Journal Pre-proof

Software defined satellite networks: A survey

Weiwei Jiang

PII: S2352-8648(23)00029-9

DOI: https://doi.org/10.1016/j.dcan.2023.01.016

Reference: DCAN 613

To appear in: *Digital Communications and Networks*

Received Date: 23 January 2022

Revised Date: 13 January 2023

Accepted Date: 17 January 2023

Please cite this article as: W. Jiang, Software defined satellite networks: A survey, *Digital Communications and Networks* (2023), doi: https://doi.org/10.1016/j.dcan.2023.01.016.

Title Page

- **Title**

Software Defined Satellite Networks: A Survey

- **Author names and affiliations**

Weiwei Jiang
School of Information and Communication Engineering
Beijing University of Posts and Telecommunications, Beijing 100876, China
E-mail: jww@bupt.edu.cn

- **Corresponding author**

Weiwei Jiang

Digital Communications and Networks(DCN)

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/dcan

Software defined satellite networks: a survey

Abstract

In recent years, satellite networks have been proposed as an essential part of next-generation mobile communication systems. Software defined networking techniques are introduced in satellite networks to handle the growing challenges induced by time-varying topology, intermittent inter-satellite link and dramatically increased satellite constellation size. This survey covers the latest progress of software defined satellite networks, including key techniques, existing solutions, challenges, opportunities, and simulation tools. To the best of our knowledge, this paper is the most comprehensive survey that covers the latest progress of software defined satellite networks. An open GitHub repository is further created where the latest papers on this topic will be tracked and updated periodically. Compared with these existing surveys, this survey contributes from three aspects: (1) an up-to-date SDN-oriented review for the latest progress of key techniques and solutions in software defined satellite networks; (2) an inspiring summary of existing challenges, new research opportunities and publicly available simulation tools for follow-up studies; (3) an effort of building a public repository to track new results.

KEYWORDS:
Mobility management, Satellite network, SDN controller placement, Software defined networking, Virtual network embedding

1. Introduction

Since the establishment of the Advanced Research Projects Agency Network (ARPANET) in 1969, the Internet has undergone tremendous changes in the past half a century. With the continuous enrichment of the Internet business and the continuous expansion of the network scale, the Internet has gradually penetrated all aspects of society. Internet users have increasingly higher requirements for network availability, bandwidth and Quality of Service (QoS). However, based on the Last-mile Internet Solutions Guide released by International Telecommunication Union (ITU) Development Sector, 49% of the world's population (or 3.7 billion people) was still living with no Internet connectivity at the end of 2019 [1]. In recent years, driven by the launch of low earth orbit satellite constellations operated by commercial satellite communication corporations, e.g., Iridium [1] and Starlink [2], satellite networks have become the dominant solution for global and ubiquitous Internet connections, especially for areas without cellular networks.

Compared with traditional terrestrial networks, satellite networks have several advantages. From an economic perspective, the satellite network is a cost-effective choice when providing communication coverage for remote areas. With on-board processing techniques and inter-satellite link paths, satellite networks are also capable of providing seamless and low-latency mobile connectivity for vehicles, trains, planes, Unmanned Aerial Vehicles (UAVs), etc. In addition, satellite communication is not restricted by the terrain and the infrastructure in the space will not be damaged by natural disasters on the ground, making it suitable for disaster emergency communications. With its wide coverage, the satellite can also provide a large-scale broadcasting service with multimedia content. Finally, the satellite-to-earth link provides an alternative option for terrestrial networks, which can provide the space-based backhaul when the capacity of the terrestrial network is saturated, with an increase in the overall network capacity and the quality of service.

Since the satellite network is a hierarchical and three-dimensional complex network composed of different satellites distributed at different orbital alti-

1 https://www.iridium.com/
2 https://www.starlink.com/

tudes, e.g., Geosynchronous Equatorial Orbit (GEO) satellites, Medium Earth Orbit (MEO) satellites and Low Earth Orbit (LEO) satellites, and ground stations, there are still many challenges for deploying a satellite network and integrating it with terrestrial networks. The satellite network is becoming bigger and bigger, e.g., Starlink is planned as an LEO constellation with 42,000 satellites [3], making it more challenging to manage the network resources efficiently. An even higher management demand is required for the space-air-ground integrated network, which is a heterogeneous network across multiple domains with mutually independent sub-networks and requires the cross-domain operations. In addition to those in the geostationary orbit, satellites in medium and low Earth orbits are constantly revolving around the Earth, which makes inter-satellite links change frequently and constellation topology changes constantly. Therefore, the satellite network operator must have a control system with agile reconfiguration capabilities.

In addition, the cost of building and launching a satellite is expensive, e.g., between \$10 million and \$400 million, depending both on the satellite functionalities and the vehicle used. With limited computation, storage and communication abilities, it is necessary to allocate network resources to meet service requirements with high resource utilization efficiency. Finally, with the tremendous enrichment of users and services, the satellite constellation is no longer dominated by a single function, but focuses on more diverse scenarios with more complex services. It is still a challenging issue to provide the communication services for vertical applications with different QoS levels.

However, the existing satellite networks are far from meeting the requirements of growing communication services. The traditional satellite system follows the distributed architecture inspired by the traditional terrestrial network. Each satellite node is responsible for performing various tasks, including data exchange, storage and forwarding, link state collection, link information synchronization, routing flow table storage, etc., which consumes the already limited on-board resources. Without the lack of a global perspective and the centralized approach of collecting topology and state information, the decisions made by a single satellite node, e.g., the routing flow table, are both time-consuming and inefficient. The tightly coupled hardware and software integration of a satellite makes the network configuration non-universal, cumbersome, and inflexible. It is not easy to recycle and upgrade the satellite hardware which is already in space.

