IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 24, 2020, accepted March 27, 2020, date of publication March 31, 2020, date of current version April 16, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2984485

A Shared Satellite Ground Station Using User-Oriented Virtualization Technology

YANDU LIU, YUDI CHEN, YIWEN JIAO, HONG MA, AND TAO WU
Department of Electronic and Optical Engineering, Space Engineering University, Beijing 101400, China

Corresponding author: Yudi Chen (chenyudi9438@163.com)

This work was supported by the Beijing Science and Technology Major Project of China under Grant Z181104002900000.

ABSTRACT With the development of space missions, the increasing communication data volume, the diversity of mission-specific interfaces, and the growing security needs, the costs and system complexity of ground stations have increased. The architecture of the existing ground terminal is outdated and the operation and maintenance are labor-intensive, so the terminal components are unable to meet the demand of multi-satellite TT&C in the future. In this paper, a Shared Satellite Ground Station(SSGS) using user-oriented virtualization technology is proposed for coping with complex multi-satellite TT&C in the future. Based on a pool architecture, SSGS utilizes baseband processor virtualization and software-defined networking to implement resource sharing and a network that fuses high-speed and low-speed data streams with customization control. The case analysis verifies that when SSGS has a virtualization rate greater than 1, the execution rate of tasks is much larger than that of traditional ground stations. The case analysis also verifies that the virtualization rate of current commercial equipment is no less than 1.25 through equipment testing.

INDEX TERMS Satellite ground station, baseband processor virtualization, software-defined network, TT&C.

I. INTRODUCTION

Ground stations are used for receiving payload data and Spacecraft telemetry, tracking, and command (TT&C). Traditional ground station networks generally belong to the government or the military, e.g.NASA's STDN (Spaceflight Tracking and Data Network), the United States' AFSCN (Air Force Satellite Control Network) and ESA's ESTRACK. Whereas with the development of civil and commercial aerospace, e.g. Space Imaging, Orbital Space Imaging, OneWeb and Planet Labs, more space launch missions and satellites in orbit have brought considerable challenges to ground stations, i.e. it is difficult for traditional ground station networks to provide flexible services for numerous commercial satellites. The contradiction between limited ground stations and the increasing demand has become increasingly prominent. Hence, the development of commercial ground stations becomes an inevitable trend [1], [2].

Civil and commercial ground station networks distributed around the world came into being. GENSO (Global Educational Network for Satellite Operations) is a network of university and amateur ground stations managed by ESA., which accommodates numerous ground stations and improves educational spacecraft communication[3]. NASA, JPL and the Center for EUV Astrophysics have evaluated a commercially available ground station for telemetry reception, processing, and routing of data over a commercial, secure data line[4]. SSC (Swedish Space Corporation)'s PrioraNet is a global ground station network consisting of a network management center, SSC's core stations, and cooperative stations all over the world. It provides reliable mission management, TT&C (Tracking, Telemetry and Command) and payload data reception for the global satellites. KKS(Kongsberg Satellite Services)'s ground station network is composed of TNOC (Trom's network operations center) and four ground stations, which mainly provides services for polar-orbiting satellites. Reference [5] proposed a modular ground station used to support nanosatellites and microsatellites. The literature adopts a flexible and layered method to establish the ground station network, which is suitable for multiple satellites and allows more frequency bands and missions to be added.

Many kinds of research on the commercialization and flexibility of ground stations have been carried out. Reference

The associate editor coordinating the review of this manuscript and approving it for publication was Rosario Pecora.

[6] proposed and verified the application of GPU-accelerated demodulation of high-speed signals within software-defined radios to satellite ground stations. Reference [7] proposed a ground station based on an adaptive polarization SDR platform, which supports uplink and downlink from 1GHz to 6GHz. Reference [8] used SDR to implement a ground station receiver with multi-channel reception, flexible data rates, and flexible modulation types, and can eliminate CCI (co-channel interference). Reference [9] proposed to use modular software and hardware to establish a full-featured ground station for NanoSat, so that the system can be easily modified and upgraded to meet the needs of future missions. Reference [10] contributed to the improvement of the ground station network from three aspects: low-cost ground station network scheduling, satellite downlink data synchronization, and ground station network data management. References [11] and [12] demonstrated that a highly distributed network of ground stations offers new opportunities for the operation of distributed satellite systems.

Moreover, to improve support for small satellites, some researches on resource virtualization and resource sharing of ground station network have been carried out. Reference [13] introduces the concept of virtual satellite ground station and its potential application with a short case, where the core of the virtualization architecture is software-defined networking, while two basic aspects of the network were described in [14]: Resource Management & Routing and Networking. According to [15], the virtualization layer is intended to facilitate sharing resources by ground stations service providers and provide low-level network access to the antenna system. Reference [16] proposed a total station computing environment (TSCE), providing a unified general computing environment for the entire ground station network. It is also mentioned in [17], [18] that cloud computing reduces the cost of ground station network deployment and implementation.

With the development of space missions, the increasing communication data volume, the diversity of mission-specific interfaces, and the increasing security requirements have increased ground station costs and system complexity. The existing ground station equipment is out of date, and the cost of maintenance, operation, maintenance, and reconstruction is getting higher and higher. Restrictions on hardware, software, and firmware pose significant risks to system reliability. In addition, since the architecture of the ground terminal is outdated and the operation and maintenance are labor-intensive, so the terminal components cannot meet the future demand for extended functions.

This paper proposes a shared satellite ground station(SSGS) using user-oriented virtualization technology. SSGS is based on a pool architecture and utilizes baseband processor virtualization and software-defined network technologies. Hence, SSGS implements resource sharing and reducing overall costs and possesses the ability to cope with complex multi-satellite TT&C in the future, which is also easier to expand, upgrade and maintain. The main contributions of this paper can be summarized as follows.

- A pool architecture for establishing SSGS is proposed, where SSGS is divided into six functional domains: RF link, signal processing, service gateway, system management, task scheduling, and infrastructure. By comparison with traditional ground stations, the advantages of the architecture proposed in this article are summarized.
- It is proposed to use baseband processor virtualization to isolate TT & C applications from the physical platform, efficiently and securely promote the sharing of ground station equipment. By this method, the owner of the ground station system reduces the number of equipment, increases the hardware utilization rate, and reduces capital and operating expenses.
- Software-defined networking technology is used to implement a network that fuses high-speed and low-speed data streams. The article proposes a controller that uses the OpenFlow protocol. This controller replaces traditional routing equipment and implements network customization. control.

The remainder of this paper is organized as follows. In Section II, we define the SSGS, summarize goals of SSGS, introduce the architecture and operational process of SSGS and summarize the advantages of SSGS by contrast with conventional ground stations. Virtualizing the baseband processor is described in detail in Section III. Section IV shows the application of software-defined networking to SSGS and Section V shows a case analysis. Finally, the conclusion is drawn in Section VI.

II. PRELIMINARIES

In this section, the basic definition of Shared Satellite Ground Station is first given. Then, we summarize the goals and operational process of SSGS. Finally, the architecture of SSGS is proposed to achieve the goals above and based on the contrast to conventional ground stations, the advantages of SSGS are summarized.

