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Software-Defined Next-Generation Satellite Networks: Architecture, Challenges, and Solutions

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ABSTRACT Traditional satellite networks depend on the closed and planned architecture. Thus, there are many challenges such as configuration update, new communication and networking technologies introduction, truly-differentiated services provision, satellite network device interoperability, and the integration of satellite and terrestrial networks. Software-defined networking (SDN) has the features of flexibility, programmability, and logical centralization, which increases network resource utilization, simplifies network management, reduces operating cost, and promotes the evolution and innovation. In this paper, a new software-defined architecture for next-generation satellite networks, called SoftSpace, is presented. The concepts of network function virtualization, network virtualization, and software-defined radio are exploited in the SoftSpace to facilitate the incorporation of new applications, services, and satellite communication technologies. This can not only reduce the capital expenditures and operational expenditures but also integrate satellite networks with terrestrial networks seamlessly, as well as can improve the interoperability of satellite network devices. In addition, we discuss the challenges and solutions for network management. The necessary network management instruments including multi-layer controller architecture, cooperative traffic classification, and utility-optimal network virtualization are presented. Finally, we discuss the challenges and solutions for space networking. The software-defined space networking solutions including quality of experience-aware space routing, SDN-enabled hybrid fault recovery mechanism, and software-defined space mobility management are developed.

INDEX TERMS Next-generation satellite networks, software-defined networking, virtualization, network management instruments, space networking solutions.

I. INTRODUCTION

Although the Internet has transformed people's daily life, almost two-thirds of the humankind have not accessed the Internet, wired or wireless [1]. Satellite networks with global coverage capability and without the limitation of geographic conditions have attracted much attention from the research community and industry [2]. Compared with traditional satellite networks, next-generation satellite networks are characterized by onboard processing, affordable tracking antennas, and inter-satellite links [3]. They prefer utilizing the satellites orbiting at low altitude to reduce propagation delays, which enables real-time communications [4]. Moreover, the transport services with quality of service (QoS) provision can be offered in the next-generation satellite networks by using the technologies of addressing, routing, etc. [5]. However, existing satellite networks upgrade hardware/software inflexibly and depend on the closed and planed architecture [6]. It imposes great challenges for rapid introduction of new communication and networking technologies [7], puts a brake on really differentiated services provision for the highly various and increasing satellite network applications [8], brings large obstacles to the interoperability between satellite communication devices provided by different operators (or based on various communication technologies) [9], and hinders the seamless integration of heterogeneous satellite and terrestrial networks [8].

It is desired to design a radical networking paradigm for the next-generation satellite networks to address these challenges. Software-defined networking (SDN) [10], network function virtualization (NFV) [11], network virtualization (NV) [12] and software-defined radio (SDR) [13] are considered as the promising enablers. SDN and SDR have a common feature: 'software-defined' which brings programmability, flexibility and reconfigurability into networks [14]. NFV and NV have a common feature: 'virtualization' which simplifies network management and facilitates resource sharing, aggregation, dynamic allocation, etc [15]. Integrating these technologies can pave the way for innovative network design, operation, and management [16].

SDN, a promising networking paradigm, receives increasing attentions from industry and academia. Its main ideas are (i) the separation of control plane and data plane, (ii) the centralized control model of network states, and (iii) the deployment of novel network control and management functions based on network abstraction [10], [17]. The means of implementing SDN are (i) to decouple control decisions from hardware infrastructure, (ii) to incorporate programmability into hardware infrastructure by using standardized interfaces (e.g., OpenFlow [18]), and (iii) to exploit one physically or logically centralized network controller to determine network management policies and define operation for the whole network [19], [20]. SDN has efficient network resource utilization, simplified network management, cost reduction, and flexible deployment of novel services and applications.

OpenFlow protocol, an SDN technology, is most commonly used to communicate between OpenFlow switch and controller. The OpenFlow switch uses flow tables to forward packets, and each flow table consists of a list of flow entries. Each flow entry constitutes a matching rule, actions, and counters. The matching rule matched by incoming packets is defined by the matching fields and priority. The matching fields include source and destination Ethernet addresses, source and destination IP address, source and destination transport ports, and others [21]. The matching packet executes corresponding action. The possible actions consist of (i) forwarding the packet to one or more particular ports, (ii) encapsulating and forwarding the packet to the controller, (iii) sending the packet to the normal processing pipeline, or (iv) sending the packet to the next flow table when group tables are supported [18]. Counter is used to keep statistic about packets. The benefits of OpenFlow are (i) to update the forwarding rules dynamically, (ii) to simplify the forwarding devices, and (iii) to control the whole network centrally.

NFV, a new approach to design, deploy and manage network services, has aroused considerable concern in both industry and academia [11]. Its main ideas are (i) the separation of network function and physical device, (ii) the flexible deployment and management of network functionalities, and (iii) the reconfigurable service provision [22]. The means of implementing NFV are (i) to decouple network function from the dedicated physical device, (ii) to implement virtual network functions (VNFs) on virtual machines, and (iii) to assemble and chain VNFs to create services [16]. The major benefits of NFV are (i) to run and create network services with high flexibility by adaptively assembling and chaining software-based network functions without changing network architecture, (ii) to lower capital expenditures (CAPEX) and operational expenditures (OPEX) by using the centralized servers instead of installing the specialized hardware equipment for new services, and (iii) to facilitate controlling and managing the network globally and optimally by implementing the software-based network functions in centralized network servers [23].

NV, whose essence is resource sharing, is designed to solve the ossification problem of existing network systems [15]. The main ideas of NV are (i) the separation of virtual network and physical network, (ii) the coexistence of multiple heterogeneous virtual networks, and (iii) the independent deployment and management of virtual networks [12]. The means of implementing NV are (i) to abstract links, devices, and services from the physical network, (ii) to create logical virtual networks on the shared network infrastructure, and (iii) to allocate the network resources using hypervisors [24]. With NV, customers can customize their private networks. NV improves infrastructure resource utilization and promotes innovations and diversified applications.

SDR is a collection of hardware and software technologies [13]. Its main idea is exploiting software to perform partial or total physical layer functions in radio, such as modulation/demodulation and signal processing. SDR is achieved by implementing the operating functions of radio through the modifiable software or programmable hardware [14]. The SDR is flexible and reconfigurable. It creates the adaptability to new communication protocols and channel assignment policies without hardware changes [13].

To date, the basic idea of SDN has been integrated into many new networking paradigms and techniques, such as academic campus networks [25], data center networks [26], 5G systems [28], [29], underwater communication systems [27], and NFV [30], [31], thus providing promising solutions to the specific issues in networking. The newly emerging studies on SDN/NFV-enabled satellite networks mainly aim at the softwarization and virtualization in the ground segment [6], [9], [16]. The virtualization level of infrastructure is above network layer [32]–[34]. SDR, as a decoupling technique for hardware-integrated wireless functionalities, can be used to implement wireless virtualization. However, the utilization of SDR in MAC/physical-layer function virtualization does not obtain enough attentions.

Given the above, this paper integrates SDN, NFV, NV, and SDR with the next-generation satellite networks to design a novel satellite network architecture. The softwarization and virtualization in both space and ground segments are achieved. And the virtualization is extended to MAC and physical layers. Furthermore, this study differs from the existing researches, which mainly focus on the architecture design, in that we discuss the essential network management instruments and propose software-defined space networking solutions for software-defined satellite networks. The major contributions of this paper are as follows. (i) The software-defined satellite network architecture, called SoftSpace, is proposed. SDR is exploited to implement the MAC/physical-layer function virtualization in space forwarding devices. The network-layer function virtualization is realized by OpenFlow. (ii) We discuss how SDN, NFV, NV, and SDR benefit from each other and present the promising features and properties brought by softwarization and virtualization. (iii) The primary management instruments including multi-layer controller architecture, cooperative traffic classification, and utility-optimal network virtualization are proposed to realize these features. (iv) Based on this architecture, quality of experience (QoE)-aware space routing, SDN-enabled hybrid fault recovery mechanism and software-defined space mobility management are developed for space networking in SoftSpace.

The remainder of this paper is organized as follows. In Section II, the related work is discussed. Section III presents the current satellite communication systems. Section IV introduces the architecture of SoftSpace and summarizes its promising features. Section V identifies the challenges and solutions for network management in the SoftSpace. The software-defined space networking solutions are presented in Section VI. The implementation roadmap is presented from three dimensions in Section VII. Finally, Section VIII concludes this paper and outlines the future works.

II. RELATED WORK

Some explorations have been conducted in the area of introducing SDN into satellite networks. Kapovits *et al.* [35] identified that SDN was a promising enabler in the evolution of service delivery over the integrated satellite-terrestrial networks. Bao *et al.* [6] proposed a novel satellite network architecture based on the idea of decoupling data plane and control plane to gain high efficiency, fine-grained control and flexibility. Tang *et al.* [36] proposed a software-defined satellite networks which used inter-satellite links and GEO broadcasting links as control channels to update network status and distribute control messages. Barritt and Eddy [37] proposed the temporospatial SDN technique on the top of using SDN technique to control low earth orbit (LEO) satellite networks. However, Bao *et al.* [6], Kapovits *et al.* [33], Tang *et al.* [34], and Barritt and Eddy [35] just adopt the main ideas of SDN without introducing NFV.