Software Defined Networking (SDN) [2] has been proposed as a potential solution for solving the above challenges and improving satellite network efficiency in recent years. Compared with the existing solutions, the SDN-based solution has several advantages. The separation of the control and data planes would decrease the requirement for a single satellite node. For satellites in the data plane, only the simple tasks of data forwarding and network configuration are performed with minimal computation and communication resources. The more complex tasks of resource allocation, routing strategy design, and network management are performed in the SDN controller, which is deployed in the more powerful satellite or ground stations.

Compared with the terrestrial network, the space environment is complex and changeable, making it more difficult for an efficient network configuration. This problem becomes even more challenging with the launch of recent large-scale LEO constellations with tens of thousands of satellites. The centralized management ability provided by SDN forms the foundation of a global satellite network management scheme, which is capable of monitoring the global network topology and the latest satellite status information and is aware of node failure, network congestion, and link delay situations to achieve more efficient resource allocation and network management performance. The decoupling of hardware and software makes it feasible for remote maintenance and software upgrades with open Application Programming Interfaces (APIs), which resolves the problem of updating the satellite function and decreases the deployment and upgrade costs. The network heterogeneity caused by different hardware devices is eliminated with controllable cross-domain collaborative resource scheduling and network programmability. Different application modules can be further defined and invoked on demand, making the satellite network more flexible for supporting various scenarios.

The need of SDN in satellite networks is summarized as follows: (1) the increasing network management requirement caused by the growing satellite network size, especially for those large-scale LEO constellations; (2) the expensive cost of building and reconfiguring satellite networks compared to terrestrial networks; (3) the agile reconfiguration capability requirement caused by the constantly changing inter-satellite link properties and constellation topologies.

There are some existing surveys about software defined satellite networks and integrated satellite-terrestrial networks. SDN and Network Function Virtualization (NFV) technologies are identified as central technology enablers, with the objective of integrating satellite communications into the 5G ecosystem [3]. Three main typical scenarios are further analyzed, namely, the improvement of satellite network infrastructures, satellite backhauling services to 4G/5G networks and satellite-terrestrial hybrid access services. The technical challenges for fully realizing these described scenarios are also summarized. The

[3] https://spacenews.com/spacex-submits-paperwork-for-30000-more-starlink-satellites/

SDN-based integrated satellite-terrestrial network architecture is introduced and discussed in [4], with an illustration of two fundamental aspects of integrated network application functions, namely, resource management and routing mechanisms. Ongoing challenges are also identified from three aspects, namely, flexibility and scalability, security, and performance evaluation.

A summary of relevant surveys is shown in Table 1. Although there are more recent surveys [7, 8] of the broader scope of general satellite networks (e.g., both with and without SDN), a summary of the latest work about software defined satellite networks is lacking. Compared with these existing surveys, this paper provides the latest progress by investigating and reviewing the most recent publications, a comprehensive summary by identifying key techniques, existing solutions, challenges and opportunities, and a practical guide by summarizing the simulation tools of software defined satellite networks. In addition to this paper, we have created an open GitHub repository on this topic [4], where relevant publications will be updated continuously.

The main contributions of this survey are summarized as follows:

1. This survey contributes a review of the latest progress of architectures, key techniques and solutions for a series of research problems in software defined satellite networks;
2. This survey presents a summary of existing challenges, new research opportunities and publicly available simulation tools, which can be further discussed or used in follow-up studies;
3. To the best of our knowledge, this survey makes the first effort of building a public GitHub repository to track new results on relevant topics in the literature.

The taxonomy of software defined satellite networks and the organization of this survey is given in Fig. 1. The key components (e.g., segments and layers) of traditional satellite networks and software defined networking are described in Fig. 1, which consist the basis for software defined satellite networks. The key enablers and features of software defined satellite networks are categorized as inter-satellite links, routing & switching, virtual ground stations, software defined satellites and satellite-as-a-service. Then the relevant architectures, key technologies and simulation tools are further divided into sub-categories, as shown in Fig. 1. As a reference, the abbreviations of the terminologies used in this survey are listed in Table 2.

The remainder of this paper is organized as follows. In Section 2, the background knowledge about SDN is introduced. In Section 3, the background knowledge about satellite networks is introduced. In Section 4, common software defined satellite network architectures are categorized. In Section 5, key technologies and existing solutions are discussed. In Section 6, simulation tools for software defined satellite networks are summarized. In Section 7, both challenges and research opportunities are identified. In Section 8, the conclusion is drawn.

[4] `https://github.com/jwwthu/SDN-Satellite`

2. Software Defined Networking Background

As a novel network architecture that supports a dynamic and flexible management scheme, SDN adopts a hierarchical structure, that decouples and separates the data plane and the control plane as shown in Fig. 2, which are tightly coupled in the traditional TCP/IP network structure [15]. Unified and open southbound APIs are designed for a centralized control of the switches and routers in the network by the SDN controller. Network virtualization technology is used to abstract the physical network and its components, which breaks the binding relationship between the infrastructure layer and the application layer. The NFV approach separates the software and hardware and realizes the abstraction, segmentation and flexible scheduling of network functions in a distributed fashion. The network is no longer bounded by the underlying hardware architecture and fast and flexible networking can be achieved for on-demand applications with customized and efficient network resource orchestration. In addition, an open programmable interface is designed and provided in SDN, which is convenient for the continuous update and function expansion of hardware devices.

2.1. SDN Control Layer

As the core of the SDN structure, the control layer adopts southbound and northbound APIs for interacting with the infrastructure layer and the application layer, respectively. The main functional modules of the SDN control plane include the link discovery module, the topology manager module, the decision making module, and the flow manager module [16]. The link discovery module enables the building of the network topology for the SDN controller with two kinds of network protocols, namely, the Link Layer Discovery Protocol (LLDP) and Broadcast Domain Discovery Protocol (BDDP). The topology manager module collects and manages the connection and working status of the SDN switches in a real-time manner. Once the connection status changes, the whole network topology is updated accordingly. The decision making module is responsible for handling the data forwarding behaviors. With the real-time updated global topology and the centralized network management ability, a better decision can be made by the SDN controller, e.g., improved performance compared to routing protocols that have only local information.