A. BASIC DEFINITION

SSGS is a ground station using user-oriented virtualization technology, Which uses pool architecture and baseband processor virtualization to realize resource sharing, and uses software-defined networking to achieve a network that fuses high-speed and low-speed data streams.

B. GOALS OF SSGS

The goal of sharing is to maximize resource utilization. The concept of satellite ground station virtualization is to separate the ownership of the ground station from its operation with appropriate abstraction, where the originally fixed relationship between the user and the ground station is broken, and the efficiency of the ground station is improved. Its main goals can be described as:

① Realize flexible and scalable ground terminal architecture to meet all kinds of users:

- Adopt mature technology to realize the architecture of the ground station
- Simplify the expansion process to support more spacecraft
- Expand and improve equipment functions so that users can execute satellite TT&C more flexibly.
- Deploy equipment of the same type at all ground stations
- Increase user data throughput and data rate
- Promote the integration of terminals into the integrated world information network

② Be capable of covering existing ground station functions

- Be capable of monitoring and controlling the status of spacecraft and ground equipment
- Send and receive TT&C signals
- Implement TT&C scheduling and management
- Support the access of old versions of the monitoring system
- Provide positioning and timing services for spacecraft
- Provide analysis tools for spacecraft fault diagnosis
- Provide built-in testing and simulation functions

③ Reduce life cycle cost

- Replace the outdated system
- Make full use of off-the-shelf products
- Realize the routine maintenance of the system through redundant design and simple function matching
- Maximize Operation and Maintenance Personnel Efficiency

④ Enhance the continuity of conventional ground stations

⑤ Integrate into conventional ground stations, which can gradually replace existing systems after passing offline tests

C. ARCHITECTURE OF SSGS

Satellite ground stations provide tracking, telemetry, and control services for spacecraft, and are capable of receiving scientific data from satellites. Both conventional ground stations and SSGS can implement the functions mentioned above, but their architectures differ entirely.

As shown in Fig. 1, the basic functions of conventional ground stations can be abstracted into signal receiving and sending, signal processing, data format conversion and distribution, ground station management. The modulated signals are sent and received through the RF link, while the tracking information and telemetry information are obtained through down-conversion, filtering, demodulation, etc. At the same time, the scientific data obtained from the spacecraft are also transmitted back to the ground through a similar process. In Fig. 1, the upper link is used to transmit Satellite TT&C signals, while the lower link is used to receive payload data.

It can be seen from Fig. 2 that current conventional ground stations use a chimney architecture. Although a redundant set of equipment can be deployed in a ground station, it cannot support other spacecraft with different signal systems. It means that the same user also needs to use two sets of equipment to receive the spacecraft's TT&C signals and operate the spacecraft. This architecture limits the flexibility of ground stations and increases the amount of equipment required for each ground terminal, as each spacecraft requires its own set of primary and redundant ground equipment.

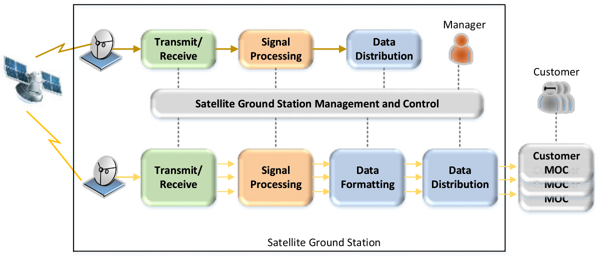


FIGURE 1. Basic functions of conventional ground stations.

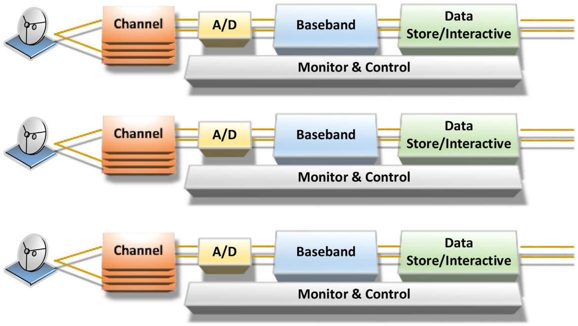


FIGURE 2. Chimney architecture of conventional ground stations.

In traditional ground station networks, multiple facilities are usually deployed in a ground station, and each performs independent tasks. Each set of equipment includes channel equipment, multifunctional digital baseband, time-frequency division system, and monitoring subsystem. There is no mechanism of equipment sharing between multiple sets of systems, and hardware resources in-ground stations are not fully utilized. The design of SSGS breaks the traditional tree architecture and redefines the sharing mechanism between the user and the ground station resource.

SSGS uses a flexible pool architecture without setting special equipment for a specific spacecraft mission. The device supporting TT&C consists of idle resources in the resource pool, which will be returned to the resource pool for the next task when the current task ends. As shown in Fig. 3, SSGS consists of six independent functional domains, including RF link, signal processing, service gateway, system management, task scheduling, and Infrastructure.

① RF Link

RF Link provides the physical connection between satellites and SSGS and implements the digitization of the analog signal. The RF Link carries payload data and TT&C signals, which includes up/down converter and implements the conversion of IF and RF. The module includes an antenna system, where because of the low data rate, the small aperture antenna can be selected, such as flat antenna, eccentric feed paraboloid antenna, reflection array antenna, etc. The RF

