.

Laser Communication: From the description above, we can roughly categorize communication links in the extended space network into ISLs and space-terrestrial links. The most widely used frequency spectrum for satellite communications is in the microwave band, for example, C band (4–8 GHz), Ku band (10–18 GHz) and Ka band (18–31 GHz) [6]. An alternative communication medium is laser, which can be used in both ground-to-satellite links [7] and ISLs in, for example, ISICOM [2]. Compared to microwave, laser communication has the advantages of high bandwidth, short alignment time, high security and high anti-interference capability. However, when laser is used in space-terrestrial links, weather conditions can significantly affect the communication quality. Furthermore, given the narrow beam of laser and high orbiting speed of satellites, the positions of satellites need to be precisely tracked to successfully establish laser ISLs. ISLs over other frequency bands, for example, millimeter wave band, can also be investigated.

Multi-Beam Satellites: Advanced antenna techniques for satellite communications are of great importance. Multi-beam satellites are common in space networks thanks to the high power density, high data rates and frequency multiplexing [8]. With multi-beam antennas, a satellite can serve a large number of users in its coverage area simultaneously. In order to reduce energy consumption and flexibly control the number and shape of beams to satisfy integrated services in STIN, combining large-scale phased array antennas with multi-beam satellites is a possible solution.

Relay: Relay plays an important role in satellite communications. For example, as discussed above, SBN can forward packets from SANs to TNs. In other words, satellites in SBN can serve as relay nodes for other nodes in the extended space network. Moreover, the complex network topology provides multiple possible relaying paths with different link states, transmission rates, transmission power and MAC layer mechanisms. Cognitive techniques should be developed that can effectively exploit such relay diversity in the network by adaptively identifying the best transmission links, as discussed in [9]. For instance, given that the spectrum resources are dynamically changing, cognitive radio techniques can be used to sense the vacant frequencies and enable quick responses. Relay diversity brings better load balancing and higher utilization of network resources.

Other techniques such as the powerful Multiple-Input Multiple-Output (MIMO) communication technology that has been developed for cellular wireless communications can be adopted on satellites to boost the data rate and system reliability [10]. Moreover, considering the ubiquitous storage capabilities in STIN such as data centers in SBN and TN, how to efficiently design distributed storage systems to achieve the best trade-off among communications, computing and caching for STIN is yet another interesting research direction.

Integrated Network Routing

Considering the high heterogeneity and high complexity of STIN, designing an efficient routing mechanism is a key challenge to enable packet transmission across different network components. The time-varying topology of the space network necessitates frequent update of the routing strategy, and if not properly designed it may lead to routing oscillation in ground networks. Moreover, given the large network scale, the resulting large routing table requires large storage and high computing power on space and ground routers.

For the Internet, the concept of an Autonomous System (AS) [11] was introduced to reduce