Table 1: The summary of relevant surveys.

Survey	Year	Summary	Key Technologies	SDN-oriented
[3]	2016	Analyze the improvement of satellite network infrastructures, satellite backhauling services to 4G/5G networks and satellite-terrestrial hybrid access services	Satellite Network Virtualization, Satellite Backhauling, Satellite-terrestrial Hybrid Access	Yes
[4]	2016	Introduce SDN-based integrated satellite-terrestrial network architecture and fundamental resource management and routing mechanisms	Resource Management, Routing and Networking	Yes
[5]	2018	Define energy and spectral efficiency optimization problem and introduce related resource allocation algorithms in integrated satellite and terrestrial networks	Resource Allocation	No
[6]	2020	Review the standardization process for 5G satellite communications and the related system architectures and interfaces	Downlink Synchronization, Random Access, Hybrid Automatic Repeat reQuest (HARQ)	No
[7]	2021	Discuss main drivers, promising applications and five fundamental aspects for satellite communications (namely, system aspects, air interface, medium access, networking, and testbeds & prototyping)	Air Interface, Medium Access Control, Networking, Testbeds and Prototyping	No
[8]	2021	Concentrate on new opportunities with ML, AI, and edge intelligence and Satellite 5G standardization for multi-layer non-terrestrial networks	Mobility Management, Radio Resource Management, Routing, SDN/NFV	No
[9]	2021	Survey traditional and recent advances in IoT application layer protocols and relevant real-time applications	IoT Application Layer Protocols	No
[10]	2021	Review key technologies for UAV/satellite-based communications and 6G-enabled space-air-ground integrated network	Physical Layer, Mobility Management, Mobile Crowd Sensing, Offloading, Task Scheduling, Super IoT, Stringent Authentication, Network Fixed Point, Service Function Chaining, Ultra-dense Cell Free Massive MIMO	No
[11]	2021	Summarize current solutions for the deployment of IoT services with low-orbit satellites	Satellite IoT Communications and Networking Technologies	No
[12]	2022	Review security studies on security threats, attack methodologies, and defense countermeasures in space-air-ground-sea integrated networks	Anti-Jamming Techniques, Secure Routing, Secure Handover Schemes, Secure Key Management, Intrusion Detection System	No
[13]	2022	Discuss the security threats and blockchain-based solutions in space-air-ground integrated networks	Blockchain Technologies	No
[14]	2022	Review the network architectures and latency/flexibility problems in space-air-ground integrated networks and propose a new flexible, low-latency and flat architecture	Intelligent Deployment of Network Elements, Mobility Management, Intelligent Session Management, Air Interface	No
This work	2022	Review the architectures, key techniques, challenges, opportunities, and simulation tools in software defined satellite networks and build a public GitHub repository to track new results on relevant research topics	SDN Controller Placement, Mobility Management, Routing, Virtual Network Embedding	Yes

The flow manager module is responsible for the flow table distribution, in an active or passive approach. In the active approach, pre-configured flow tables are designed and distributed for SDN switches, which requires a higher complexity for managing the flow table entries with proactive ability. In the passive approach, the SDN switches would only request a new flow table entry for the data packet without any matched routing table entry from the SDN controller, which increases the data forwarding delay.

In a giant and complex network, more than one SDN controller can be used and connected with east-west bound interfaces, in which each SDN controller is responsive for managing a sub-network. Depending on the network configuration and usage, these SDN controllers can be in a leader-follower relationship or a peer-to-peer relationship. The east-west bound interfaces are also used to interact with third-party applications.

2.2. SDN Infrastructure Layer

The SDN infrastructure layer consists of various networking switches, focusing on forwarding the data with various physical hardware devices. Unlike the most traditional switches that only work in the data link layer, the SDN switches work across multiple layers, e.g., the transport, network, and data link layers, based on the data forwarding decisions from the SDN

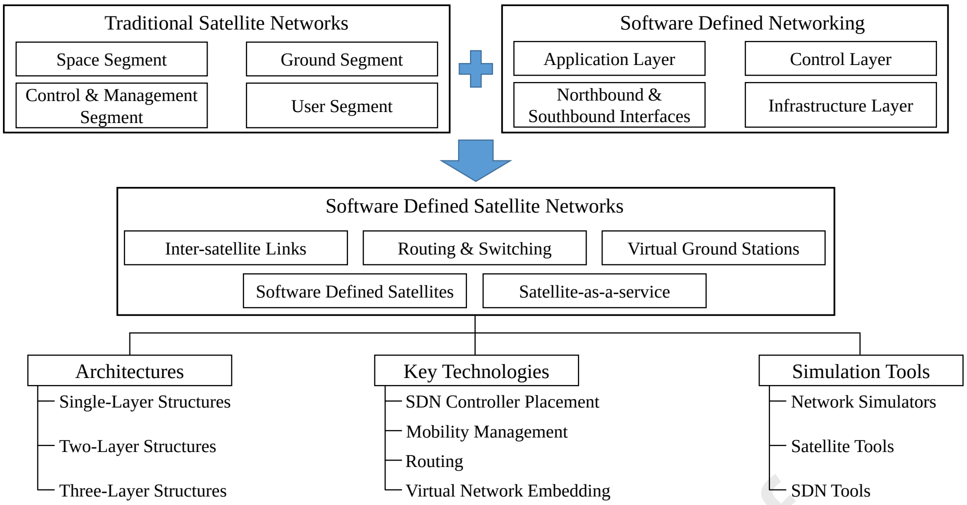

Fig. 1: The taxonomy of software defined satellite networks and the organization of this survey.