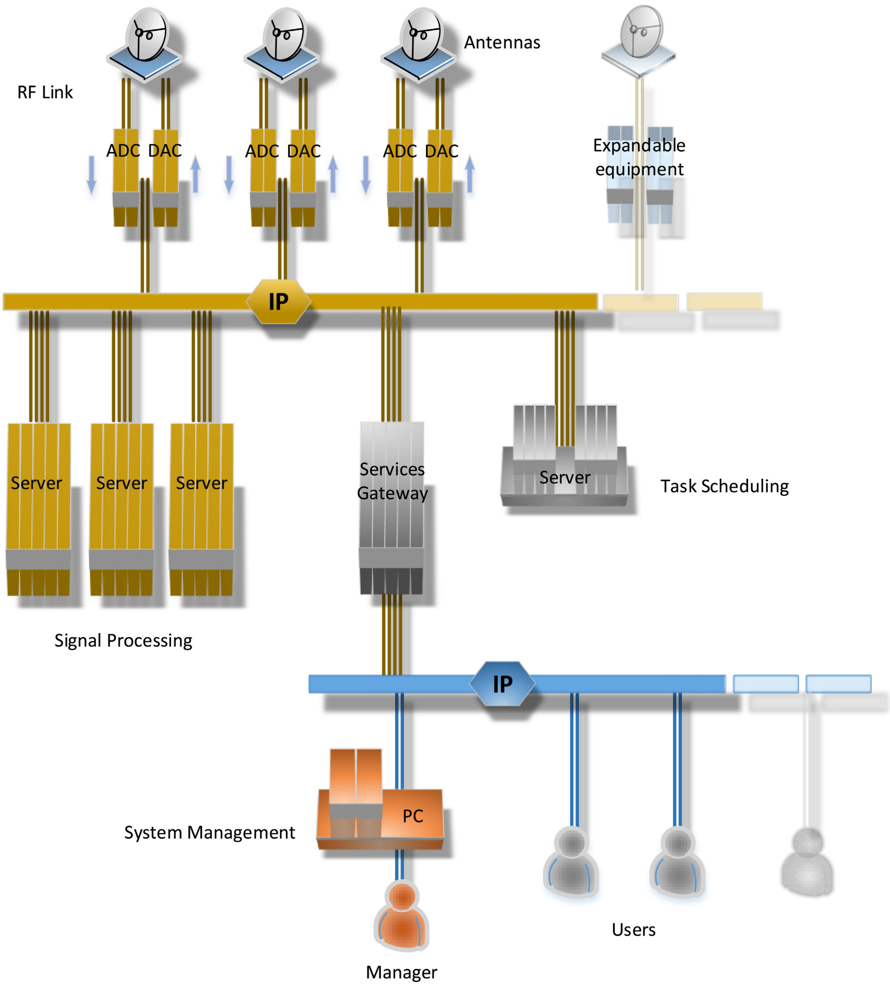


FIGURE 3. Architecture of SSGS.

Link also includes a time-frequency synchronization module, which can provide accurate time and frequency reference.

② Signal Processing

Signal Processing provides services required for processing digital signals, which is implemented as a pooled server group. The computing resource pool can generate an inventory for configuration according to the virtual device generated by the task scheduling, automatically analyze task parameters, and configure idle computing resources and storage resources as a baseband signal processor.

The virtualization technology of the signal processor is the soul of SSGS. With the virtualization of physical equipment, the functions of the ground station can be flexibly expanded, and the equipment performance, functions, and quantity can be flexibly defined. Therefore, the equipment of the ground station can be shared and reused, and the utilization rate of the infrastructure is maximized.

③ Service Gateway

Service Gateway is the information center of SSGS. It provides a TT&C service interface for users according to registered users' type. According to users' demand, the demand list is generated in the form of the XML file and submitted to the task scheduling system. After the satellite is tracked successfully and the signal is demodulated correctly, software-defined networking is used to automatically sort and transmit users' data. At the same time, Service Gateway stores available databases such as user information, usage records, parameter information, and data information.

④ System Management

SSGS ought to be based on digital reception and distribution at the front end of the system, and based on efficient network interconnection and system management. System Management implements status monitoring and health management, which is a modular software that provides a remote interface and local operation interface for administrators to monitor system operation. Furthermore, the data flow of the System Management is isolated from the payload data. System Management is also capable of monitoring network data traffic, the number of virtual devices, and resource pool load in real-time, locating faulty devices quickly and switching backups to a certain extent automatically.

⑤ Task Scheduling

Whether it is a conventional TT&C device or a virtualized TT&C device, when a satellite transits, it is a point-to-point communication process. Therefore, there is always a contradiction between the availability of ground equipment and the TT&C task. In order to improve the efficiency of equipment use, many scholars have studied dynamic and real-time resource scheduling algorithms in response to this problem. In traditional ground stations, the number of physical antennas and signal processors are fixed. However, in SSGS, the signal processor is generated through virtualization technology, and the number is elastically variable. Therefore, it brings great flexibility to task scheduling, and at the same time further improves the utilization rate of the equipment. The task scheduling functional domain is composed of parallel computing software of a certain size. It receives TT&C demands from the service gateway according to the task priority and generates task schedules and virtual device generation and parameter configuration lists based on information such as spacecraft orbits and station geography. Task scheduling always keeps the information (knowledge) of the equipment available in the resource pool updated, and is able to schedule emergency requests automatically or manually. At the same time, task scheduling also reports users' accounting data in order to commercialize the system.

⑥ Infrastructure

Unlike other functional domains, the infrastructure does not belong to the application level. It contains a wide range of hardware and software to provide computing resources and network connections for SSGS, enabling signal processing, task and resource scheduling, system management, and service gateways to run smoothly. The infrastructure of the SSGS adopts enterprise-level products and mature technologies, uses shelf-type products, uses highly versatile software and common commercial standards, and can be expanded to accommodate more consumers, higher bandwidth and more types of processing systems.

D. OPERATIONAL PROCESS OF SSGS

The operation scenarios of SSGS include conventional operation scenarios such as satellite TTC mission, telemetry signal receiving, on-board load data receiving and sending. The business flowchart of SSGS is shown in Fig. 4.

A user submits a service application to the ground station, and the input parameters include basic elements such as satellite orbit parameters and signal formats. The ground station terminal calculates the period that can be supported for TT&C according to the parameter file submitted by the user, resolves the conflict with the system log file according to the user priority, and finally obtains TT&C service report. After the user's confirmation, the system automatically generates a task list, deploys tasks, loads a virtual baseband processor configuration file, and generates a virtual baseband processor. Service data is sent to the user after the TT&C mission begins. During the execution of the system, the system status information is fed back to the administrator in real-time. The system monitors the system operation status at any time and has the ability of manual task scheduling and conflict resolution. When the task ends, the system automatically reclaims the resources occupied by the virtual baseband processor, returns the resource pool, and reports the list of spare resources for system reuse. Users can preview the data they need online or download the data files they need from the server.

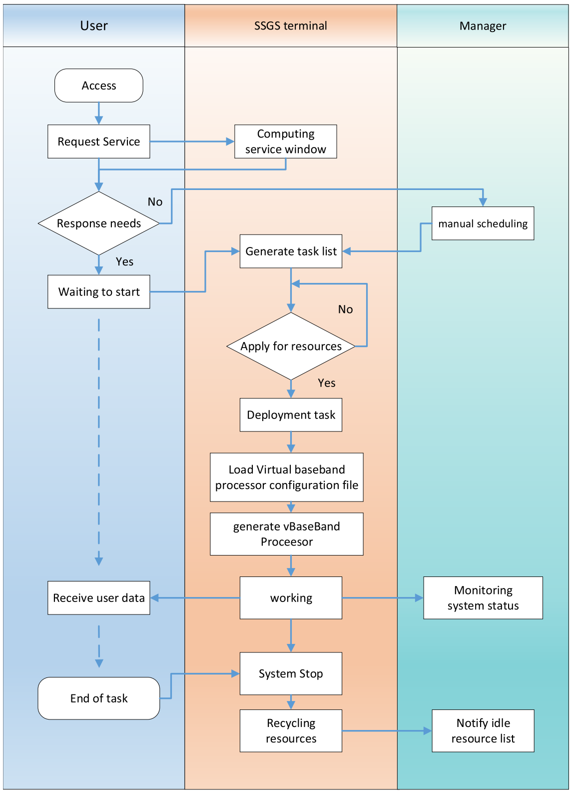


FIGURE 4. **Business folwchart of SSGS.**

E. CONTRAST BETWEEN CONVENTIONAL GROUND STATION AND SSGS

The new architecture brings a lot of benefits to the ground station network and users. Through the virtualization of core processors, the system becomes simple and flexible. The commercial interface and standard infrastructure are widely used, which breaks the limitation of the supplier, and reduces the equipment cost and operation cost. Compared with the conventional ground station, the advantages of SSGS are shown in Table 1.