Gardikis *et al.* [38] investigated the applicability of NFV in satellite networks and identified the benefits as well as challenges. The applicability of network softwarization (SDN and NFV) technologies in satellite networks was investigated in [34]. It also presented the benefits of integrating SDN/NFV into satellite infrastructure via specific use cases and proposed a hierarchical architecture for SDN/NFV-based satellite-terrestrial networks. Ferrús *et al.* [9] investigated the benefits and technical challenges brought by introducing SDN/NFV technologies into the satellite ground segment. Agapiou *et al.* [39] elaborated a novel satellite-terrestrial architecture which brought NFV into satellite communication domain and exploited SDN-based resource management. Ferrus *et al.* [40] described the system architecture of satellite ground segment built on SDN and NFV technologies, which facilitated the integration of satellite communication into 5G systems. Based on this architecture, a solution for the dynamic orchestration of satellite communication services was proposed in [41], and a gateway diversity solution was proposed in [42] to manage failover and resiliency flexibility. Ahmed *et al.* [32] proposed a SatCloudRAN framework which integrated SDN, NFV and cloud based infrastructure into satellite radio access networks and described a specific roadmap for SatCloudRAN implementation in satellite ground system. The SDN/NFV-enabled satellite-terrestrial network architecture proposed in [30], [32], and [37]–[40] are identical, while they focus on different research aspects and handle different challenges stemming from the implementation of the architecture.

Bertaux *et al.* [16] demonstrated the benefits of integrating SDN, NV and NFV into satellite network services through practical use-cases. Rossi *et al.* [43] adopted SDN and NFV in broadband satellite access networks and listed the benefits provided by these paradigms through analyzing four satellite SDN/NFV application scenarios. The VITAL [44] project brought SDN/NFV into satellite domain to address the combination of terrestrial networks and satellite networks. The EESA [45] concluded that introducing SDN/NFV into satellite communication industry could reduce CAPEX and increase revenues. References [9], [16], [30], [32], [37]–[40], [42], and [43] mainly focus on how to design the satellite ground segment by incorporating SDN/NFV. They just regard the space segment as transmission channels without considering its softwarization and virtualization.

Huang *et al.* [46] integrated SDN, NFV and mobile edge computing (MEC) into space-terrestrial integrated networks for unified management, the quality improvement of user experience and network service, and cooperative scheduling. Wang and Yu [47] proposed an SDN and virtualization based satellite network architecture which had ground center controller and layer controllers in each satellite layer. While, it just described the function units of controller and switch without giving a detailed description. Shi *et al.* [48] presented an OpenFlow-based space-terrestrial integrated network architecture and qualitatively described four management strategies which ranged from physical resource management to application management. Miao *et al.* [49] described an SDN-enabled satellite-terrestrial network architecture and presented its fundamental applications (i.e., resource management, routing, and networking). Sheng *et al.* [33] designed a flexible and reconfigurable network architecture for resource management in broadband satellite networks by embracing SDN and NFV, and the resource management architecture and resource allocation strategy were elaborated. The work in [31] and [44]–[47] combines SDN and virtualization technology in satellite networks, but they mainly focus on the virtualization above the network layer without considering the virtualization in MAC and physical layers.

Pinto *et al.* [50] exploited SDR in small satellite systems to design an inter-satellite communication model which could be easily reconfigured to support any encoding/decoding, modulation and other signal processing schemes. Combined field programmable gate array (FPGA) and radio frequency (RF) programmable transceiver, Maheshwarappa *et al.* [51] proposed an SDR architecture to solve the reconfigurability challenges in traditional ground stations and small satellites. Daneshgaran and Laddomada [52] designed an architecture of receiver front-end based on SDR which could be employed in broadband satellite communication systems. Hurskainen *et al.* [53] presented a multicore SDR architecture for global navigation satellite system receiver, which had the potential of high flexibility and low production cost. Although Pinto *et al.* [48], Maheshwarappa *et al.* [49], Daneshgaran and Laddomada [50], and Hurskainen *et al.* [51] exploit SDR technology to design transceiver for satellite systems to improve reconfigurability and flexibility, they do not consider coupling SDR with SDN, NFV and NV.

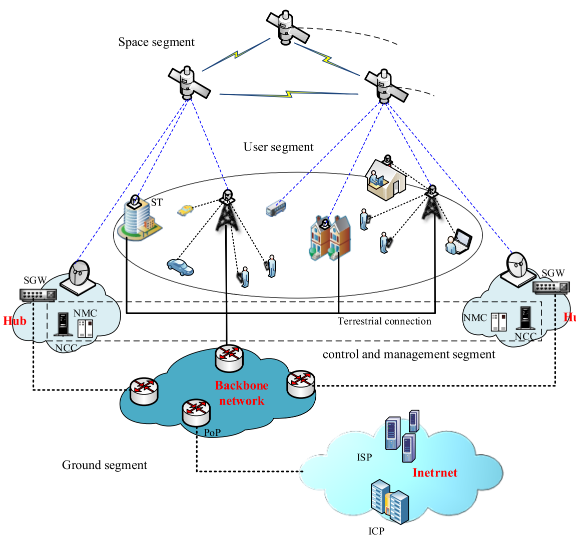

FIGURE 1. Satellite network architecture.

III. OVERVIEW OF SATELLITE NETWORKS

As depicted in Fig.1, satellite network architecture is composed of space segment, ground segment, control and management segment, and user segment [54]. (i) The space segment comprises satellites organized in the constellation and supports routing, adaptive access control, and spot-beam management [5]. (ii) The ground segment consists of satellite gateways (SGWs) interconnected by optical backbone networks and satellite terminals (STs) that provide connections for end-user devices. The backbone network connects to external networks (e.g., Internet or corporations) through some point of presences (PoPs) [11]. The SGWs and STs are interconnected through the space segment. (iii) The control and management segment is made up of network control centers (NCCs) and network management centers (NMCs) [55]. NCCs and NMCs provide real-time control and management functions for satellite networks. They perform the establishment, monitor and release of connections, admission control, resources allocation, the configuration of satellite network elements, and the management of security, fault and performance. The co-located SGW, NCC and NMC are commonly referred as satellite hub. (iv) The user segment comprises all the end-user devices that are used by end users to consume satellite-based services, fixed or mobile. They access satellite networks directly or through terrestrial access points.

There are one or many business actors to deliver satellite network services to end-users. Each actor is a company entity which plays one or many roles. The major roles [56] are (i) satellite operator (SO), who takes charge of maintaining, managing, deploying and operating the satellite platform; (ii) satellite network operator (SNO) [16], who owns the satellite network and takes charge of its maintenance, management, deployment, and operation; (iii) network access provider (NAP), who uses the services from one or more SNOs to share its transmission resources among service providers; and (iv) service provider (SP), who sells services and/or equipment to customers and bills the customers based on the information received from NAPs.

Who owns and manages the network infrastructure and customer relationships is impacted by the satellite network architecture. Thus, some business models have emerged and co-existed with traditional ones [9].

- *Vertically integrated model* in which there is only one single satellite network operator actor who owns all infrastructure, operates the network and service provision, and manages customer relationships. It serves as SO, SNO, NAP and SP at the same time.
- *Managed service model* in which there are two actors. One is the satellite network operator who owns all infrastructure and operates the network. It plays the roles of SO, SNO and NAP. The other one is the service provider who resells network services and manages customer relationships. It plays SP role.
- *Partially managed model* is a variant of the managed service model. Compared with the managed service model, the service provider in this model has certain control over network operation and services provision. Consequently, the service provider can offer the customized satellite network services based on the hosting networks of satellite network operators.
- *Hub co-location model* is a shared infrastructure model which can reduce CAPEX and OPEX. The satellite network operator plays the roles of SO and partial SNO. The actor of satellite virtual network operator (SVNO) plays the roles of SP, NAP and partial SNO [38].

- *Virtual network operator model*, a variant of hub co-location model, is attractive to the service providers for reducing their investments. In this model, the actor of satellite network operator plays the roles of SO and SNO, and the SVNO plays the roles of SP and NAP. The SVNO can lease hub equipment and purchase bandwidth from satellite network operator to establish satellite network services.

Although there are many advances in satellite communication technologies, satellite networks still suffer some limitations due to the traditional system design [9], [57].

- Since the manufacture and launch of satellites spend a lot of money and time, satellite networks usually use the static and scheduled configuration. As a result, the update and reconfiguration of satellite networks are inflexible. The maintenance cost of satellite networks is very high.
- The development of satellite communication and networking technologies enhances the increasing prosperity of satellite networks. Satellite services and applications increase fast. However, not all kinds of new services and applications can be supported by satellite payload. The establish and configuration of new services and applications are time-consuming and high-investment.
- The communication technologies, networking protocols and satellite services are vendor-specific in the current satellite networks, so that the interaction between different satellite systems is considerably difficult.
- Satellite networks are different from terrestrial networks since they inherently confront the challenges of high propagation delay, dynamical topology and limited resources. As a consequence, mechanisms designed for terrestrial networks are unsuitable for satellite networks of which settings are specified. In addition, the development of satellite communication technologies has not evolved at the same speed as terrestrial networks. These bring huge challenges to the integration of satellite networks with terrestrial networks [58].
- It is inflexible, huge investment and high-latency to introduce new communication technologies, algorithms, and protocols into satellite networks since this involves software/hardware updates.
- The satellite resource provision for users is essential since it has a significant influence on user's QoE. However, the scheduled and static satellite resource allocation makes it inflexible to optimize resource utilization and satisfy user demands.

IV. SOFTSPACE ARCHITECTURE DESIGN

The architecture of SoftSpace comprises a data plane and a control plane, as illustrated in Fig. 2.