Table 2: The abbreviations and their full names used in this survey.

Abbreviation	Full Name	Abbreviation	Full Name
ACPA	Adaptive Controller Placement and Assignment	NFV	Network Function Virtualization
AI	Artificial Intelligence	NMC	Network Management Center
API	Application Programming Interface	NOCC	Network Operations Control Center
APSO	Accelerate Particle Swarm Optimization	OSI	Open Systems Interconnection
ARPANET	Advanced Research Projects Agency Network	POF	Protocol-oblivious Forwarding
ASIC	Application-specific Integrated Circuit	PoP	Point of Presence
AWS	Amazon Web Services	QoS	Quality of Service
BDDP	Broadcast Domain Discovery Protocol	SaaS	Satellite-as-a-service
CCSDS	Consultative Committee for Space Data Systems	SACA	Simulated Annealing and Clustering Hybrid Algorithm
CERNET	China Education and Research Network	SAPKM	Simulated Annealing Partition-based K-Means
CFDP	CCSDS File Delivery Protocol	SBD	Short Burst Data
DCPA	Dynamic Controller Placement and Adjustment	scMPTCP	SDN-cooperated Multi-Path Transmission Control Protocol
DCT	Dynamic Classified Timeout Algorithm	SCPS	Space Communications Protocol Specifications
DDoS	Distributed Denial of Service	SDN	Software Defined Networking
DTN	Delay Tolerant Networks	SDR	Software Defined Radio
DTNRG	Delay-Tolerant Networking Research Group	SDS	Software Defined Satellite
FCC	Federal Communications Commission	SD-WAN	Software Defined Wide Area Network
ForCES	Forwarding and Control Element Separation	SFC	Service Function Chaining
GEO	Geosynchronous Equatorial Orbit	SGW	Satellite Gateway
HAP	High Altitude Platform	SILLEO-SCNS	Large LEO-Satellite Communication NetworkS
HAPS	High Altitude Platform Station	SIS	Satellite Information System
ICN	Information-centric Networking	SNMC	Satellite Network Management Center
IDT	Intelligent Dynamic Timeout Algorithm	SoC	System-on-chip
ILP	Integer Linear Programming	SPDA	Static Placement With Dynamic Assignment
IoT	Internet of Things	SR	Segment Routing
IP	Internet Protocol	ST	Satellite Terminal
ITU	International Telecommunication Union	STK	Satellite Tool Kit
LAP	Low Altitude Platform	TCAM	Ternary Content Addressable Memory
LEO	Low Earth Orbit	TSMM	Timeout Strategy-based Mobility Management
LLDP	Link Layer Discovery Protocol	TT&C	Telemetry, Tracking, and Command
LSNS	Large-scale Satellite Network Simulator	UAV	Unmanned Aerial Vehicle
MEO	Medium Earth Orbit	VNE	Virtual Network Embedding
MILP	Mixed Integer Linear Programming	VNF	Virtual Network Function
MPTCP	Multi-Path Transmission Control Protocol	VNMR	Virtual Node Matrix Routing Algorithm
NCC	Network Control Center		

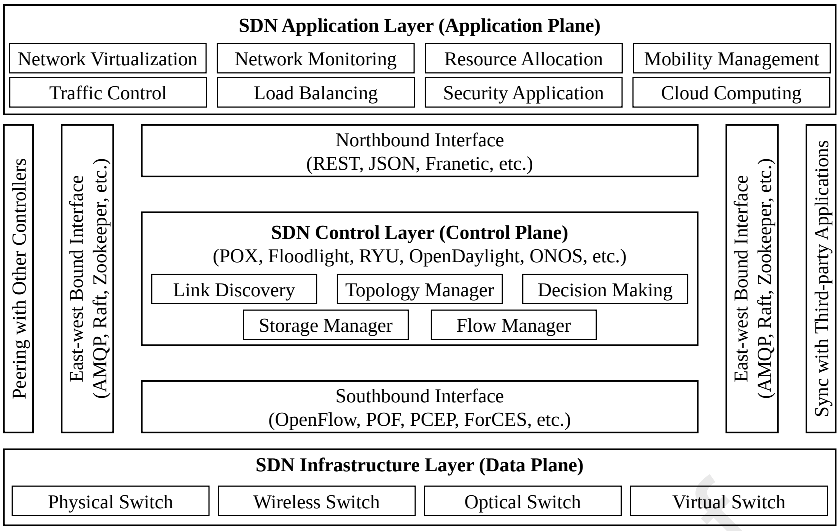

Fig. 2: The SDN structure.

controller. The SDN switch consists of the channel, port, and flow table. The communication channels are maintained by the SDN controller for the connection between the SDN controller and SDN switches. Data packet receiving and forwarding use different ports. The flow table is used to store the decisions made by the SDN controller, with a similar function as the traditional switches. With the development of SDN techniques, hierarchical flow tables are supported, and the outdated flow table entries are discarded automatically.

Compared with traditional switches, SDN switches have several advantages. The first advantage is centralized management ability. Different SDN switches can be managed by a single SDN controller with the global network status. The second advantage is the softwarized management ability. With the development of network virtualization techniques, SDN switches can be realized with softwarized solutions, e.g., Open vSwitch [5]. The third advantage is the low deployment cost. There is no need to use customized Application-Specific Integrated Circuit (ASIC) chips, and universal chips would be sufficient for building SDN switches. The last advantage is the fast recovery ability from link failure. Manual operations are replaced with intelligent and automated diagnosis and measurement, which greatly decreases the fault occurrence rate and maintenance time.