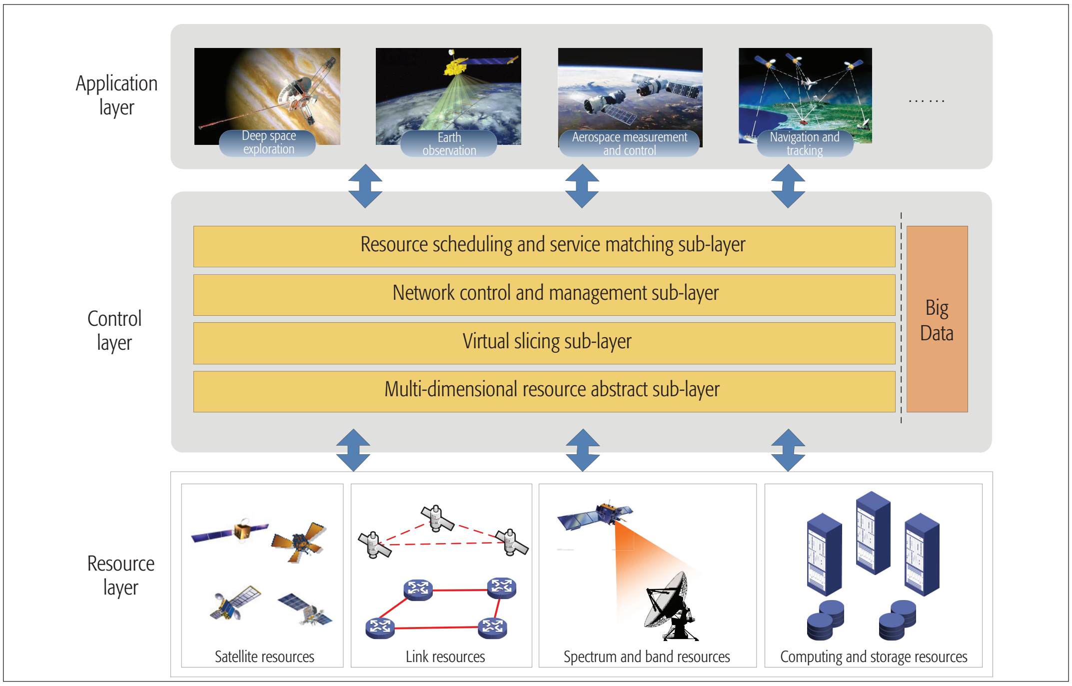

Figure 4. The logical architecture of SNOS.

the complexity of the network structure and simplify network management. Any local topology update information and local routing tables are constrained within each AS. Due to the heterogeneity of STIN, introducing ASs in the space network is a potential approach to routing where SBN and TN are static ASs, and each SAN is a dynamic AS. Within each AS, certain private routing protocol can be employed. Thus, the complex STIN routing problem is simplified into a routing problem among ASs. However, we are still faced with the following challenges.

In a dynamic AS, the time-varying topology makes it hard to maintain the mapping relationship between physical nodes and routing addresses, which leads to packet losses and severe delays. To avoid this problem, link states, satellite positions and orbits, as well as illuminating duration, have to be taken into account in designing routing algorithms. Therefore, the dynamic routing problem can be considered as a real-time cross-layer optimization. We outline the following two possible solutions:

- Given that the terrestrial network has more computing power and storage capacity compared to the space network, a possible routing management method is to let the terrestrial network compute the routing table and then distribute it to the space nodes. Space data centers in SBN are responsible for collecting topology information of the space nodes and then passing it to the terrestrial network for routing calculation. On the other hand, they also receive the computed routing table from the TN and forward it to the space nodes.
- Another possible solution is to introduce the concept of software defined network (SDN) [12] to help increase the efficiency of routing management thanks to the separation of control and data transmission. However, conventional SDN routing algorithms are designed for fixed topologies and they cannot be directly applied to networks with changing topologies. Thus dynamic SDN routing algorithms need to be developed. Moreover, given the large network scale and the heterogeneous structure of different components, distributed routing is of great interest.

Resource Integration and Management

Given the new network architecture, efficient integration and management of the heterogeneous resources in STIN is another challenge. In the recent development of resource management schemes for the Internet, the concept of a network operation system (NOS) has attracted significant attention. NOS is an operating system designed for the purpose of sharing resources and applications among multiple nodes in a network. The Open Network Operating System (ONOS) project aims to create an open source SDN operating system for service providers to make it easier to create network services and applications thanks to its scalability, high availability, high performance and abstraction capability [13].

Inspired by the development of NOS, we introduce the space network operating system (SNOS) for the extended space network to achieve effective resource integration and management. Its logical architecture is shown in Fig. 4, which contains four sub-layers: multi-dimensional resource abstraction, virtual network slicing, network control and management and resource mapping. To further improve service performance and network intelligence, we anticipate that various big-data tools can be employed in SNOS to optimize the system.

One of the main functions of NOS is to abstract the diverse physical network elements, such as switches and links. Through this abstraction, the network controller can manage and control the network without having to know the

> The effective design of dynamic resource virtualization for such time-varying networks is key to resource integration. Moreover, real-time topology and resource detection, topology prediction and global view generation are essential technologies to ensure the satisfactory performance of resource management.

Given the high complexity and highly dynamic nature of the extended space network component of the STIN, system evaluations cannot be performed by software simulations alone, nor by isolatedly testing of various system components. Rather, a dedicated and scalable testing network infrastructure needs to be built to perform various integration.