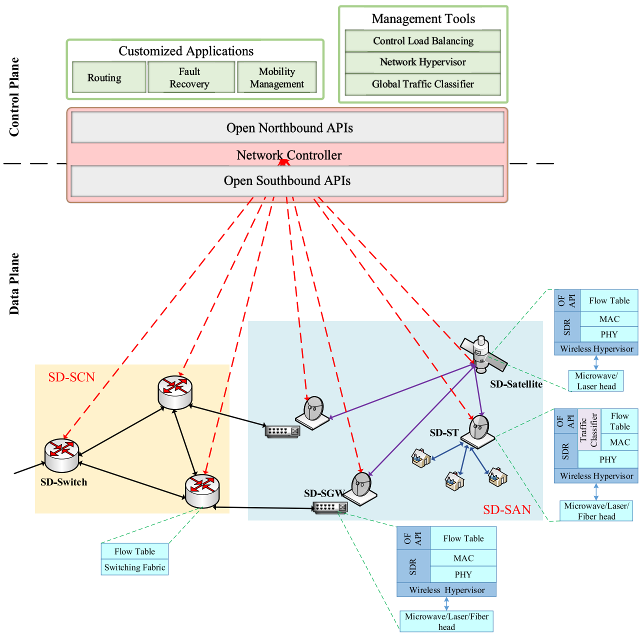

FIGURE 2. Overall architecture of SoftSpace.

- The data plane includes both software-defined satellite access network (SD-SAN) and software-defined satellite core network (SD-SCN). The SD-SAN comprises software-defined satellite gateways (SD-SGWs), software-defined satellite terminals (SD-STs), and software-defined in-orbit satellites (SD-Satellites). The SD-SCN is a collection of software-defined switches (SD-Switches). As shown in Fig.2, each SD-Satellite has four parts: (i) the SDR, which creates programmable MAC and physical-layer functions for SD-Satellites by using its hardware programmability, enables SD-Satellites to support multi-mode operation, radio reconfiguration, and remote upgrade, and allows SD-Satellites to adapt to new applications and services without hardware changes; (ii) the flow table supporting extended OpenFlow, which describes the packet handling rules and can be configured by the network controller through southbound APIs; (iii) the wireless hypervisor, which enables to create several virtual SD-Satellites operating various communication technologies or protocols on a shared SD-Satellite; and (iv) multiple hardware front-ends (e.g., optical head and RF antenna), which support various satellite communication technologies (e.g., laser and radio wave communications). Each SD-Satellite defines physical/MAC/network-layer functions with software and supports multiple communication technologies. SD-SGW is similar to the SD-Satellite, except support of fiber communications. Moreover, SD-ST is identical to the SD-SGW, except that it is equipped with traffic classifier for efficient uplink resource allocation. The SD-SCN is composed of SD-Switches, thus it has high flexibility.
- The control plane, network brain resting in the network controller, includes two critical components: network management instruments and customized satellite network applications. Furthermore, unified and

programmable interfaces are provided for both network management instruments and satellite network applications by network controller to access and manage network resources. In the SoftSpace, the network controller exploits the broadcast control channel reserved for control flows and the intra-layer control channel shared by data and control flows to configure and regulate software-defined satellite network devices. The broadcast control channel is realized by GEO satellite broadcasting to ensure the one-hop connection between network controller and LEO satellites. The intra-layer control channel is realized by point-to-point links between LEO satellites.

The SoftSpace architecture is described in more detail below. Firstly, the NFV of SoftSpace is presented regarding network/MAC/physical-layer functions. Then, the network virtualization is explained. Following, the promising features of SoftSpace are summarized. Finally, necessary network management instruments are introduced.

A. SCALABLE NETWORK FUNCTION VIRTUALIZATION

NFV aims at replacing dedicated network appliances with software modules running on the centralized network servers. The benefits of NFV are reducing CAPEX and OPEX and improving network scalability and service agility. In the SoftSpace, the function virtualizations of network/MAC/physical layers are performed simultaneously, which maximizes the benefits of NFV.

1) NETWORK-LAYER FUNCTION VIRTUALIZATION

Network-layer function virtualization decouples the routing function from the packet forwarding devices and implements it at a centralized network controller by using an open southbound interface. OpenFlow, as the most popular SDN technology, may be a practical criteria for southbound interface. The OpenFlow-enabled platform and solutions have been developed for mobile and wireless networks [59], [60]. The OpenFlow-based satellite terminal has been proposed and validated on OpenSAND platform [61]. So the adoption of OpenFlow in satellite networks is promising and mandated, although the deployment of OpenFlow in satellite payloads may raise issues. The essence of OpenFlow-based network-layer function virtualization is to abstract the data plane by flow tables. More specially, applications running on the controller leverage the functions offered by open northbound APIs to implement routing algorithms. Then, the routing policies are ultimately translated into OpenFlow instructions to configure the flow table entries of forwarding devices. The effectiveness and practicability of network-layer function virtualization have been well demonstrated by instances. For example, a cloud-based SDN controller that can communicate with terrestrial and satellite infrastructure has been developed, which enables the delivery of near real-time services [62]. Moreover, the OpenFlow-enabled software-defined networks, e.g., Google B4 [63], have been successfully deployed in terrestrial networks.

In the SoftSpace, the network-layer function virtualization is realized by equipping each space forwarding device with the extended OpenFlow interface. Equipping the space forwarding devices with OpenFlow-alike capabilities can (i) facilitate their control and management in a transparent manner through a unified interface, (ii) enable the implementation of fine-grained flow management by developing the customized flow control policies for any traffic class, and (iii) allow to dynamically reconfigure flow table for space forwarding devices, which facilitates the development of QoE-aware flow routing solution, hybrid fault recovery mechanism and seamless mobility management.

2) MAC AND PHYSICAL-LAYER FUNCTION VIRTUALIZATION

SDR technology is applied to implement MAC/physical-layer function virtualization, namely software is used to implement the above functions on a universal hardware platform. More specially, the MAC-layer functions include time/frequency/code division multiple access, etc. The physical-layer functions include modulation/demodulation, channel coding, source coding, etc. In the SoftSpace, MAC/physical-layer function virtualization of space forwarding devices is implemented on the reconfigurable and multipurpose processing hardware such as FPGA [64] and digital signal processor (DSP) boards [65]. Abstracting MAC/physical-layer functions from the underlying hardware provides flexibility for the independent development of radio technology, resource sharing scheme and baseband processing solution. Moreover, each space forwarding device is equipped with a variety of hardware front-ends to support various space communication technologies. This greatly promotes the interoperability of space forwarding devices. In addition, the network controller can adaptively select the communication technology, reconfigure the MAC/physical-layer function parameters, and allocate the network-wide resources to optimize network performance.

B. NETWORK VIRTUALIZATION

As illustrated in Fig. 3, the network virtualization allows several isolated virtual networks to co-locate on the shared physical network infrastructure. Especially, network infrastructure resources (e.g., bandwidth and computing power) are divided into several mutually separated slices. Each slice is assigned to one virtual network which is leased and utilized by a satellite network customer, such as government, private enterprise, SVNOs, etc. Thus, in the SoftSpace, the shared physical infrastructure can be allocated to multiple customers according to their demands, and the customers can customize their private network/MAC/physical-layer protocols. These customers just need to lease the infrastructure instead of owning them, and they do not interfere with the operations and performance of each other. In addition, the innovation of space communication technologies is rapid, as the isolated network resources can be assigned to deploy and test novel technologies.

Two hypervisors are required to realize the network virtualization in the SoftSpace. One is for the high-level

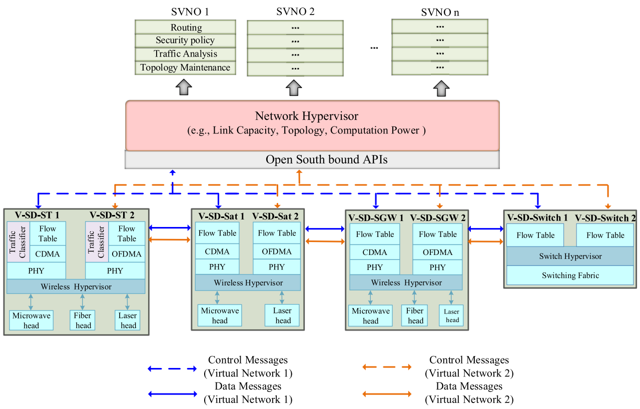

FIGURE 3. Network virtualization of SoftSpace.

virtualization, referred as network hypervisor; the other one is for the low-level virtualization, including wireless hypervisor and switch hypervisor.

- The network hypervisor, as a high-level resource management instrument, is responsible for adaptively allocating non-conflicting multi-dimensional network resources to satellite network applications or virtual network operators.
- The wireless hypervisor, as a low-level resource scheduler, is responsible for guaranteeing the isolation among virtual networks. Varieties of wireless resource dimensioning schemes are employed to enforce the resource management policies which are determined by network hypervisor [55].
- The switch hypervisor is responsible for bandwidth management in a single SD-Switch to provide bandwidth guarantee for the assigned virtual network.

C. PROMISING FEATURES

The introduction of SDN, NFV, NV, and SDR in the SoftSpace offers the following properties: (i) programmability, the network/MAC/physical-layer functions of packet forwarding devices are performed by software, thus these devices can be dynamically reconfigured by remote controller through deploying different resource scheduling, communication and networking mechanisms; (ii) cooperativeness, network functions (e.g., traffic classification) implemented at SoftSpace nodes can be combined in network controller for joint control and optimization, and different modules such as access control and routing can be run in a collaborative manner; (iii) virtualization, multiple independent virtual networks coexist and share the same network infrastructure. Each virtual network can be fully controlled by its tenant and deployed with private service model, resource scheduling mechanism, communication mechanism, and networking mechanism; (iv) openness, the configuration, monitoring and management of heterogeneous devices are simplified by equipping the packet forwarding devices with open and common interfaces; (v) visibility, network controller collects states from data plane to build the global view of network.