2.3. SDN Protocols and Tools

SDN has become technically mature in academia [17], with both the traditional OpenFlow [2] protocol and more recent SDN protocols, e.g., Forwarding and Control Element Separation (ForCES) [18] and Protocol-oblivious Forwarding (POF) [19]. SDN is also successfully deployed in the industry. Open vSwitch has become the dominant solution for realizing softwarized SDN switches, which are built on open-source technologies, can be integrated with server virtualization, and supports traditional standard APIs and flow monitoring tools, e.g., NetFlow, sFlow, etc. Various SDN controllers are widely used, including NOX [20], POX [6], OpenDayLight [21], Ryu [22], ONOS [23], Floodlight [7], etc. SDN is also validated in the data center and enterprise networks, e.g., B4 [24] and SD-WAN [25].

2.4. SDN Modeling

Both deterministic and stochastic models are built in the literature to analyze the SDN performance in theory from different perspectives. Two typical modeling approaches include the network calculus theory and the queueing theory.

The network calculus theory is used in [26] for the first time to describe the functionality of an SDN switch and controller. The delay and queue length boundaries of an SDN switch and the buffer length of SDN controller and SDN switch are analyzed with the deterministic network calculus-based model and compared with the previous measurement. The stochastic network calculus model is further used in [27].

The queueing theory is introduced in [28] for SDN performance prediction and network configuration, coupled with real-time measurements taken from the network devices. A priority queueing model is used in [29] for analyzing an OpenFlow–based SDN when externals packets arrive according to a Poisson process. Then the queueing model is compared with simulations in terms of packet loss probability and average packet transfer delay. The results show an obser-

[5] `https://www.openvswitch.org/`

[6] `https://noxrepo.github.io/pox-doc/html/`

[7] `https://floodlight.atlassian.net/wiki/spaces/floodlightcontroller/overview`

vation of 7.1%-10.3% prediction error for different average flow sizes.

3. Software Defined Satellite Network Background

3.1. Existing Satellite Network Protocols

Without using SDN, there are already some existing solutions for building a satellite network in space, e.g., the Space Communications Protocol Specifications (SCPS) protocols proposed by the Consultative Committee for Space Data Systems (CCSDS) and the Delay Tolerant Networks (DTN) protocols proposed by the Delay-Tolerant Networking Research Group (DTNRG).

Different from the standard Open Systems Interconnection (OSI) model with seven separate layers, some of the SCPS protocols are defined across multiple layers, e.g., the CCSDS File Delivery Protocol (CFDP) and the Proximity-1 protocol. IP over CCSDS is further proposed to support the integrated satellite-terrestrial network with the Internet Protocol (IP). However, the initial scenario of CCSDS protocols is designed for point-to-point communication in satellite-to-Earth microwave links, without considering the flexible routing ability among the heterogeneous nodes. While this problem is partially resolved by the IP over CCSDS protocol, it is still not optimal or efficient for modern satellite-terrestrial networks, especially those with large LEO constellations.

DTN protocols are proposed for the connection-less problem between satellites in deep space exploration. The existing Internet protocols are not suitable for the satellite networks limited by long transmission distances, the high mobility, the unpredictable space environment, and limited storage and computation capabilities. To incorporate both the satellite network and the terrestrial network, the bundle layer is introduced in the DTN protocol to support and integrate the different protocols in the data link layer (e.g., the CCSDS protocol in the space part and the existing Internet protocols in wired and wireless networks in the ground part) with the unified IP protocol. However, it is still challenging for the DTN solution to maintain the global network topology and latest network status information. The separate routing protocols running in different parts would cause both implementation difficulty and an inefficient routing scheme.

Besides SCPS and DTN protocols, more protocol types in the literature are used for data transmissions and communications, which may also be migrated to satellite networks. For example, conventional IoT application layer protocols [9] may be extended to the scenario of satellite based IoTs.

3.2. Software Defined Satellite Network Enablers

Several technological advancements have been achieved in several aspects in the past few years to turn software-defined satellite networks closer to reality.

3.2.1. Inter-satellite Link

The first aspect is the development of inter-satellite links. Two different kinds of inter-satellite links are often considered, namely, the microwave inter-satellite link (20-300 GHz) and the optical inter-satellite link (380-790 THz). For example, the microwave inter-satellite link already used by Iridium Next has a frequency of 23 GHz. Inter-satellite microwave link technology is relatively mature, with high reliability and a relatively wide beam. The link is also easier to track and capture. However, the data transmission rate is lower, and the anti-interference ability is weaker, compared with the optical inter-satellite link which uses the laser as the carrier of information transmission between satellites. Optical inter-satellite links have a large transmission capacity and a strong anti-interference ability. However, it also has many shortcomings, such as high cost, complex equipment structure, large size, high power consumption, short distance, and a larger influence by many factors such as space illumination. Most LEO constellations are equipped with or have a plan to add optical inter-satellite links, e.g., Starlink, Leosat, Telesat, etc. In November 2021, the first-ever demonstration of multi-orbit connectivity with a single multi-link terminal is accomplished by a British startup Isotropic Systems, with multiple satellites in geostationary and medium Earth orbit at the same time [8].

3.2.2. Routing and Switching Technique Development

The second aspect is the development of switching techniques in satellite networks. Routing and switching are the key technologies for realizing space networking and the core parts of the integration of space networks and terrestrial networks. Different switching technologies are in use, e.g., transport forwarding, channel switching, and packet switching (including ATM switching, MAC switching, MPLS switching, IPv4/IPv6 switching, etc). In transport forwarding (or microwave switching), the received signal is forwarded with a pre-configured carrier frequency and no further processing techniques. Contrary to transport forwarding, multiple steps are conducted in packet switching mode, e.g., demodulation, decoding, coding and modulation, supported by the on-board processing ability. Channel switching occurs between these two switching modes by using some of the on-board processing functions, e.g., digital filtering. Transport forwarding is the earliest and still the most popular switching technique due to its low cost and high stability and is adopted in Inmarsat, OneWeb, SpaceX, etc. However, there are still some problems with the transport forwarding mode, such as the accumulated transmission noise and the two-hop transmission delay. To integrate with terrestrial networks, packet switching is

[8] `https://spacenews.com/isotropic-systems-announces-successful-multi-orbit-antenna-field-tests/`

more favorable. However, it requires a stronger on-board processing ability and has not yet been fully developed. Some experiments with on-orbit satellite systems have been conducted to further develop different packet switching techniques, especially IPv4/IPv6 switching, e.g., in Iridium Next satellites.