III. VIRTUALIZING THE BASEBAND PROCESSOR

Virtualization technology abstracts various physical resources into logical resources and hides various physical limitations. This characteristic provides the possibility for management and application in a more detailed perspective. The baseband processor mainly completes the TT&C signal processing. It is the core component of the satellite ground station. Different function and model number of it limits the execution of the TT&C tasks. The virtualization of the baseband processor

TABLE 1. **Contrast beteewn conventional ground station and SHARED satellite ground station.**

Aspects	Conventional Ground Stations	Shared Satellite Ground Station	Advantages
Function Implementation	Each set of equipment is only used for dedicated satellites	The service is provided by the resource pool, and the equipment is highly shared and reused	System flexibility is increased and equipment costs are reduced.
System Topology	The dedicated signal processor is bound to physical hardware such as the antenna in a chimney architecture	Computing resources can be flexibly configured according to TT&C tasks in a pool architecture	The number of facilities is reduced and the same TT&C capabilities are achieved
Ground terminal equipment	The terminal equipment is developed according to specific demand and deployed one by one. The non-uniform system's function and performance are customized by the supplier. Software radio technology is widely used, and FPGA and DSP are used for baseband processing. Private platforms limit the possibility of upgrading.	The terminal equipment mainly consists of commercial servers, network infrastructure and board with fixed functions. The system is uniformly deployed.	The supplier base is larger and terminal costs are lower
Digitizing	Analog signal and digital signal coexist in the system	RF sampling is used, and digital devices are closer to RF front-end. Almost all the signals in the system are digital.	Signals are easier to record, store, and distribute, and digitization allows for lossless distribution, unlimited replication, and widespread use of open standards infrastructure.
Fault Tolerance	To improve the reliability of the system, hot backup is widely used to ensure that when a single point's error occurs, it will quickly switch to the backup system	The adoption of general equipment, the mature commercial interface technology, and redundant configuration of the system form the multiple fault-tolerant mechanisms of the system	A variety of fault-tolerant methods are provided, and the system availability and reliability is improved. Required maintenance personnel are reduced.
Network and Transmission	The signals and data are onefold in the system and the paths are exchanged serially.	The software-defined network is based on the OpenFlow protocol, which is also based on IP and ports to flexibly distinguish control and transmission signals, user data, control instructions, and configuration parameters	SSGS can be expanded in all aspects-software, firmware and interfaces. It also supports interoperation between ground stations, which further expands system functions.
System maintenance and upgrade	The system software and hardware are tightly coupled, and the hardware adopts CPCI architecture or VME architecture	The system is distributed and loosely coupled. It adopts the x86 architecture, uses a common operating system and modern programming languages, and uses a standardized interface for data interaction.	The system is distributed and decoupled, adopts the x86 architecture, uses a common operating system and programming language, and uses a standardized interface for data interaction.

isolates TT&C applications from the physical platform. For users or upper-layer applications, virtual baseband processors provide the same signal modulation and demodulation function as physical baseband processors. The (high proportion) digitization of the SSGS makes the virtualization of the baseband processor available on commercial servers. In addition, the performance of today's commercial servers is sufficient to deal with the demodulation processing of satellite TT&C signals and communication signals. The performance of a virtual baseband processor is similar to the physical performance of a dedicated device. It allows multiple virtual baseband processors to run on a server with little impact on performance.

The virtual baseband processor covers all the functions of the physical baseband processor. Followings are its prominent features:

- Support different tasks by loading different applications;
- It can quickly reconfigure different models of virtual baseband processors on the same platform to achieve different tasks by sharing a physical computing platform according to task scheduling;

The hierarchical logical architecture of virtual baseband processor is clearly shown in Fig. 5. Conceptually, the virtualization of the baseband processor is similar to server virtualization, that is, multiple virtual machines actually run on one physical machine.

A. RESOURCE POOL LAYER

Hardware resources such as computing devices, storage devices, and network devices are virtualized into resource pools to form the basis of the virtual baseband processor through the resource pool layer. The resource pool layer provides an operation plane for resource configuration, resource scheduling, resource recovery, and parameter configuration.

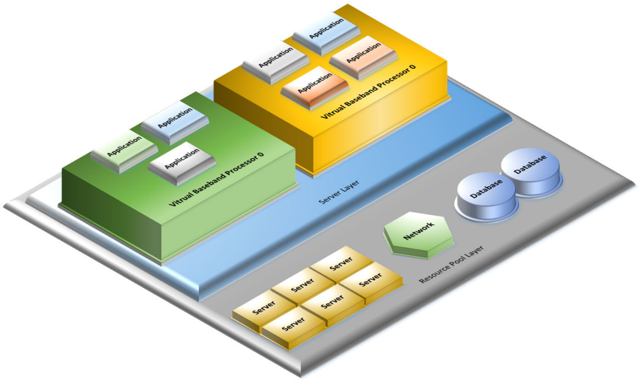


FIGURE 5. Hierarchical logical architecture of virtual baseband processor.

All SSGS use commercial products, including analog-to-digital converters, high-performance computing servers, and network equipment. All devices use PCI-e interfaces and can be easily inserted into rack servers with x86 architecture. Devices using the PCI-e interface generally adopt open commercial standards. Fig. 6 show AD capture cards. The commonly used S-band TT&C system has an operating bandwidth of 100 MHz. When the ADC chip is used for sampling, it is limited by the chip's sampling frequency, operating frequency, and data accuracy. etc., it will face problems such as poor data accuracy and large sampling synchronization error between channels. Direct RF sampling is a feasible method to solve the problems above, where the main process is to first perform band-pass filtering and high-rate sampling on the RF signal (sampling rate 1024MSPS), and then obtain the required sub-band IF or zero-IF signals through structured polyphase filtering and decimation, and finally send low-rate signals to the next processor. The advantage of this scheme is that the signal is down-converted into the required frequency band by using the aliasing effect of bandpass sampling. Also, since the use of mixers and local oscillator signal generators is avoided, the design of the hardware is simplified, and different signals input can be received by adjusting the sampling rate.

The virtual baseband processor operating environment is created through the service layer. It shields the underlying hardware from the operating system, and provides the necessary virtual resources (such as vCPU, vGPU, vMemory, vI/O) to establish a virtual baseband processor., Resources are acquired on demand through the service layer, also, management and monitoring of resource pools are implemented at this layer.

B. THE CORE FUNCTION LAYER

The core function layer is the carrier of signal processing functions, including the signal processing engine, calculation library, function library, interface specifications, etc. A virtual baseband processor with TT&C signal processing capabilities is constructed at this layer.