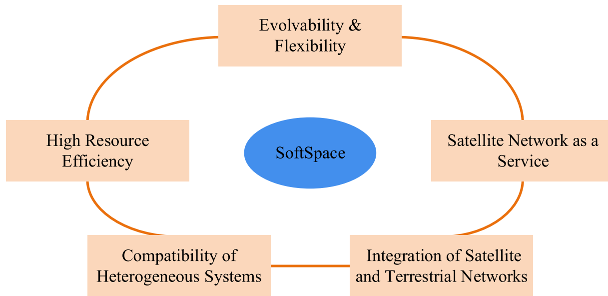

FIGURE 4. Attractive features of SoftSpace.

The above properties make the next-generation satellite networks possess the following attractive features, as shown in Fig. 4.

- *Evolvability and flexibility*. The separation of control plane and data plane in the SoftSpace makes the network infrastructure and networking schemes update independently. Thus, the physical network devices can easily introduce emerging communication technologies, and the network controller can rapidly deploy novel network management and networking strategies, which facilitates network evolution and innovation. Moreover, the programmable data plane allows network controller to dynamically adjust routing and resource provision solutions according to traffic states, unexpected satellite failures, and the QoS requirements of network applications.
- *Satellite network as a service*. The virtualization of network/MAC/physical-layer functions in the SoftSpace enables satellite networks with fully virtualized capabilities, and the NV allows satellite network to be offered as a service rather than vendor-specific communication system. Thus, an end-to-end fully virtual satellite network can be managed by an SVNO. More specially, the SVNO does not own the entire underlying infrastructure but can request the customized hardware and software network resources from satellite network operators via customer portals.
- *Efficient integration of satellite and terrestrial networks*. In the SoftSpace, the forwarding devices are equipped with open and standardized interfaces, which enables the interoperation among vendors. Moreover, although satellite communication technologies develop rapidly, they are hardly synchronized with the terrestrial communication systems. Enabling NFV in the SoftSpace simplifies the provision of networking services and the introduction of novel technologies, which fills the gap of technology development between satellite networks and terrestrial networks. The SDN-enabled control and management across satellite and terrestrial domains facilitate the flexible and efficient integration of satellite and terrestrial networks.
- *Compatibility of heterogeneous satellite systems*. Due to the lack of common standards in satellite networks, the evolution of satellite network architecture is hardly

identified and the network functionalities tightly depend on vendor-specific network appliances. This leads to vendor-specific network infrastructure setting, complex network infrastructure management, and non-interoperable solutions from multiple vendors. Thus, it is reasonable to assume that satellite networks are heterogeneous. In the SoftSpace, the SDR technology provides the satellite network devices with hardware programmability, which enables multi-mode operation, radio reconfiguration and remote upgrade. Thus, the satellite network devices can accommodate new applications and services without hardware changes, the heterogeneous satellite systems can be interconnected conveniently.
- *High resource efficiency*. Introducing SDN and NFV paradigms into SoftSpace brings great benefits to the network management. Utilizing the global knowledge gained from the data plane, the network controller can determine efficient resource allocation solutions and rescale service resources on demand adaptively.

D. SOFTSPACE MANAGEMENT INSTRUMENTS

As shown in Fig. 2, to implement the attractive features and optimize the network performance of SoftSpace, network management instruments need to be provided. Moreover, the OpenFlow should be extended and modified to provide function abstractions for network/MAC/physical layers, so that cross-layer control function can be easily designed and implemented in the control plane.

- *OpenFlow extension*. OpenFlow is an essentially specific abstraction designed for the routing functionality of forwarding devices in the wired networks. The wireless and mobile working group has been formed by ONF to explore how to enhance the adaptability of OpenFlow for wireless environments. To extend OpenFlow protocol for software-defined satellite networks will be an enthusiasm of this group. In our proposed SoftSpace architecture, new abstractions and certain modifications are required to be introduced into the OpenFlow. The extended OpenFlow for SoftSpace will be designed to offer the control plane functionalities across different layers. Firstly, the abstractions of MAC and physical layer functions will be incorporated into the OpenFlow to manage and configure satellite network resources. Secondly, for satellite networks, the network transmission mostly depends on the data link layer and the network layer. Therefore, the matching fields associated with TCP/UDP can be discarded in the extended OpenFlow. If the matching fields about transport layer are kept, these matching fields also need to be modified. This is because the TCP protocol performs inefficiently over satellite links owing to the long propagation delay, high bit error rate and data rate asymmetry [66], [67]. Thirdly, the existing satellite networking technology is mainly based on ATM, so the information about ATM protocol should be added into the OpenFlow for the better compatibility with legacy systems. In this way, the cross-layer protocols can be easily designed and implemented on SoftSpace. Furthermore, a set of port properties (e.g., modification, statistics, and description) should be added to support radio wave ports. They include fields to configure and monitor transmit and receive frequency of a wave, as well as its power. Experimenter multipart messages can be utilized to request and reply satellite state information including available bandwidth, radiation power, carrier to noise ratio, etc. In addition, error report messages should be defined to notify the controller the problems of satellite failure, overload, and high bit error rate.
- *Multi-layer hierarchical controller architecture*. The distance between satellite and Earth is long. Satellites are configured by ground stations only when they fly over the stations. As a consequence, using single centralized controller architecture based on ground NCC/NMC need to construct plenty of ground stations, and this prolongs the delay of global network configuration. Therefore, the potential features of distributed controller architecture and wide coverage broadcast attribute of GEO satellite are exploited to design the multi-layer controller architecture to reduce the cost of network control.
- *Cooperative traffic classification*. The increase of satellite applications presents challenges to guarantee the QoS and user's QoE in the integrated satellite-terrestrial networks. The traffic classification is needed to identify the application types or categorize the traffic flows into different QoS classes, so that the differentiated resource provisioning and optimal routing path can be developed. The classical approaches based on port number are ineffective due to the increasing usage of private and dynamic ports [68]. Deep packet inspection (DPI) and machine learning (ML) approaches are developed to address the drawback of port-based approaches. However, these approaches are inaccurate due to encryption, frequently emerging applications, etc [8]. Thus, a fine-grained, adaptive and accurate traffic classification is required in the SoftSpace.
- *Utility-optimal network virtualization*. The essence of satellite network as a service is exploiting the NV paradigm to support that a variety of emerging satellite applications share the same underlying physical devices. Because of the limitation of satellite network resources, the utility-optimal satellite network virtualization solutions are extremely favorable. In the SoftSpace, the utility-optimal network virtualization can be implemented from high-level to low-level. The network hypervisor is designed to optimize the resource utilization of the whole network, while satisfying the QoS requirements of each virtual network. Moreover, the wireless/switch hypervisors are devised to manage multiple isolated virtual networks on each satellite network device, guaranteeing that the throughput is improved with efficient resource utilization.

- *Fast lightweight security strategy*. In the SoftSpace, space forwarding devices are frequently disconnected and reconnected with network controllers over wireless channels, which makes the information transmission vulnerable to interception, tamper, disruption, etc. A fast lightweight security strategy is required to solve the security problem in the SoftSpace, as satellite networks have long propagation delay, high bit error rate, and limited computing and storage capacity. The encryption technology with low computational overhead should be utilized to realize authentication to reduce the requirement for node processing capacity. The periodicity and predictability of topology can be exploited to negotiate session key in advance, which shortens the connection establishment delay.

V. CHALLENGES AND SOLUTIONS IN SOFTSPACE MANAGEMENT

Three essential management instruments are developed in this section, including multi-layer hierarchical controller architecture, cooperative traffic classification, and utility-optimal network virtualization.

A. MULTI-LAYER CONTROLLER ARCHITECTURE

It is incredibly challenging to achieve the reliable and scalable SoftSpace by employing one single centralized controller since the global-wide distribution of satellites causes long signaling delay to the network state collection and control message distribution. Moreover, the future satellite Internet will be composed of hundreds or thousands of satellites [69]. Thus, the scalability issue will be faced by the single controller with limited computing capability, especially when the network size expands or the number of flows increases. In addition, the single point failure problem exists in the single centralized controller architecture. Thus, the network reliability is another crucial issue. The distributed controller structure including flat controller architecture and hierarchical controller architecture is considered in the SoftSpace to address these challenges. For flat controller architecture, all controllers distributed in different regions are at the same level. Each controller knows the network-wide state. If the flat controller architecture is adopted, multiple ground controllers need to be deployed in different regions to reduce the signaling delay of network state collection and control message distribution. This involves in national and political issues, thus it is difficult to be fulfilled. If multiple satellites are deployed as controllers to overcome the problem of multiple ground controllers, the satellites have to gain network-wide states and only control the local area. This leads to the waste of satellite resources, so it is unsuitable for satellite networks with limited resources.

An extended OpenFlow-enabled multi-layer controller architecture which consists of three levels of controllers is developed to address the above challenges, as shown in Fig.5. The extended OpenFlow-enabled LEO (SD-LEO) satellites are responsible for forwarding data and collecting network state information. The GEO satellite has wide coverage area,

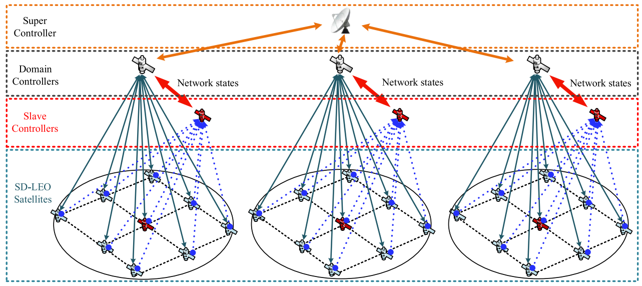

FIGURE 5. Multi-layer hierarchical control architecture.

broadcast communication ability, relatively long life, and high computation capability. They can maintain a stable connection with the ground station without link switching. Consequently, the GEO satellite is designated as the domain controller. The SD-LEO satellites are grouped into various domains according to the coverage of GEO satellites. The GEO satellite has full access to all SD-LEO satellites in its coverage through broadcast links and takes charge of the management of these SD-LEO satellites. The increasing number of LEO satellites creates a huge control workload to GEO satellites. More GEO satellites are required to be deployed to control and manage LEO satellites. While the orbit of GEO satellite is limited and the GEO satellite is unable to cover the polar areas completely. Thus, some LEO satellites are deployed as slave controllers to address the above problems. The slave controller collects the network states through inter-satellite links and sends them to the domain controller. Each domain contains a domain controller, one or multiple slave controllers, and many underlying SD-LEO satellites. The NCC/NMC with high computation capability and abundant storage is in charge of monitoring and controlling the communication performance of on-orbit satellites. The NCC/NMC located on the ground surface is easy to be updated and upgraded. Therefore, the NCC/NMC is suitable to be the only one super controller to facilitate the entire network control.