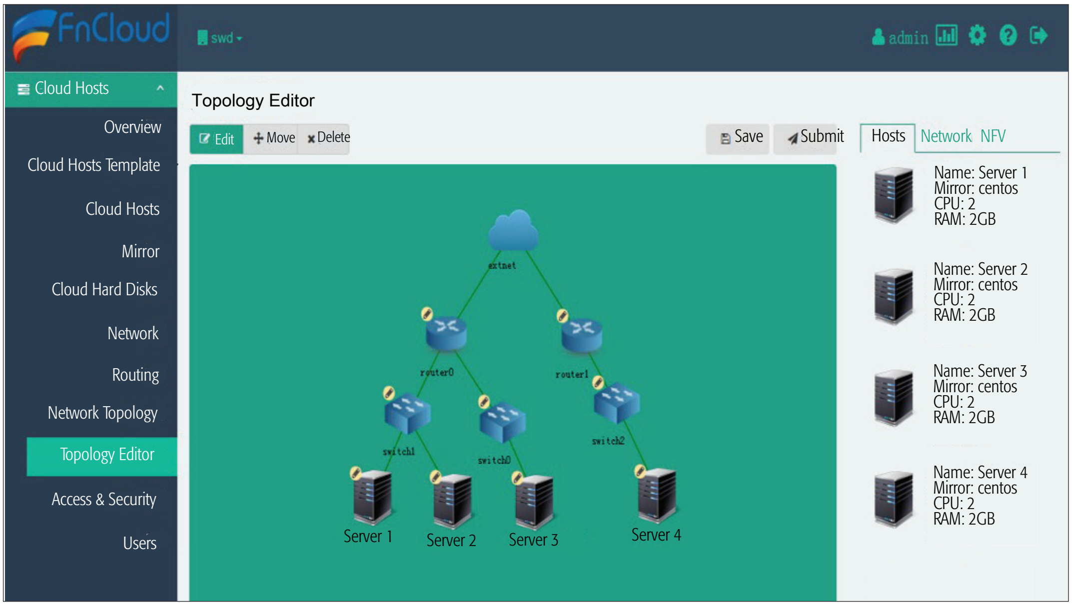

Figure 5. Operation of the control platform for TN.

specifics of the physical devices. This process is called resource virtualization. However, in contrast to NOS, which operates on networks with fixed topologies, SNOS will operate on networks with topologies that change over both time and space. Thus, the effective design of dynamic resource virtualization for such time-varying networks is key to resource integration. Moreover, real-time topology and resource detection, topology prediction and global view generation are essential technologies to ensure the satisfactory performance of resource management.

Integrated Network Security

Due to the diverse types of nodes in STIN, designing a proper management mechanism of attestation identity keys and session keys for different security areas with different functions is an important issue. Typical approaches include unicast and multicast communication key management [14]. Unicast aims to improve key management efficiency through the generation, distribution, storage, update, cancellation, destruction and negotiation of the key. Multicast aims to maintain the communication key for legal group members so that the information is only shared within the group when multicasting is enabled in STIN.

Considering the dynamic topology of the space network, centralized key management may lead to information blockage. Thus, a distributed key management mechanism is more suitable for STIN. Moreover, the distributed key computing mechanism is also preferable thanks to the ubiquitous computing resources in STIN. To resolve the key negotiation failure caused by the long delay in space-ground communications, the definition of a public key can be based on any local data string, for example, an IP or MAC address, rather than through information exchange in the network. In order to improve the performance of multicast key management, several dynamic nodes can be considered as a service group to assist generating the multicast key and avoid the problem caused by one node failure while achieving load balance.

Experimental Verification and Testing

The development of STIN consists of both theoretical research and system implementations. Given the high complexity and highly dynamic nature of the extended space network component of the STIN, system evaluations cannot be performed by software simulations alone, nor by isolatedly testing of various system components. Rather, a dedicated and scalable testing network infrastructure needs to be built to perform various integration. Moreover, considering the new architecture and innovative technologies used in STIN, designing a new testing environment and a set of evaluation techniques with demonstrations for typical applications will support the verification of various system design objectives. Specifically, the test-bed should include the following components.

Protocol and Equipment Testing Merit System: For different equipment and protocols, the corresponding testing merits need to be proposed for the evaluation of functionalities, information consistency and network performance. Note that the different subsystems of STIN have different performance criteria, for example, long delay in satellite systems versus short delay in terrestrial networks. Hence the selection of proper metrics to measure the performance of STIN is another interesting research topic.

Experimental Verification and Testing Methods: For all STIN components, specify the testing requirements and design the experiments.