Virtual machines is built on-demand through an abstraction layer on a server cluster. The baseband processing software of the corresponding mode is deployed to realize the dynamic loading and dynamic configuration of the local stations' function and to form a virtual baseband processor with definable functions. Real-time I/O of signals and information is guaranteed between different functional sections through a high-speed bus. Eventually, general-purpose server resources are coupled with dedicated applications. And the processing resources of the pool are called as needed according to TT&C tasks.

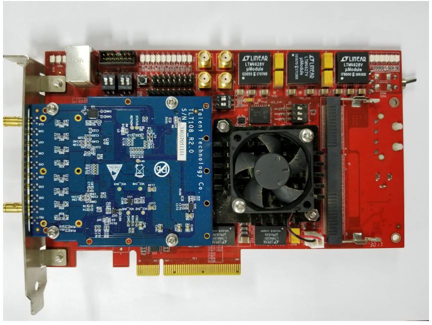


FIGURE 6. ADC card.

The virtual baseband processor based on general server clusters redefines the functions and performance of baseband processors in a software-defined manner. It provides an opportunity for transparent technology updating and optimization of machine utilization. The core idea of SSGS's sharing function is to promote the sharing of ground station systems simply and securely. Ground station system owners can reduce the number of equipment, increase hardware utilization, and reduce capital and operating expenses. Users who need satellite TT&C services do not need to build their satellite ground station system, do not need any system TT&C expertise, do not need to learn the operation and maintenance of the TT&C system. They only need to temporarily rent the service to easily achieve the required tasks.

C. THE APPLICATION LAYER

The application layer is the user's main interface, which can implement different applications such as TT&C, data transmission, navigation, and data visualization display. The virtual baseband processor is capable of realizing the filtering and sorting of subband signals flexibly, adapting to various communication transmission systems such as standard TT&C, spread spectrum, continuous phase modulation, separating and demodulating signals, and extracting the distance and Doppler information of satellite measurement signals. Then the demodulated baseband data is sent to the Service Gateway. At the same time, the function of tracking the satellite can be implemented by the antenna system automatically or by the task scheduling system according to the data in the satellite orbit configuration file.

IV. SSGS's NETWORK ARCHITECTURE BASED ON SDN

The dense digital network is one of the most prominent features of SSGS. The network mainly uses multiple 10 Gigabit

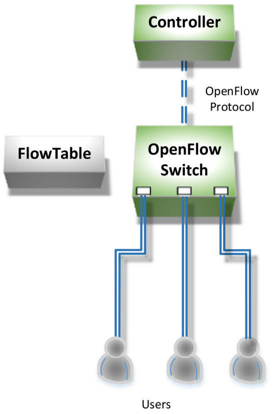


FIGURE 7. **Typical architecture of OpenFlow network.**

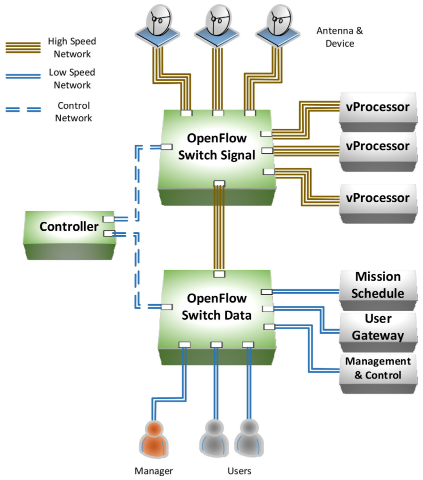


FIGURE 8. **Network architecture of SSGS.**

network segments to form a composite network, which guarantees nearly 100Gbps information exchange between terminal equipment. The network is mainly divided into two parts, one is for transmitting high-speed digital TT&C signals, and the other is for transmitting low-rate baseband data and configuration files.

Software-defined networking technology was selected to implement this high-low mixed speed network. For a review of software-defined network technology, you can refer to[19],[20]. The basic idea is to use a centralized controller to achieve custom control of the entire network. The packet flow direction in the traditional network is artificially specified. Although the switches and routers have control rights, they have not formed a stable data flow, only packet-level information is switched. In software-defined networks, a unified Controller replaces the routing device and determines the transmission path of all data packets in the network.

OpenFlow is a mature network communication protocol that implements a wide range of applications in software-defined networking technology, bringing programmable features to the network[21]. It belongs to the data link layer and controls the forwarding plane of the switch or router in the flow table mode, thereby changing the path taken by the data packet. Typical OpenFlow network architecture is shown in Fig. 7. The OpenFlow network is mainly composed of an OpenFlow switch, a network virtualization layer, known as FlowVisor, and a controller. The controller is a program that runs on a general server and connects to the SDN switch. Its main functions are as followsčž

- Be capable of monitoring and controlling the status of spacecraft and ground equipment
- Find schedule updates

- Switching users to the specified antenna system at the scheduled time by changing the SDN switch flow table.
- After the end of the scheduled time, the flow table is also changed to disconnect the OE from the receiving system.
- Record all exchange activities with timestamp

The main reasons for choosing OpenFlow is as follows:

- Network equipment manufacturers including HP, IBM, CISCO, NEC, HUAWEI, etc., can already provide network hardware equipment using the OpenFlow protocol.
- It can effectively isolate different information flows. The information in the SSGS is very complicated. There are high-speed digital signals from the RF front-end to the virtual baseband processor, low-speed data transmitted from the virtual baseband processor to the user terminal, demand files submitted by users, and configuration files generated by the task scheduling system. The data type, data rate, and destination address of each type of information are different. The OpenFlow controller controls the FlowTables to force specific data flows to be input or output on certain physical ports of the switch, and does not allow any external users to exchange data. The same mechanism (change data flow table) is also used to change the logical network architecture by allowing certain data flows and disallowing other data flows.
- Data rate. Another reason for choosing software-defined networking technology rather than traditional firewalls is the data rate. A typical earth observation satellite has a downlink data rate between 100Mbps and 500Mbps. If two users receive data at the same time, the data rate is close to 1Gbps considering system redundancy. If a user has multiple antennas working at the same time, the overall data rate will be higher. Traditional firewall technology can only
- support 10Gbps data flow, and the cost of system unit time throughput is high.