The GEO satellite receives asynchronous messages of flow setup requests and modifies the states of SD-LEO satellites in its coverage by broadcasting control messages. The NCC/NMC accesses to SD-LEO satellites and manages the entire network functionalities through GEO satellites. The interaction between GEO satellite and NCC/NMC fulfills the global flow setup and responds to every control action. The slave controllers are dedicated to distributing control messages to various applications through inter-satellite links, and they do not require network-wide states. In this way, a logically centralized control plane with the global knowledge is established by a physically distributed system. It dramatically reduces the disturbance caused by GEO satellite broadcast and the signaling delay between controllers and switches, as well as balances control load.

B. COOPERATIVE TRAFFIC CLASSIFICATION

Traffic classification aims at identifying the exact application of every traffic flow or categorizing the traffic flows into different QoS classes, so that the differentiated resource provisioning and feasible routing path can be determined. Advanced satellite communication and networking technologies enable satellite networks to transmit various traffic flows. Novel satellite network applications are continuously emerging, and existing applications are updated to adapt to the ever-changing user's demands. Therefore, an adaptive and fine-grained traffic classification is desired at the SD-STs to allocate uplink resource for highly dynamic traffic efficiently. On the other hand, the accuracy and rapidity of traffic classification are required to satisfy the requirement of the automatic and real-time system.

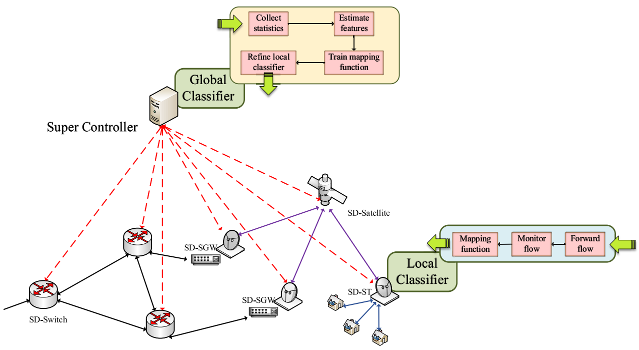

FIGURE 6. Traffic classification.

The cooperative traffic classification system is developed for SoftSpace to achieve the above goals, as shown in Fig. 6. The proposed solution utilizes DPI to label the known applications and jointly exploits the global view and high computational capability of the super controller to identify the unknown applications. More specially, our proposed traffic classification system is composed of local traffic classifiers located at distributed SD-STs and global traffic classifier located at the super controller. The local traffic classifier monitors the traffic flows and notifies the super controller of flows information. The local traffic classifier simply performs the mapping function got from the super controller. The global traffic classifier is responsible for guaranteeing the accuracy and adaptability of traffic classification. It uses ML algorithm to build mapping function for flows between their statistical properties and the most likely QoS classes. The credible mapping function based on ML is heavily dependent on massive amounts of integral and meaningful data. Thus, it is necessary for the super controller to update the reference database periodically to adapt to the ever-changing network environments and applications. Then, the super controller learns the updated database to get new mapping function and uses it to refine the local classifiers through the secure channels.

C. UTILITY-OPTIMAL NETWORK VIRTUALIZATION

In the SoftSpace, the purpose of network virtualization is to create a series of isolated virtual satellite networks based on the shared physical infrastructure. To realize network virtualization, we propose the network hypervisor (Fig.3) for high-level virtualization and the wireless/switch hypervisor (Fig.7) for low-level virtualization.

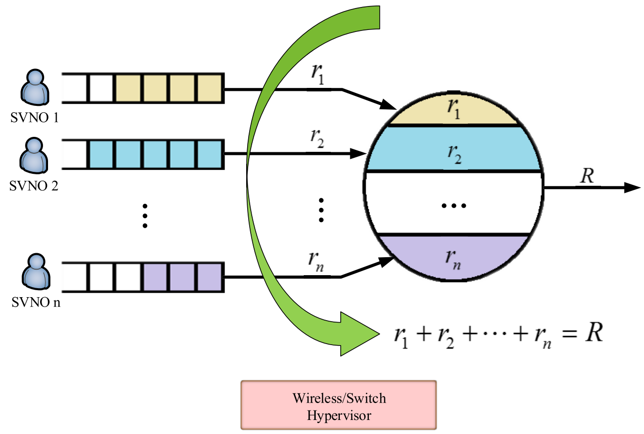

FIGURE 7. Wireless/switch hypervisor of SoftSpace.

1) NETWORK HYPERVISOR

The network hypervisor aims at allocating non-conflicting network resources among satellite network virtual operators according to their demands. A utility-optimal network hypervisor is required in the SoftSpace to maximize the global network resource utilization and satisfy the QoS requirement of each virtual operator. The network resources of SoftSpace contain (i) spectrum resources, comprising time slots and frequency channels, (ii) infrastructure resources, including SD-SGWs, SD-Satellites, SD-STs, and SD-Switches, and (iii) communication technologies, such as radio wave communication and optical communication. The data rate required by each virtual operator can be formulated, and then the wireless resources can be allocated to the virtual operators by the network controller. It means that the time percentage of the channel occupied by each virtual network is determined. For each virtual operator, its power and radio access technologies are determined by the network hypervisor. With the resources and communication technologies allocated by the utility-optimal network hypervisor, the QoS requirements of all virtual operators are satisfied, while ensuring the optimal resource utilization.

2) WIRELESS/SWITCH HYPERVISOR

The wireless hypervisor is designed to execute the resource management policies that are determined by the network hypervisor. Varieties of wireless resource dimensioning schemes are employed by the wireless hypervisor to ensure the isolation among virtual networks. Thus, the customized network/MAC/physical-layer protocols can be implemented by each virtual network. For satellite networks, the wireless hypervisor can be implemented by FDMA, TDMA, or CDMA, etc. However, each scheme has specific advantages and disadvantages, so none of these schemes can be suitable for all satellite applications. FDMA is not adaptive to the increasing number of users, since it has low band utilization and limited bandwidth caused by adjacent channel interference and band spacing reservation. TDMA overcomes these problems effectively, but it requires network-wide time synchronization. The time synchronization is difficult to be achieved considering the long propagation delay and the diversity of user terminals in satellite networks. CDMA is characterized by high transmission bandwidth, anti-multipath fading performance, and anti-jamming capability, while it is mainly used in low-speed data services. Non-orthogonal multiple access (NOMA) gives a new dimension, i.e., power domain, to separate signal from each other. NOMA is characterized by its better compatibility with other communication technologies, the capability of supporting more connections, etc. It has been investigated to implement in satellite-terrestrial integrated networks [70], [71]. Thus, NOMA, as a promising technology, can be exploited to realize wireless hypervisor.

Besides offering the absolute isolation for virtual networks, the wireless hypervisor also has to utilize the limited spectrum resources efficiently. The wireless scheduling solution proposed for wireless hypervisor in terrestrial networks is just at its early stage [72], [73], not to mention in satellite networks. Flow-oriented hybrid (fixed, random and on-demand) resource scheduling scheme is required for the introduction of SDN in satellite networks. The trade-off among fairness, delay, and throughput need to be considered so that the isolation among virtual networks can be guaranteed, while enhancing the fairness, delay and throughput of each virtual network. The switch hypervisor aims at allocating bandwidth at SD-Switches, namely, providing the scheduled bandwidth for virtual operators. FlowVisor as a well-known switch hypervisor based on OpenFlow is a leading enabler in the SoftSpace.

VI. CHALLENGES AND SOLUTIONS IN SOFTSPACE NETWORKING

Software-defined space networking solutions leveraging the potentiality of the SoftSpace architecture are proposed in this section. More specifically, the QoE-aware space routing is presented to maximize the user's QoE for different flows (such as video, audio, or data transfer) by exploiting global network knowledge and configuration flexibility. SDN-enabled fault recovery mechanism is designed to timely recover the network operations with the minimum network performance degradation when satellite failure happens. Software-defined space mobility management is exploited to minimize the disconnection time caused by changing communication link from one satellite or spot beam to another, meanwhile ensuring that the rerouting paths satisfy the QoS requirements of traffic flows.

A. QoE-AWARE SPACE ROUTING

The multimedia services provided by ubiquitous satellite networks boost varieties of novel and emerging applications such as recreation, e-health, situational awareness, and disaster rescue [8]. In order to achieve high QoE, the QoS requirements of applications need to be considered. Nevertheless, the limited QoS offered by satellite networks has a significant influence on user's QoE. Almost 90% of users just choose to change the provider instead of continuing to accept a low quality service. Thus, the business of telecommunication companies is highly dependent on customer satisfaction. Providing users with high QoE is a great challenge for network service providers. Existing researches on QoE mainly focus on its measurement and evaluation or QoE-based resource scheduling [74]–[76]. It is rarely used to design routing solutions for satellite networks. Although most satellite network routing protocols are designed based on the network-oriented parameters [77]–[79], they may not correlate well with user perception. Consequently, it is necessary to develop QoE-aware routing protocols for satellite networks, which monitors various impact factors to estimate QoE and employs the QoE measure as routing metric to maximize QoE.