3.2.3. *Virtual Ground Stations*

The third aspect is the development of virtual ground stations. A virtual satellite ground station is defined as a system that transparently exposes the operation and data path of a real ground station to an external operating entity for a defined amount of time [30]. Considering the increasingly crowded satellite spectrum resources, a Software Defined Radio (SDR) architecture is proposed for parallel satellite reception, which is based on the modern System-on-Chip (SoC)-based embedded system and enables flexible Telemetry, Tracking, and Command (TT&C) communication for small satellites [31].

In the industry, giant Internet companies are actively cooperating with satellite communication service providers to promote the development and implementation of satellite Internet, including Amazon, Microsoft, and Google. These Internet companies have accumulated much experience in the fields of Internet infrastructure, cloud services, and software-defined networks, which can help satellite systems quickly deploy software solutions.

The pioneer is Amazon with the AWS Ground Station, which can be used to control satellite communications, process data, and expand operations, without requiring customers to think about how to build or manage the ground station infrastructure. Amazon Web Services (AWS) announced a partnership with Iridium in September 2018 to develop a satellite-based network called CloudConnect for Internet of Things (IoT) applications. Launched in 2019, CloudConnect is the first satellite cloud-based solution that can provide truly global coverage for IoT applications. CloudConnect enables IoT devices to send and receive messages through AWS-hosted services without the need to develop a connection service to the Iridium Short Burst Data (SBD) gateway. Data are transferred via a private operator network and a dedicated secure private connection between Iridium and AWS. The Iridium system uses dedicated secure and private connections for CloudConnect traffic and directly connects to AWS without using the public Internet to ensure data security.

Then there is Microsoft and Google. Microsoft has launched the Azure Orbital service, which is similar to the AWS Ground Station and can be integrated with other Azure services to process and store satellite data. The processed data can be safely delivered to the customer's virtual networks. Based on Azure Orbital, Microsoft has formed cooperation with a series of satellite service providers, including SpaceX, SES, KSAT, Viasat, Kratos, AMERGINT, Kubos and US EIectrodynamics. Microsoft and SpaceX reached cooperation in October 2020 to provide satellite-driven Internet connections on Azure. The global satellite connection would be provided to both the public and private sectors through the Starlink satellite network and supported by the Azure data centers.

Google and SpaceX also reached cooperation in May 2021. SpaceX will deploy a ground station for its Starlink broadband satellite in Google's data center. The cooperation is mutually beneficial. Google users can use the Starlink network to obtain the global Internet connection, while Starlink customers can use Google's infrastructure and network functions to achieve a secure connection.

3.2.4. *Satellite-as-a-service Commercial Mode*

The last but not the least one is the new commercial mode of Satellite-as-a-Service (SaaS). SaaS is a new approach of providing virtualized satellite services without the huge expenditure of building and launching satellite networks. This service is based on a subscription mode, which can provide private networks for vertical customers on demand. The network functions can be customized by the users based on their own needs.

SaaS mode is based on Software-Defined Satellites (SDS), which are satellites with on-demand update and reconfiguration capabilities. SDS was originally proposed in [32] for solving the shortcomings of Satellite Information Systems (SISs). The first shortcoming is the fixed task design, which is inflexible and cannot meet the changing needs of users. The single task design per satellite is the second shortcoming, which requires a larger number of satellites to perform multiple tasks, wasting valuable orbit-spectrum resources. The previous satellite payloads are hardware-driven, without the flexibility and reconfigurability to adapt to environmental changes. Software-defined radio is used as the generic hardware platform in the SDS payload, which supports the upload of different software packages. Multiple tasks can be performed with a single SDS, e.g., communication, positioning, navigation, object detection, etc. The life cycle of an SDS is extended by software updates, to keep up with technological progress and user requirement changes.

3.3. *Software Defined Satellite Network Progress*

In the past few years, software-defined satellites have made a series of progress. The first software-defined satellite, ArduSat-1, was launched by the startup Spire Global from the International Space Station in November 2013. Later, in February 2019, Iridium completed the deployment of the Iridium NEXT constellation composed of 75 LEO satellites manufactured by Thales Alenia Space. The Iridium NEXT satellite has a processor with software that can be reprogrammed and upgraded, to provide new and improved services that the old satellite cannot provide.

More satellite service providers, e.g., Inmarsat and Intelsat, are also designing their software-defined satellites, with cooperation with vertical customers, e.g., Airbus and Boeing.

Driven by the above technological progress and more technical developments, software-defined satellite network solutions have become more popular among satellite operators in recent years, deployed in satellite payloads, ground facilities, and backhauling networks. The feasibility of these solutions is discussed in a series of studies [33, 3, 34, 35, 36, 37]. Empowered by the on-board processing and switching abilities, satellites are incorporated in the SDN diagram by performing the simple forwarding rules distributed from the controller [38]. The SDN controller is responsible for designing the centralized routing scheme and lowering the on-board processing cost, in the presence of frequent satellite handover, long round-trip time delay, and high configuration cost. On the ground side, the satellite network is connected with the Internet through satellite gateways and terminals, which can be involved in the SDN diagram with programmable and reconfigurable ability, achieving more intelligent handover management and data forwarding [39]. The satellite gateway diversity solution is further supported with SDN/NFV-enabled satellite ground segments, which provide reasonable flexibility to handle failover and resiliency [40]. SDN is further proposed for achieving a more efficient routing scheme in the satellite backhauling network, especially when multiple routes are available in the satellite space information network, e.g., terrestrial, space-terrestrial, and air-terrestrial links, with the ability to make a globally optimal decision [41]. Fine-grained traffic offloading and resource allocation can also be supported with the centralized and dynamic management ability of SDN [42].