The core of the entire network is OpenFlow Controller. The network architecture of SSGS is shown in Fig. 8. The network includes OpenFlow Switch Signal switches that control high-speed data flows and OpenFlow Switch Data switches that control low-speed data flows. The controller ensures that the FlowTable allows only registered users to initiate TCP/IP connections and ensure that a stable connection between the

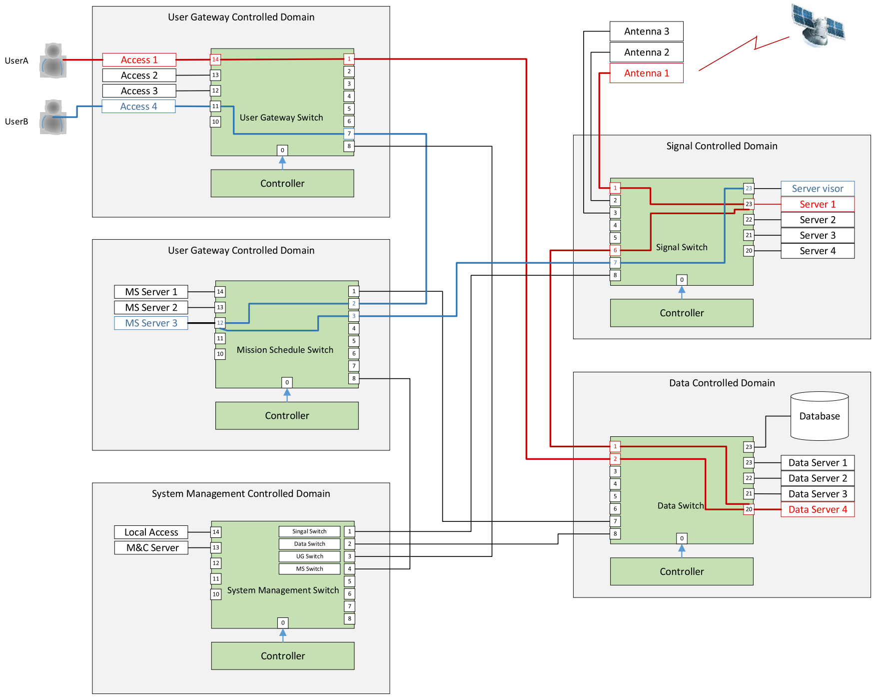


FIGURE 9. A example of describe the function of the software-defined network of SSGS.

antenna device and the virtual baseband processor is established at the task time, and ensure absolute isolation of task scheduling, system monitoring, user gateway configuration files, user demand list, and user data.

The purpose of deploying high-speed and low-speed OpenFlow switches separately can not only isolate signals and data but also prevent users from accessing the underlying physical hardware. And according to the principle of symmetry, an OpenFlow switch is deployed on each side of the network. Only when both OpenFlow switches are in an acceptable "position" can data transmission begin between the device and the control system or data processing system.

Effective isolation of multiple types of information in SSGS is ensured. Every user can be secure without the help of an extra firewall. Fig. 9 shows the software-defined network topology of the SSGS.

The connection between the antenna and the server is established through the Signal Switch. As shown in Fig. 9, Signal Switch is connected to three antenna systems. You can achieve an independent exchange of data flows between antennas by configuring the FlowTable through the Controller. Multiple antenna data flows can also be sent to one port at the same time, or the same antenna data flow can be distributed to multiple ports. Also, Signal Switch has established a high-speed data exchange network with high isolation. Users do not need to care about or operate the data flow in the Signal Switch control domain.

The connection between the virtual baseband processor and the data server is established through Signal Switch port 6, which runs on a physical server. It sends the processed user data to a data server or database. User data flow is sent from Data Switch port 2 to User Gateway Switch port 8.

Users can log in to the SSGS through User Gateway Switch ports 11 to 14, establishing a connection to the task scheduling server via User Gateway Switch port 7, and submitting TT&C requirements.

The task schedule and device configuration list are sent to Mission Control Switch port 7 through Mission Schedule Switch ports 1, 2, and 3 respectively to establish a task scheduling data flow.

System control and status data flows are collected to System Management Switch ports 1 to 4. The system administrator can either access locally through port 14, or establish a connection to the system monitoring server through the User Gateway Switch.

To describe the function of the software-defined network of SSGS, an example is given here. Assuming that user A needs to receive the load data of satellite B.

As shown in Fig. 9, the red line in the figure is the working online topology. The system selects antenna 1 to receive the downlink signal of satellite B. In the Signal Switch control domain, port 1 is connected to the virtual baseband processor running in server 1. The demodulated user data is sent to data server 4 through port 6. The user accesses the data server through Data Switch ports 2 and 20 to receive the required data.

The blue dotted line shows user B's requirements of service. The system configures the phased network topology, while the dispatch server connecting to ServerVisor through port 3, and sending a virtualization configuration list.

TABLE 2. Main parameters of the Walker constellation.

Parameters	Value
Constellation Satellites N	400
Number of Orbital Planes P	16
Phase Factor F	2
Orbital Height（km）	423.4846
Orbit Inclination	53.0027
Ground Station Field Angle	-175°~175°
Latitude and Longitude of Ground Station	（116.6E，40N）

V. CASE ANALYSIS

The development direction of TT&C and satellite data transmission is to build a Space-Air-Ground integrated network (SAGINs) [22],[23]. The network includes thousands of satellites and near earth vehicles. It is unrealistic to build the satellite-ground connection by the way of the traditional ground station. The advantages of SSGS are embodied in SAGINs. The SSGS can establish stable satellite ground connection in the most economical and efficient way, no matter how many satellites there are. The virtual baseband processor can switch among various communication modulation modes.

In this section, we take the multi-satellite connection scenario as an example of SAGINs to show how the SSGS can improve the equipment utilization and quantify the execution efficiency. The scenario assumes the following conditions:

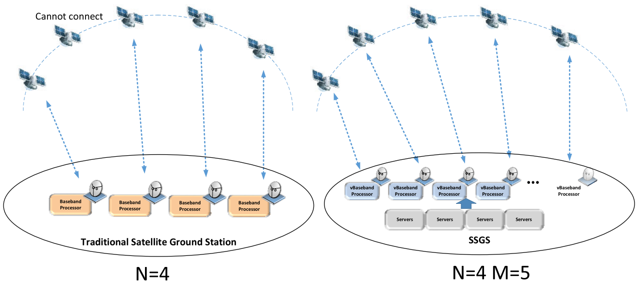
- ➢ One ground station processor can only connect to one satellite at a time.
- ➢ This paper assumes that a set of processors can achieve the connection to the satellite without considering the constraints of other physical equipment.
- ➢ Do not consider the system difference between different satellite TT&C and communication.

Due to the assumptions, in this paper, we use a simplified structure shown in Fig.10 as the considered scenario.

The Walker constellation is a distributed topology with symmetry. It is the most effective constellation for global latitude band coverage[24]. The orbits of most low-orbit satellites are similar to this configuration. Therefore, the Walker constellation was selected to construct a complex near-Earth satellite group, which was used to simulate a single station to a multi-satellite TT&C scenario. The satellite constellation parameters are described in Table 2.

It is assumed that the number of processors in the conventional ground station and the number of SSGS hardware servers are both N. The virtualization rate is defined as $R = M/N$, which represents the virtualization capabilities that a hardware device can provide. While M is the number of virtual baseband processors in SSGS.

R = 1 means that a physical server can only be virtualized as a baseband processor; R = 2 means that one server can be virtualized into 2 baseband processors; R = 0.5 means that a baseband processor needs to occupy two servers. In Fig. 10, the number of conventional satellite ground station (CSGS) equipment N = 4, the number of SSGS equipment N = 4, and the number of virtual baseband processors is 5 (M = 5).



N=4

N=4 M=5

FIGURE 10. The connection topology in the simulation.

TABLE 3. Proportion of satellites visible at the same time.