A QoE-aware flow routing scheme is presented for the SoftSpace. This scheme takes advantages of global view, configuration flexibility and superior computational power provided by SoftSpace. The pseudo-subjective assessment approach is exploited to estimate QoE. This is because that the subjective elevation is long time and high manpower consumption, and the objective approaches do not correlate well with user perception. Based on the estimated QoE, the QoE-aware reward function is designed to support reinforcement learning based QoE-aware routing. Then, according to traffic types, network controllers use reinforcement learning [80] to determine the routing path with the maximal QoE-aware reward. More specifically, when a new flow arrives at an SD-LEO satellite, the first packet is sent to the corresponding domain controller. Domain controllers update the current network states according to the latest state information gathered from slave controller(s). The domain controller computes a feasible path for the flow using reinforcement learning and modifies the flow tables of SD-LEO satellites in the feasible path. If the destination is not in the subnet of the domain controller, the domain controller will send the first packet to super controller. The super controller computes the forwarding path among subnets and sends notification to the involved domain controllers. Then, several involved domain controllers perform routing calculation simultaneously to find the forwarding path for the flow. In this way, the time cost of computing forwarding path is reduced and the time efficiency of the routing scheme is improved.

B. SDN-ENABLED HYBRID FAULT RECOVERY MECHANISM

Satellite nodes are susceptible to various failures in the space environment. A satellite may fail or be shut down for some reasons such as maintenance, energy saving, or orbital transfer for emergency communication [81]. The failed or shutdown satellite not only makes the paths passing through it invalid but also influences the communication of a new geographical area where it moves. The local faults cause that the entire network operation is destroyed. Therefore, in the case of satellite failure, to recover the affected routing in time is essential.

A strategy which can deal with the detected failure to recover the service effectively is required. The existing researches on fault-tolerant routing in satellite networks are classified into the reactive mechanism and the proactive one. The former calculates a recovery path to restore the affected service when the working path is failed [79]. The latter protects the working path by providing a recovery path before path failure occurs [82]. Both of them can be enforced in the SoftSpace.

- As for the reactive mechanism, upon receiving satellite failure notification, the controller updates the network topology. According to the new network topology, a recovery path is calculated by using any feasible routing algorithm. The following possible operations on flow entry include modification, addition, and deletion. If the affected SD-LEO satellite is simultaneously on the failed working path and the recovery path, the involved flow entry will be modified; otherwise, for the affected SD-LEO satellite solely on the failed working path, the involved flow entry will be deleted, and for the affected SD-LEO satellite solely on the recovery path, the new flow entry will be added.
- As for the proactive mechanism, the recovery path is pre-computed and installed into the SD-LEO satellites along with the working path before the failure occurs. Thus, the flow entry of each SD-LEO satellite contains two forwarding information. When the failure happens on the working path, the recovery path will be used to protect the forwarding flow from interruption. The group table or flow entry priority proposed for OpenFlow can be used to accomplish the switching between working path and recovery path.

The failure recovery duration of proactive mechanism based on group table is short, but it suffers from low resource utilization and large storage overhead for a great number of discrete topologies. The reactive mechanism gains the optimal recovery path with high resource utilization but suffers from large computation overhead and slow reaction for random satellite failure. Its failure recovery duration is determined by the recovery path length, the number of flows required to be recovered, and other unknown random factors, thus the recovery duration may be long. While, satellites have limited compute ability and storage space [82]. It needs long time and high cost to repair the fault satellite.

A hybrid fault recovery mechanism is proposed for SoftSpace to address these challenges. It combines the advantages of proactive mechanism and reactive mechanism to reduce the failure recovery time and guarantee the optimal recovery path. More specially, the working path and recovery path are pre-computed by the network controller and are installed into SD-LEO satellites simultaneously. When satellite failure is detected, the affected satellite firstly changes from the working path to the recovery path, so that the failure recovery time is reduced. Then, the failure notification is sent to network controller by the affected satellite. Following, the reactive mechanism in network controller is triggered to compute new recovery path, since the recovery path may be not the best routing path under the new network topology. If the newly calculated recovery path is better than the previous recovery path, it will be enforced by modifying the flow entry in the affected SD-LEO satellite. In many case that the failure is temporary. The recovery path can not provide the optimal route when the affected SD-LEO satellites return to normal. This leads to resource waste, thus the failure recovery notification is sent to the network controller. Once the network controller receives the notification, the original working path is reused.

C. SOFTWARE-DEFINED SPACE MOBILITY MANAGEMENT

The number of mobile terminal devices and traffic volume are increasing at a remarkable exponential rate. The non-geostationary satellites have the characteristics of small latency, low free space loss and good reuse of available communication frequencies. Thus, they are approved to provide global communication for current applications, especially for the real-time interactive services. The mobility management is essential to sustain the suitable connection for mobile users when their communication links are changed from one satellite or spot beam to another [83], [84]. The disconnection time caused by handover should be minimized to realize seamless mobility management. At the same time, the QoS requirements of traffic flows should be satisfied. It is different from terrestrial mobile networks in which mobility problems are caused by user movements, the mobility management in satellite networks has to take satellite motion, Earth rotation, and user movements into account [85].

In the SoftSpace, forwarding rules can be set up on all SD-LEO satellites simultaneously, which facilitates the seamless mobility management greatly. The QoS guarantees for each flow can be achieved by leveraging the information of per-flow and the global topology. Furthermore, satellite orbit model in the conventional terrestrial coordinate is planed. And the user mobility model that can predict the location where a mobile user would move to can be established by exploiting the geographical location information provided by the global position system. Based on the above facts, the mobility prediction based dynamic re-routing approach can be used [6], [84]. More specially, based on the satellite motion (i.e., moving speed, current location, moving direction and orbital position) and user movement (i.e., the user's current location, moving speed, moving direction and historical mobility pattern), where and when handovers will take place can be calculated. According to the prediction results, the traffic flows that need to be rerouted and the new routes of these flows are determined by network controller before the handover occurs. A QoS-guaranteed routing algorithm can be used to calculate new routes which can satisfy the QoS requirements of flows [86]. Then, the new routes are installed on related SD-LEO satellites and will be wake-up when the mobile users move to the predicted locations.

VII. IMPLEMENTATION ROADMAP

The roadmap is identified to provide guideline for the actual development of the SoftSpace architecture, and it is presented from three dimensions: timescale, technology and research focus.

- With the evolution of SoftSpace, a ***time roadmap*** can be divided into three periods, including short term, medium term, and long term. In particular, there are two division criteria, one is which network components are redefined by softwarization and virtualization, and the other one is which functions are separated from the network components. In terms of network components, the short term is focused on integrating softwarization and virtualization into gateway. The medium term aims at extending softwarization and virtualization to satellite terminals. The long term is concentrated on softwarization and virtualization in satellite payloads. While, from the point of network component functions, the softwarization and virtualization can be envisaged only for the network layer in the short term, MAC layer in the medium term and the physical layer in the long term, respectively.
- Based on the well-established technology platform of softwarization and virtualization, a ***technology roadmap*** can be identified as follows. The extended OpenFlow is used to standardize the information exchange between controller and forwarding devices in the SoftSpace. Open vSwitch based software switch that supports the extended OpenFlow, is the implementation of SoftSpace infrastructure. FlowVisor is devoted to complete network virtualization. The GNU Radio is for SDR implementation, and the OpenDaylight which supports the extended OpenFlow is for the unified network management in the SoftSpace.
- The ***roadmap of research focus*** can be divided into three steps. In the first step, the studies should focus on designing solutions to deal with challenges. The next step should aim at turning the study results into standards and giving some early demonstrations. The last step is applied to pre-operational demonstrations and service delivery.

VIII. CONCLUSION

In this paper, a highly flexible architecture, SoftSpace, is proposed as a new networking paradigm for next-generation satellite networks. It brings the following benefits. (i) The innovations of hardware infrastructure and software algorithm are accelerated through the separation of control plane and data plane. (ii) The differentiated and adaptive network control and management for diverse satellite network applications are made possible through NV. (iii) Hybrid space communication technologies are encouraged to be jointly exploited through NFV. (iv) Based on the global knowledge about network state and customer requirement, network resource utilization is enhanced.

To realize the promising properties of SoftSpace, three necessary management instruments are developed, including multi-layer controller architecture, cooperative traffic classification, and utility-optimal network virtualization. In addition, the software-defined space networking solutions are given, including QoE-aware space routing, SDN-enabled fault recovery mechanism, and software-defined space mobility management. We theoretically presented the feasibility and effectiveness of the proposed SoftSpace architecture, management instruments and networking solutions, but much more investigations and validations are required. In the near future, we will provide numeral analysis for our proposed solutions. There are many other challenges need to be tackled before implementing the SoftSpace, such as northbound definition, slave controller selection, security issues, etc. We will further enhance the SoftSpace architecture and explore solutions to solve these challenges.

REFERENCES

[1] F. Khan. (Aug. 2015). "Mobile Internet from the heavens." [Online]. Available: https://arxiv.org/abs/1508.02383

[2] G. Araniti, I. Bisio, M. De Sanctis, A. Orsino, and J. Cosmas, "Multimedia content delivery for emerging 5G-satellite networks," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 10–23, Mar. 2016.