In the industry, the satellite operator SES has selected the Network Function Virtualization Software Defined Wide Area Network (NFV SD-WAN) solution from Amdocs to orchestrate and manage the SD-WAN and other virtual network services in 2020 [9]. Including the famous MEO constellation O3b, SES has over 50 GEO satellites and 20 MEO satellites, and the numbers are still growing. The NFV SD-WAN solution combines the MEO and GEO satellites with terrestrial connectivity options, while enabling unmatched flexibility for traffic management for vertical customers and decreasing the complexity and cost associated with network integration and deployment. Inmarsat also develops SDN and NFV infrastructures in ground facilities, e.g., ground stations, data centers and meet-me points and many of the routing, management and security functions are software-driven and hosted within the cloud [10].

[9] `https://solutions.amdocs.com/Network-NFV-NaaS-SES-Case-Study-LP.html`

[10] `https://www.inmarsat.com/en/about/technology/ground-network.html`

4. Software Defined Satellite Network Architectures

In this section, we first introduce the basic satellite network and satellite-terrestrial integrated network structures. Then, we present the common types of software defined satellite network architectures, i.e., single-layer, two-layer and three-layer structures.

4.1. Satellite Network Architecture

A typical satellite network architecture is shown in Fig. 3, which consists of space segment, ground segment, control and management segment, and user segment [43]. The space segment is responsible for user access and data transmission with different satellites organized in the constellation, e.g., LEO, MEO, and GEO satellites. Network functions including routing, adaptive access control, and spot-beam management are supported in the space segment. The ground segment is responsible for the interconnection of the space segment with other networks, e.g., the Internet or enterprise private networks, which consist of Satellite Gateways (SGWs) and Satellite Terminals (STs). The interconnection is enabled through Points of Presence (PoPs) in the backbone network. The control and management segment is responsible for managing the system operation, which consists of Network Control Centers (NCCs) and Network Management Centers (NMCs). Network functions including the establishment, monitoring and release of connections, admission control, and resource allocation, are supported in the control and management segment. The user segment is responsible for providing satellite-based network services for end-users, which consists of various end-user devices, fixed or mobile. Both direct access to satellite networks or indirect access through terrestrial access points are incorporated into the user segment. The user association problems are considered in the user segment, when different users are associated with the best serving base stations to improve the network performance, e.g., load balance, network capacity, and energy efficiency [44]. Different solutions have been proposed, e.g., the greedy-based user association algorithm with task classification [45] and the greedy-based user association algorithm with user grouping [44].

As a further reference, a comparison of different satellites is presented in Table 3. Some typical LEO constellations include Starlink [11], Kuiper [12], OneWeb [13], Globalstar [14], Iridium [15], etc. The number of satellites in some large LEO constellations has

[11] `https://www.starlink.com/`

[12] `https://www.aboutamazon.com/news/company-news/amazon-receives-fcc-approval-for-project-kuiper-satellite-constellation`

[13] `https://oneweb.net/`

[14] `https://www.globalstar.com/en-us/`

[15] `https://www.iridium.com/`

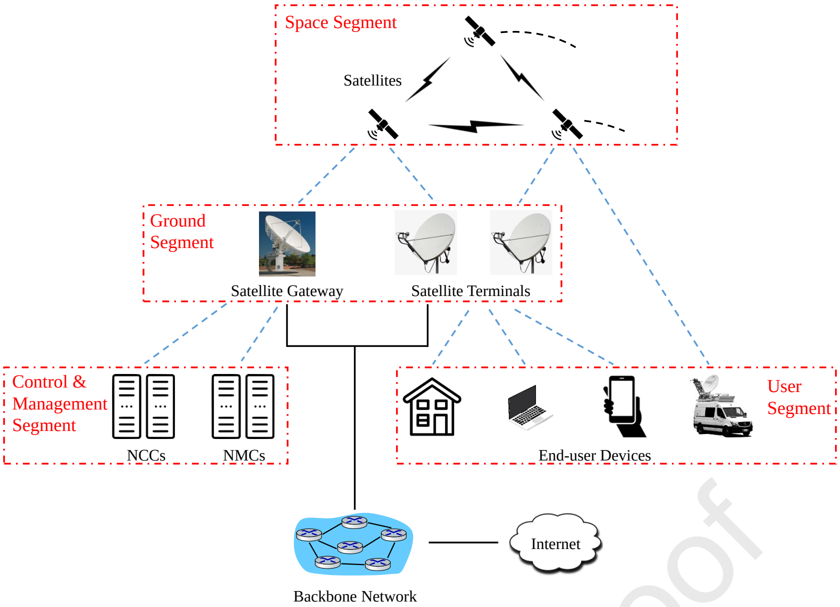

Fig. 3: The satellite network architecture.

dramatically increased, e.g., Stralink has applied for the launch of 30,000 more satellites in addition to the 12,000 it has already planned [16]. Other than Starlink, the approval of nearly 38,000 total satellites is requested from the Federal Communications Commission (FCC) by other space companies in November, 2021 [17]. The number of satellites launched into space is recorded and tracked in the satellite database released by the Union of Concerned Scientists [18].