Concurrent Visibility	Total Contacts(s)	Percentage(%)
4	4731	5.48
6	4578	5.3
7	14047	16.26
8	25703	29.75
9	16808	19.45
9	20215	23.4
10	318	0.37

Virtualization technology is the core of SSGS. A mathematical model can be established to measure the advantages of SSGS over conventional ground stations by defining the virtualization rate.

The ground station can track the satellite if the elevation angle is greater than 5°. In this article, every 1 second is set as a simulation period, and the total simulation time is 1 day (86400 seconds). The number of satellites that simultaneously appear in the coverage area of the station at each period is calculated. For this satellite constellation, the statistics of the proportion of simultaneous occurrences of multiple satellites are shown in Table 3.

According to the assumptions, the circumstance that the number of satellites appears simultaneously in the coverage area is greater than the number of baseband processors that the ground station can provide in a certain period of time means that the ground station cannot meet the satellite connection requirements. Defining the ratio of the time period that can satisfy the connection demand to the total time period in the constellation simulation time is the ground station execution rate. Taking the number of different devices and the virtualization rate into account, the execution rates of conventional ground stations and SSGS are simulated and calculated. The results are shown in Table 4.

The following conclusions can be drawn.

- ➢ Since the time period when the number of simultaneous satellites exceeds the maximum number of equipment accounts for 23.77% in the conventional situations, the maximum implementation rate is 76.23%. The task execution rate is less than 60% when the number of equipment is less than 8.
- ➢ It can hardly meet the task requirements when R is less than 1 for SSGS.

TABLE 4. Statistics of station execution rate (%).

Quantity of Device	CSGS	SSGS R=0.25	SSGS R=0.5	SSGS R=1	SSGS R=1.25	SSGS R=1.5	SSGS R=2
2	0	0	0	0	0	0	5.45
3	0	0	0	0	0	5.45	26.92
4	5.45	0	0	5.45	10.72	26.92	76.23
5	10.72	0	0	10.72	26.92	56.71	100
6	26.92	0	0	26.92	56.71	99.64	100
7	56.71	0	0	56.71	76.23	100	100
8	76.23	0	5.45	76.23	100	100	100

TABLE 5. Statistics of hardware load under different virtualization rates.

R	SERVER 1		SERVER 2		SERVER 3		SERVER 4	
	CPU %	RAM %	CPU %	RAM %	CPU %	RAM %	CPU %	RAM %
0.25	67.3	34.7	2.3	9.1	5.7	11.3	1.7	9.7
0.5	13.7	38.4	12.3	39.0	15.4	31.3	19.7	37.9
1	69.7	41.2	64.7	44.2	58.1	39.7	55.7	40.5
1.25	76.1	56.8	66.7	51.1	55.9	50.3	61.0	57.2
1.5	88.3	60.8	91.0	62.5	88.9	70.4	92.7	69.9
2	100.0	78.9	99.9	80.9	100	91.2	100	90.8

- ➢ The execution capacity is the same as the conventional ground station when $R = 1$.
- ➢ The execution rate of the task will increase exponentially with the number of equipment when $R > 1$.

The virtualization rate depends on the computing power of the underlying hardware, network capacity, and quality of the virtualization technology. The underlying hardware uses general-purpose equipment, and it is difficult to derive accurate numerical solutions theoretically. Therefore, the paper builds a virtual baseband processor operating environment based on four commercial servers and simulates the virtualization rate. The simulation takes the scenario of receiving data on satellite. The downlink signal is BPSK modulated with a code rate of 12.6Mbps. Virtual baseband processors are constructed with different virtualization rates from the resource pool composed of 4 commercial servers. Using the CPU usage and memory usage as indicators to define the system load. The simulation platform is a workstation with Intel Xeon E5-2650 CPU, 64GB Random Access Memory (RAM). The Network bandwidth is 10 Gigabit Double port. The ADC sampling Rate is 1024MSPS.

It can be inferred from Table 5 that the calculation is concentrated in a certain server when $R < 1$, which is equivalent to the number of virtual baseband processors less than the actual number of devices. That is caused by the load balancing strategy. The four servers are running at almost full load when $R > 1.25$. So it can be understood that the virtualization rate the current device can support is about 1.5. From the parameters of the simulation platform, we can see that the performance is not optimal. The main frequency of our CPU is only about 2.0 GHz. If we use a more powerful processor, the virtualization rate (R) will be higher under the same conditions. That is to say, we can improve the performance without changing the core architecture, algorithm and program. In the future, methods such as increasing the number of servers and (or) expanding server performance can be taken to improve the number of satellite-ground connections.

VI. CONCLUSION

In this paper, we have proposed a shared satellite ground station(SSGS) using user-oriented virtualization technology. A pool architecture for establishing SSGS is adopted, where SSGS is divided into six functional domains: RF link, signal processing, service gateway, system management, task scheduling, and infrastructure. In order to isolate TT&C applications from the physical platform, and promote the sharing of ground station equipment efficiently and securely, then we introduce the baseband processor virtualization. Moreover, software-defined networking is introduced to implement a network that fuses high-speed and low-speed data streams and and its customization control. Hence, SSGS implements resource sharing and reducing overall costs and possesses the ability to cope with complex multi-satellite TT&C in the future, which is also easier to expand, upgrade and maintain.

In the case analysis, a multi-star connection scenario was set up to quantitatively analyze the execution efficiency of SSGS. The results show that for SSGS when the virtualization rate R is less than 1, it can hardly meet the mission requirements; when $R = 1$, the execution capacity is the same as that of a conventional ground station; and when $R > 1$, the execution rate of the task will increase exponentially with the amount of equipment. Then, based on four commercial servers, a virtual baseband processor operating environment was established to analyze the virtualization rate that the current commercial equipment can support. The results show that when researching the virtualization rate, when $R > 1.25$, the 4 servers are running at almost full load, so it can be confirmed that the virtualization rate currently supported by commercial equipment is no less than 1.25.

In future studies, we will continue to work on open architecture, efficient information interaction networks, parallelization of TT&C algorithms, and visualization of scientific data to promote the improvement of related technologies for SSGS. We also use AI technology to optimize SDN gateway and controller[25]. It is foreseeable that in the near future, the effective combination of SSGS with 5G, cloud computing, and artificial intelligence will give full play to the advantages of spatial information.

REFERENCES

[1] M. C. Spinolo, "Commercial and Internet trends and the NASA spaceflight ground network," in *Proc. IEEE Aerosp. Conf.*, Mar. 2001, pp. 1–6.

[2] M. Krynitz, "The ground station of the future," *Acta Astronautica*, vol. 67, nos. 9–10, pp. 1252–1254, Nov. 2010.

[3] K. Leveque, J. Puig-Suari, and C. Turner, "Global educational network for satellite operations (GENSO)," in *Proc. 21st Annu. AIAA/USU Conf. Small Satell.*, Aug. 2007, p. SSC07-XI-6. [Online]. Available: https://www.esa.int/Education/Towards_A_Global_Educational_Network_for_Satellite_Operations_GENSO

[4] A. Abedini, J. Moriarta, D. Biroscak, L. Losik, and R. F. Malina, "A low-cost, autonomous, ground station operations concept and network design for EUVE and other earth-orbiting satellites," in *Proc. Int. Telemetering Conf., Theme, 'Re-Eng. Telemetry'*, Oct. 1995.