[3] O. Ercetin, M. O. Ball, and L. Tassiulas, "Next generation satellite systems for aeronautical communications," *Int. J. Satellite Commun. Netw.*, vol. 22, no. 2, pp. 157–179, 2004.

[4] F. Alagoz, O. Korcak, and A. Jamalipour, "Exploring the routing strategies in next-generation satellite networks," *IEEE Wireless Commun.*, vol. 14, no. 3, pp. 79–88, Jun. 2007.

[5] Y. Vasavada, R. Gopal, C. Ravishankar, G. Zakaria, and N. BenAmmar, "Architectures for next generation high throughput satellite systems," *Int. J. Satellite Commun. Netw.*, vol. 34, no. 4, pp. 523–546, 2016.

[6] J. Bao, B. Zhao, W. Yu, Z. Feng, C. Wu, and Z. Gong, "OpenSAN: A software-defined satellite network architecture," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 44, no. 4, pp. 347–348, 2014.

[7] J. Mukherjee and B. Ramamurthy, "Communication technologies and architectures for space network and interplanetary Internet," *IEEE Commun. Surveys Tuts.*, vol. 15, no. 2, pp. 881–897, 2nd Quart., 2013.

[8] C. Niephaus, M. Kretschmer, and G. Ghinea, "QoS provisioning in converged satellite and terrestrial networks: A survey of the state-of-the-art," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2415–2441, 4th Quart., 2016.

[9] R. Ferrús *et al.*, "SDN/NFV-enabled satellite communications networks: Opportunities, scenarios and challenges," *Phys. Commun.*, vol. 18, pp. 95–112, Mar. 2016.

[10] D. Kreutz, F. Ramos, P. E. Veríssimo, C. E. Rothenberg, S. Azodolmolky, and S. Uhlig, "Software-defined networking: A comprehensive survey," *Proc. IEEE*, vol. 103, no. 1, pp. 14–76, Jan. 2015.

[11] R. Mijumbi, J. Serrat, J.-L. Gorricho, N. Bouten, F. de Turck, and R. Boutaba, "Network function virtualization: State-of-the-art and research challenges," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 1, pp. 236–262, 1st Quart., 2016.

[12] N. M. M. K. Chowdhury and R. Boutaba, "Network virtualization: State of the art and research challenges," *IEEE Commun. Mag.*, vol. 47, no. 7, pp. 20–26, Jul. 2009.

[13] G. Baldini, T. Sturman, A. R. Biswas, R. Leschhorn, G. Godor, and M. Street, "Security aspects in software defined radio and cognitive radio networks: A survey and a way ahead," *IEEE Commun. Surveys Tuts.*, vol. 14, no. 2, pp. 355–379, 2nd Quart., 2012.

[14] D. F. Macedo, D. Guedes, L. F. Vieira, M. A. Vieira, and M. Nogueira, "Programmable networks—From software-defined radio to software-defined networking," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 1102–1125, 2nd Quart., 2015.

[15] R. Jain and S. Paul, "Network virtualization and software defined networking for cloud computing: A survey," *IEEE Commun. Mag.*, vol. 51, no. 11, pp. 24–31, Nov. 2013.

[16] L. Bertaux *et al.*, "Software defined networking and virtualization for broadband satellite networks," *IEEE Commun. Mag.*, vol. 53, no. 3, pp. 54–60, Mar. 2015.

[17] H. Kim and N. Feamster, "Improving network management with software defined networking," *IEEE Commun. Mag.*, vol. 51, no. 2, pp. 114–119, Feb. 2013.

[18] B. Pfaff *et al.*, "OpenFlow switch specification v1. 3.0," Open Netw. Found., Menlo Park, CA, USA, Tech. Rep. ONF TS-006, 2012.

[19] B. A. A. Nunes, M. Mendonca, X.-N. Nguyen, K. Obraczka, and T. Turletti, "A survey of software-defined networking: Past, present, and future of programmable networks," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1617–1634, 3rd Quart., 2014.

[20] A. Hakiri, A. Gokhale, P. Berthou, D. C. Schmidt, and T. Gayraud, "Software-defined networking: Challenges and research opportunities for future internet," *Comput. Netw.*, vol. 75, pp. 453–471, Dec. 2014.

[21] F. Pakzad, M. Portmann, W. L. Tan, and J. Indulska, "Efficient topology discovery in OpenFlow-based software defined networks," *Comput. Commun.*, vol. 77, pp. 52–61, Mar. 2016.

[22] B. Han, V. Gopalakrishnan, L. Ji, and S. Lee, "Network function virtualization: Challenges and opportunities for innovations," *IEEE Commun. Mag.*, vol. 53, no. 2, pp. 90–97, Feb. 2015.

[23] H. Hawilo, A. Shami, M. Mirahmadi, and R. Asal, "NFV: State of the art, challenges, and implementation in next generation mobile networks (vEPC)," *IEEE Netw.*, vol. 28, no. 6, pp. 18–26, Nov./Dec. 2014.

[24] *What is Network Virtualization?-Definition*. Accessed: Dec. 30, 2017. [Online]. Available: https://www.sdxcentral.com/sdn/network-virtualization/definitions/whats-network-virtualization/

[25] A. Lara, A. Kolasani, and B. Ramamurthy, "Network innovation using OpenFlow: A survey," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 1, pp. 493–512, 1st Quart., 2014.

[26] H. Yang, J. Zhang, Y. Zhao, J. Han, Y. Lin, and Y. Lee, "SUDOI: Software defined networking for ubiquitous data center optical interconnection," *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 86–95, Feb. 2016.

[27] I. F. Akyildiz, P. Wang, and S.-C. Lin, "Softair: A software defined networking architecture for 5G wireless systems," *Comput. Netw.*, vol. 85, pp. 1–18, Jul. 2015.

[28] I. F. Akyildiz, S.-C. Lin, and P. Wang, "Wireless software-defined networks (W-SDNs) and network function virtualization (NFV) for 5G cellular systems: An overview and qualitative evaluation," *Comput. Netw.*, vol. 93, pp. 66–79, Dec. 2015.

[29] I. F. Akyildiz, P. Wang, and S.-C. Lin, "SoftWater: Software-defined networking for next-generation underwater communication systems," *Ad Hoc Netw.*, vol. 46, pp. 1–11, Aug. 2016.

[30] C. Bu, X.-W. Wang, H. Cheng, M. Huang, K.-Q. Li, and S.-K. Das, "Enabling adaptive routing service customization via the integration of SDN and NFV," *J. Netw. Comput. Appl.*, vol. 93, no. 1, pp. 123–136, 2017.

[31] B. Yi, X.-W. Wang, M. Huang, and A.-W. Dong, "A multi-stage solution for NFV-enabled multicast over the hybrid infrastructure," *IEEE Commun. Lett.*, vol. 21, no. 9, pp. 2061–2064, 2017.

[32] T. Ahmed, E. Dubois, J.-B. Dupé, R. Ferrús, P. Gélard, and N. Kuhn, "Software-defined satellite cloud ran," *Int. J. Satellite Commun. Netw.*, vol. 36, no. 1, pp. 108–133, 2018.

[33] M. Sheng, Y. Wang, J. Li, R. Liu, D. Zhou, and L. He, "Toward a flexible and reconfigurable broadband satellite network: Resource management architecture and strategies," *IEEE Wireless Commun.*, vol. 24, no. 4, pp. 127–133, Aug. 2017.

[34] G. Gardikis, H. Koumaras, C. Sakkas, and V. Koumaras, "Towards SDN/NFV-enabled satellite networks," *Telecommun. Syst.*, vol. 66, no. 4, pp. 615–628, 2017.

[35] Á. Kapovits, S. Covaci, C. Ververidis, V. Siris, and M. Guta, "Advanced topics in service delivery over integrated satellite terrestrial networks," in *Proc. 7th Adv. Satellite Multimedia Syst. Conf.*, Sep. 2014, pp. 92–98.

[36] Z. Tang, B. Zhao, W. Yu, Z. Feng, and C. Wu, "Software defined satellite networks: Benefits and challenges," in *Proc. IEEE Comput., Commun. IT Appl. Conf. (ComComAp)*, Oct. 2014, pp. 127–132.

[37] B. Barritt and W. Eddy, "SDN enhancements for LEO satellite networks," in *Proc. 34th AIAA Int. Commun. Satellite Syst. Conf.*, 2016, p. 5755.

[38] G. Gardikis *et al.*, "NFV applicability and use cases in satellite networks," in *Proc. Eur. Conf. Netw. Commun. (EuCNC)*, Jun. 2016, pp. 47–51.

[39] G. Agapiou *et al.*, "SDN and NFV for satellite infrastructures," in *Proc. IEICE ICTF Inst. Electron., Inf. Commun. Eng. (IEICE)*, 2016, pp. 1–4.

[40] R. Ferrus, O. Sallent, T. Ahmed, and R. Fedrizzi, "Towards SDN/NFV-enabled satellite ground segment systems: End-to-end traffic engineering use case," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, May 2017, pp. 888–893.

[41] R. Ferrus *et al.*, "On the virtualization and dynamic orchestration of satellite communication services," in *Proc. IEEE 84th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2016, pp. 1–5.

[42] T. Ahmed *et al.*, "Satellite gateway diversity in SDN/NFV-enabled satellite ground segment systems," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, May 2017, pp. 882–887.

[43] T. Rossi, M. De Sanctis, E. Cianca, C. Fragale, M. Ruggieri, and H. Fenech, "Future space-based communications infrastructures based on high throughput satellites and software defined networking," in *Proc. IEEE Int. Symp. Syst. Eng. (ISSE)*, Sep. 2015, pp. 332–337.