Software Simulation Platform and Integrated Testing System: Considering the high cost of implementation, developing software simulation systems is necessary. For example, based on the structure of virtual private clouds (VPC), we have developed a control platform for the terrestrial network to optimize resource management among data centers. It supports the generation of virtual networks across data centers, and provides secure access to each virtual network. This platform can allocate virtualized computing and storage resources to different applications. The operation interface of the control platform is shown in Fig. 5.

Open Demonstration System: Based on the infrastructure of the Internet and mobile wireless networks, by using the existing satellites or newly launched spacecrafts and other platforms, construct an open demonstration system. For instance, a nationwide future network test-bed is being built in China that connects 40 cities and 111 edge networks using high-speed fiber and includes four cloud data centers, as shown in Fig. 6. This network can be used to experiment the innovative architectures, technologies, and applications in the terrestrial network.

Conclusions

We have introduced an architecture for the space-terrestrial integrated network (STIN), a large-scale heterogeneous network composed of the extended space network, the Internet and mobile wireless networks. The extended space network consists of the space-backbone of several GEO satellites, the terrestrial backbone of data centers and ground access nodes, and the space access network comprised of various satellites at different orbits and other space objects. We have discussed a number of key technical challenges associated with STIN. Meeting these challenges requires both innovative fundamental research on many fronts and extensive system-level sophisticated simulations and experimentations.

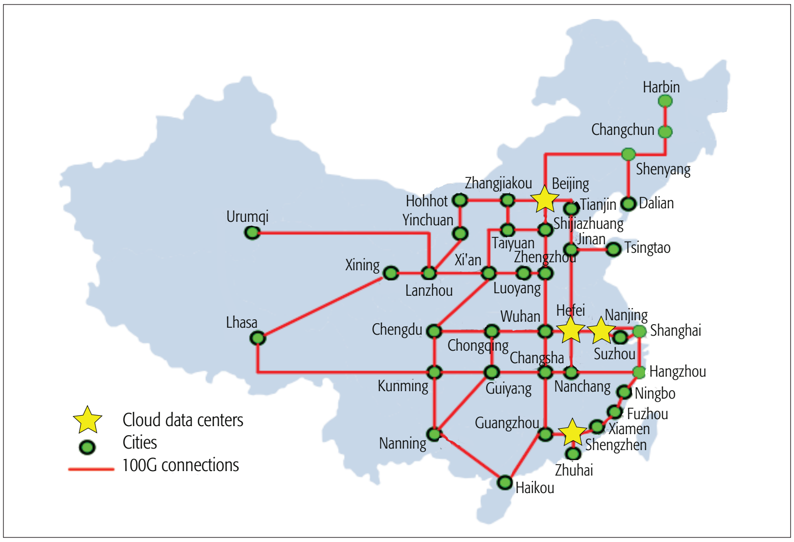

Figure 6. The architecture of China's future network test-bed.

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Biographies

Haipeng Yao is an associate professor with the School of Information and Communication Engineering, from the State Key Laboratory of Networking and Switching Technology in Beijing University of Posts and Telecommunications. His main research interests include future network architecture, big data for networking, and the architecture and key technology of the new-generation mobile communication systems.

Luyao Wang received the Ph.D. degree from the University of Wollongong, Australia. She is a lecturer with the Beijing Advanced Innovation Center for Future Internet Technology in Beijing University of Technology. Her current research areas include scheduling and routing algorithms for wireless mesh networks, architecture design and resource allocation algorithms for space-terrestrial integrated networks.

Xiaodong Wang received the Ph.D. degree in electrical engineering from Princeton University. He is a professor of electrical engineering at Columbia University in New York. His research interests are in the general areas of computing, signal processing and communications, and he has published extensively in these areas. He is a Fellow of the IEEE and an ISI highly-cited author.

Zhou Lu is a researcher and the Director of the Institute of Space-based Information Systems at the China Academy of Electronics and Information Technology. His main research interests include broadband satellite communications and space-based satellite networks. He has won several National Science and Technology Progress Awards and obtained several national invention patents.

Yunjie Liu received his B.S degree in technical physics from Peking University in 1968. He is currently an academician at the China Academy of Engineering, the chief of the Science and Technology Committee of China Unicom, and the Dean of the School of Information and Communications at Beijing University of Posts and Telecommunications. His current research interests include next generation networks, network architecture and management.