[5] M. Fischer and A. L. Scholtz, "Design of a multi-mission satellite ground station for education and research," in *Proc. 2nd Int. Conf. Adv. Satell. Space Commun.*, 2010, pp. 58–63.

[6] E. C. Young, "GPU-accelerated demodulation for a satellite ground station," M.S. thesis, Dept. Elect. Comput. Eng., Utah State Univ., Logan, UT, USA, 2019.

[7] Ø. Karlsen, "Ground station considerations for the AMOS satellite programme," M.S. thesis. NTNU, Trondheim, Norway, 2017.

[8] J.-C. Juang, C.-T. Tsai, and J.-J. Miau, "A software-defined radio approach for the implementation of ground station receivers," in *Small Satellites for Earth Observation*. Dordrecht, The Netherlands: Springer, 2008, pp. 293–298.

[9] T. S. Tuli, N. G. Orr, and R. E. Zee, "Low cost ground station design for nanosatellite missions," in *Proc. AMSAT Symp.*, 2006, pp. 1–9.

[10] M. Schmidt, "Ground station networks for efficient operation of distributed small satellite systems," Ph.D. dissertation, Würzvurger Forschungsberichte Robotik Telematik, Würzvurger, Germany, 2011

[11] D. J. White, I. Giannelos, A. Zissimatos, E. Kosmas, D. Papadeas, P. Papadeas, M. Papamathaiou, N. Roussos, V. Tsiligiannis, and I. Charitopoulos, "SatNOGS: Satellite networked open ground station," Dept. Eng., Valparaiso Univ., Valparaiso, IN, USA, Tech. Rep., 2015. [Online]. Available: https://scholar.valpo.edu/engineering_fac_pub/40/

[12] M. Schmidt and K. Schilling, "Ground station networks for distributed satellite systems," in *Distributed Space Missions for Earth System Monitoring*. New York, NY, USA: Springer, 2013, pp. 355–371.

[13] F. Riffel and R. Gould, "Satellite ground station virtualization: Secure sharing of ground stations using software defined networking," in *Proc. Annu. IEEE Syst. Conf. (SysCon)*, Apr. 2016, pp. 1–8.

[14] Y. Miao, Z. Cheng, W. Li, H. Ma, X. Liu, and Z. Cui, "Software defined integrated satellite-terrestrial network: A survey," in *Proc. Int. Conf. Space Inf. Netw.* Singapore: Springer, 2016, pp. 16–25.

[15] F. Riffel, "Making the case for satellite ground station virtualization based on software defined networking," in *Proc. 14th Int. Conf. Space Oper.*, 2016, pp. 1–9.

[16] D. Yan, Y. Wang, H. Ma, Y. Liu, and K. Sun, "Aerospace TT&C signal processing platform on cloud computing," *Telecommun. Eng.*, vol. 58, no. 5, pp. 493–499, 2018.

[17] T. D. Watson and W. A. Brown, III, "Resilient virtual ground receivers," U.S. Patent 9 979 462, May 22, 2018.

[18] E. Cianca, T. Rossi, M. Ruggieri, M. Presi, E. Ciaramella, L. Luini, C. Sacchi, G. Parca, and G. Codispoti, "Softwarization and virtualization as enablers for future EHF/FSO high throughput satellites," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2018, pp. 1–6.

[19] Y. Li and M. Chen, "Software-defined network function virtualization: A survey," *IEEE Access*, vol. 3, pp. 2542–2553, 2015.

[20] N. Bizanis and F. A. Kuipers, "SDN and virtualization solutions for the Internet of Things: A survey," *IEEE Access*, vol. 4, pp. 5591–5606, 2016.

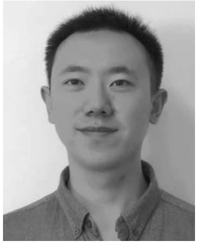
[21] N. McKeown, T. Anderson, H. Balakrishnan, G. Parulkar, L. Peterson, J. Rexford, S. Shenker, and J. Turner, "OpenFlow: Enabling innovation in campus networks," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 38, no. 2, pp. 69–74, Mar. 2008.

[22] N. Kato, Z. M. Fadlullah, F. Tang, B. Mao, S. Tani, A. Okamura, and J. Liu, "Optimizing space-air-ground integrated networks by artificial intelligence," *IEEE Wireless Commun.*, vol. 26, no. 4, pp. 140–147, Aug. 2019.

[23] J. Liu, Y. Shi, Z. M. Fadlullah, and N. Kato, "Space-air-ground integrated network: A survey," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 4, pp. 2714–2741, 4th Quart., 2018.

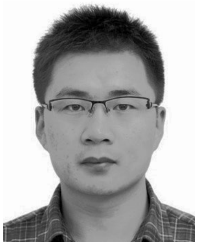
[24] Z. Qu, G. Zhang, H. Cao, and J. Xie, "LEO satellite constellation for Internet of Things," *IEEE Access*, vol. 5, pp. 18391–18401, 2017.

[25] J. Liu, Y. Shi, L. Zhao, Y. Cao, W. Sun, and N. Kato, "Joint placement of controllers and gateways in SDN-enabled 5G-satellite integrated network," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 2, pp. 221–232, Feb. 2018.



YANDU LIU received the B.S. and M.S. degrees from the Institution of Command and Technology of Equipment, China, in 2009 and 2016, respectively. He is currently pursuing the Ph.D. degree in information and communication system with Space Engineering University, China. His research interests include space TT&C technology, multi-antenna technology, and array signal processing.

YUDI CHEN received the B.S. degree from Space Engineering University, Beijing, China, in 2018, where he is currently pursuing the Ph.D. degree. His research interests include tracking telemetry and command of spacecraft, and signal processing.



YIWEN JIAO received the B.S. degree in electronic and information technology from the Beijing University of Aeronautics and Astronautics, in 2008, and the M.S. and Ph.D. degrees from the Institution of Command and Technology of Equipment, Beijing, in 2010 and 2015, respectively. From 2010 to 2019, he has been engaged in the research of DBBC for deep space exploration. He is currently working as a Lecturer at Space Engineering University, Beijing, China. His research interests include space TT&C technology, high-speed signal processing, and advanced signal processing.

HONG MA received the B.S., M.S., and Ph.D. degrees from the Institute of Equipment Command Technology, in 1997, 2000, and 2004, respectively. He is currently working as an Associate Professor at Space Engineering University, Beijing, China. His research interests include space TT&C technology, deep space communication technology, and software defined radio.

TAO WU received the B.S., M.S., and Ph.D. degrees from the Institution of Command and Technology of Equipment, in 2002, 2005, and 2009, respectively. He was an Associate Professor with Space Engineering University, Beijing, China. His research interests include space TT&C technology and signal processing.

• • •