[44] *VITAL*. Accessed: Jul. 30, 2017. [Online]. Available: http://cordis.europa.eu/project/rcn/194250_en.html

[45] *Architectural Proposal for Federated Satellite/Terrestrial Software Networks in the 5G Context*. Accessed: Dec. 25, 2017. [Online]. Available: https://5g-ppp.eu/wp-content/uploads/2016/03/5GAW_Federated_Satellite_Terrestrial_SW_Networks_v3.pdf

[46] X. Huang, Z. Zhao, X. Meng, and H. Zhang, "Architecture and application of SDN/NFV-enabled space-terrestrial integrated network," in *Proc. Int. Conf. Space Inf. Netw.*, 2016, pp. 244–255.

[47] C. Wang and X. Yu, "Application of virtualization and software defined network in satellite network," in *Proc. Int. Conf. Cyber-Enabled Distrib. Comput. Knowl. Discovery (CyberC)*, Oct. 2016, pp. 489–493.

[48] L. Shi, Z. Lu, P. Qin, and H. Yao, "OpenFlow based spatial information network architecture," in *Proc. Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2015, pp. 1–5.

[49] 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.*, 2016, pp. 16–25.

[50] F. Pinto, F. Afghah, R. Radhakrishnan, and W. Edmonson, "Software defined radio implementation of DS-CDMA in inter-satellite communications for small satellites," in *Proc. IEEE Int. Conf. Wireless Space Extreme Environ. (WiSEE)*, Dec. 2015, pp. 1–6.

[51] M. R. Maheshwarappa, M. Bowyer, and C. P. Bridges, "Software defined radio (SDR) architecture to support multi-satellite communications," in *Proc. IEEE Aerosp. Conf.*, Mar. 2015, pp. 1–10.

[52] F. Daneshgaran and M. Laddomada, "Transceiver front-end technology for software radio implementation of wideband satellite communication systems," *Wireless Pers. Commun.*, vol. 24, no. 2, pp. 99–121, 2003.

[53] H. Hurskainen, J. Raasakka, T. Ahonen, and J. Nurmi, "Multicore software-defined radio architecture for GNSS receiver signal processing," *EURASIP J. Embedded Syst.*, vol. 2009, no. 1, p. 543720, 2009.

[54] F. Alagoz and G. Gur, "Energy efficiency and satellite networking: A holistic overview," *Proc. IEEE*, vol. 99, no. 11, pp. 1954–1979, Nov. 2011.

[55] Y. Hu and V. O. K. Li, "Satellite-based Internet: A tutorial," *IEEE Commun. Mag.*, vol. 39, no. 3, pp. 154–162, Mar. 2001.

[56] *Digital Video Broadcasting (DVB); Second Generation DVB Interactive Satellite System*, D. Second Generation, document DVB A155-2, 2010.

[57] R. Ferrús *et al.*, "Enhancing satellite & terrestrial networks integration through nfv/sdn technologies," *E-Letter*, vol. 10, no. 4, pp. 17–21, 2015.

[58] J. P. Choi and C. Joo, "Challenges for efficient and seamless space-terrestrial heterogeneous networks," *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 156–162, May 2015.

[59] ONF Solution Brief, "OpenFlow-enabled mobile and wireless networks," Open Netw. Found., Menlo Park, CA, USA, White Paper, Sep. 2013, pp. 1–13. [Online]. Available: https://3vf60mmveq1g8vzn48q2o71a-wpengine.netdna-ssl.com/wp-content/uploads/2013/03/sb-wireless-mobile.pdf

[60] K.-K. Yap *et al.*, "OpenRoads: Empowering research in mobile networks," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 40, no. 1, pp. 125–126, 2010.

[61] S. Abdellatif, P. Berthou, P. Gelard, T. Plesse, and S. El-Yousfi, "Exposing an openflow switch abstraction of the satellite segment to virtual network operators," in *Proc. IEEE 83rd Veh. Technol. Conf. (VTC Spring)*, May 2016, pp. 1–5.

[62] *Software-Defined Networking From Serro Solutions Enables Global Communication Services in Near Real-Time*. Accessed: Jan. 28, 2018. [Online]. Available: https://www.serro.com/wp-content/uploads/serro-meo-white-paper.pdf

[63] S. Jain *et al.*, "B4: Experience with a globally-deployed software defined WAN," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 43, no. 4, pp. 3–14, 2013.

[64] C. Okino, C. Lee, A. Gray, and P. Arabshahi, "An autonomous evolvable architecture in a reconfigurable protocol chip for satellite networks," in *Proc. MAPLD Int. Conf.*, 2003, pp. 1–2.

[65] S. Sun, M. Kadoch, L. Gong, and B. Rong, "Integrating network function virtualization with SDR and SDN for 4G/5G networks," *IEEE Netw.*, vol. 29, no. 3, pp. 54–59, May/Jun. 2015.
[66] J. Du, C. Jiang, Q. Guo, M. Guizani, and Y. Ren, "Cooperative earth observation through complex space information networks," *IEEE Trans. Wireless Commun.*, vol. 23, no. 2, pp. 136–144, Apr. 2016.
[67] Z. Yang *et al.*, "Analytical characterization of licklider transmission protocol (LTP) in cislunar communications," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 50, no. 3, pp. 2019–2031, Jul. 2014.
[68] T. T. T. Nguyen and G. Armitage, "A survey of techniques for Internet traffic classification using machine learning," *IEEE Commun. Surveys Tuts.*, vol. 10, no. 4, pp. 56–76, 4th Quart., 2008.
[69] *Never Mind the Unconnected Masses, LeoSat's Broadband Constellation is Strictly Business*. Accessed: Nov. 20, 2017. [Online]. Available: http://spacenews.com/nevermind-the-unconnected-masses-leosats-broadband-constellation-is-strictly-business/
[70] X. Zhu, C. Jiang, L. Kuang, N. Ge, and J. Lu, "Non-orthogonal multiple access based integrated terrestrial-satellite networks," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2253–2267, Oct. 2017.
[71] E. Okamoto and H. Tsuji, "Application of non-orthogonal multiple access scheme for satellite downlink in satellite/terrestrial integrated mobile communication system with dual satellites," *IEICE Trans. Commun.*, vol. E99.B, no. 10, pp. 2146–2155, 2016.
[72] H. Wen, P. K. Tiwary, and T. Le-Ngoc, "Current trends and perspectives in wireless virtualization," in *Proc. Int. Conf. Sel. Topics Mobile Wireless Netw. (MoWNeT)*, Aug. 2013, pp. 62–67.
[73] C. Liang and F. R. Yu, "Wireless network virtualization: A survey, some research issues and challenges," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 358–380, 1st Quart., 2015.
[74] A. Lygizou, S. Xergias, and N. Passas, "rtPS scheduling with QoE metrics in joint WiMAX/satellite networks," in *Proc. Int. Conf. Pers. Satellite Serv.*, 2012, pp. 1–8.
[75] M. A. Pimentel-Niño, P. Saxena, and M. A. Vázquez-Castro, "QoE driven adaptive video with overlapping network coding for best effort erasure satellite links," in *Proc. 31st AIAA Int. Commun. Satellite Syst. Conf.*, 2013, p. 5668.
[76] I. Bisio, S. Delucchi, F. Lavagetto, and M. Marchese, "Transmission rate allocation over satellite networks with quality of experience—Based performance metrics," in *Proc. 7th Adv. Satellite Multimedia Syst. Conf.*, 2014 , pp. 419–423.
[77] Y. Zhou, F. Sun, and B. Zhang, "A novel QoS routing protocol for LEO and MEO satellite networks," *Int. J. Satellite Commun. Netw.*, vol. 25, no. 6, pp. 603–617, 2007.
[78] H. Nishiyama, D. Kudoh, N. Kato, and N. Kadowaki, "Load balancing and QoS provisioning based on congestion prediction for GEO/LEO hybrid satellite networks," *Proc. IEEE*, vol. 99, no. 11, pp. 1998–2007, Nov. 2011.
[79] F. Long, N. Xiong, A. V. Vasilakos, L. T. Yang, and F. Sun, "A sustainable heuristic QoS routing algorithm for pervasive multi-layered satellite wireless networks," *Wireless Netw.*, vol. 16, no. 6, pp. 1657–1673, 2010.
[80] R. S. Sutton and A. G. Barto, *Reinforcement Learning: An Introduction*, vol. 1. Cambridge, MA, USA: MIT Press, 1998.
[81] Z. Liu, J. Han, Y. Wang, X. Li, and S. Chen, "Performance analysis of routing algorithms in satellite network under node failure scenarios," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2014, pp. 2838–2843.
[82] Y. Lu, Y. Zhao, F. Sun, H. Li, and D. Wang, "Dynamic fault-tolerant routing based on FSA for LEO satellite networks," *IEEE Trans. Comput.*, vol. 62, no. 10, pp. 1945–1958, Oct. 2013.
[83] B. Yang, Y. Wu, X. Chu, and G. Song, "Seamless handover in software-defined satellite networking," *IEEE Commun. Lett.*, vol. 20, no. 9, pp. 1768–1771, Sep. 2016.
[84] T. Taleb, Y. Hadjadj-Aoul, and T. Ahmed, "Challenges, opportunities, and solutions for converged satellite and terrestrial networks," *IEEE Wireless Commun.*, vol. 18, no. 1, pp. 46–52, Feb. 2011.
[85] H. N. Nguyen, *Routing and Quality-of-Service in Broadband LEO Satellite Networks*, vol. 2. Dordrecht, Netherlands: Springer, 2003.
[86] R. Gopal and C. Ravishankar, "Software defined satellite networks," in *Proc. 32nd AIAA Int. Commun. Satellite Syst. Conf.*, 2014, p. 4480.

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