The typical MEO constellation is O3b [19], which consists of 20 MEO satellites. The typical GEO constellation is Inmarsat [20], which owns and operates 14 GEO satellites. One example of hierarchical constellations is SpaceWay [21], which consists of 8 GEO satellites and 20 MEO satellites, providing interactive broadband communication services such as two-way voice, high-speed data, image, telephone and video conference, multimedia, etc.

Combined with the terrestrial network and High Altitude Platform Stations (HAPS), the satellite-terrestrial integrated network or the space information network is becoming an important component in the next-generation mobile network framework, i.e., 6G, IoT [46]. As discussed in the Introduction, satellite networks have several advantages over traditional terrestrial networks and have become irreplaceable in rural areas and oceans, where terrestrial networks are economically prohibitory or technologically infeasible. However, it would be even more challenging to construct and manage a software-defined satellite-terrestrial integrated network since integration with the terrestrial network brings more diverse network devices and components into the whole diagram. A transitional approach is the SDN/IP hybrid architecture, in which the satellite part is equipped with the SDN framework, while the terrestrial part keeps the traditional TCP/IP structure [47]. While this approach is easier to implement, its performance is not comparable with a complete SDN structure that incorporates both the satellite network and terrestrial network with global optimization considerations. The software-defined satellite-terrestrial integrated network is also covered in this study for both its importance and difficulty.

Table 3: A comparison of LEO, MEO, and GEO satellites.

Type	LEO	MEO	GEO
Altitude (km)	160-3,000	3,000-20,000	35,786
Coverage	Small	Medium	Large
Transmission Delay (ms)	< 27	< 133	< 250
Capacity	Large	Medium	Small
Mobility	Fast	Medium	Geostationary

4.2. *Software Defined Architectures*

In this part, we categorize the different software defined satellite network architectures into three types, namely, single-layer, two-layer and three-layer structures, depending on the involvement of LEO, MEO, and GEO satellites.

Other differences among the various software defined satellite network architectures include the fol-

[16] https://www.cnbc.com/2021/08/19/spacex-starlink-satellite-internet-new-capabilities-starship-launch.html
[17] https://www.cnbc.com/2021/11/05/space-companies-ask-fcc-to-approve-38000-broadband-satellites.html
[18] https://www.ucsusa.org/resources/satellite-database
[19] https://www.ses.com/our-coverage/o3b-mpower
[20] https://www.inmarsat.com/en/index.html
[21] https://en.wikipedia.org/wiki/Spaceway

lowing:

- The number and the placement of SDN controllers. In most cases, one SDN controller is not enough to manage large-scale satellite networks. Multiple SDN controllers are more often used, with SDN controllers deployed in GEO, MEO, LEO satellites or ground stations.

- The relationship among different SDN controllers. In the case of using multiple SDN controllers, there is one or multiple master controllers, and the remaining controllers are slave controllers with limited or partial responsibilities as a controller under the command of the master controller.

- The ranges of control and data planes. Various network scenarios are discussed in the literature, with different combinations of satellite, aerial, and terrestrial networks. The ranges of control and data planes vary greatly even in cases with the same scenario as we will discuss and summarize later.

4.2.1. Single-layer Structures

In a single-layer structure as shown in Fig. 4, only one type of LEO, MEO, and GEO satellite is involved, in which an LEO-based network is the most common case. Compared with MEO and GEO satellites, LEO satellites have both a smaller signal propagation decay and a smaller transmission delay, which are preferred by real-world applications in vertical industries. Driven by the development of large-scale LEO constellations, e.g., Starlink and Kuiper, LEO satellite networks bring new opportunities to the telecommunication market. However, it also becomes much more difficult for network management and control. SDN is introduced as a potential solution for the management challenge.

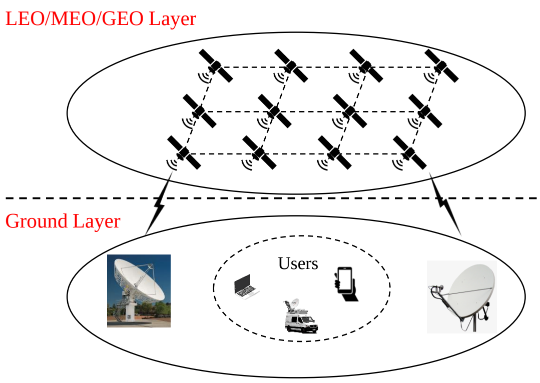

Fig. 4: The single-layer structure.

Two different approaches are proposed for SDN control plane establishment for LEO constellations, namely, out-of-band control and in-band control [48]. In the out-of-band control approach, a separate channel is set up for control traffic, i.e., the ground stations or the GEO and MEO satellites, and the LEO satellites are only responsive for data transmission. In in-band control, the control plane and the data plane share LEO satellites with different priorities. Both approaches are used in the surveyed studies as we would discuss.

In [49], LEO satellites are grouped and managed in clusters. The SDN controller is deployed in the data centers of the ground station, which collects the network information and distributes the flow tables calculated in the control center with Artificial Intelligence (AI) techniques. In [50], a hierarchical controller structure is deployed in ground stations, with one master controller and several slave controllers. Each slave controller manages a local sub-network, and the master controller manages the whole satellite network topology and calculates the routing path among multiple sub-networks.

Instead of using the ground stations, the SDN controller can also be deployed in the LEO satellite [51, 52]. In [52], the migration cost in the dynamic controller placement scenario is considered, which is caused by the change of the position of controllers and switch-to-controller assignment. Another cost is also considered, namely the reconfiguration cost, which is caused by the reconfiguration messages exchanged between the SDN controller and satellite SDN switches. The proposed space segment SDN-enabled architecture minimizes the overhead both for the migration cost and reconfiguration cost when the optimal controller placement is considered with respect to the average flow setup time given varying traffic demands.

4.2.2. Two-layer Structures

In a two-layer structure as shown in Fig. 5, two types of LEO, MEO, and GEO satellites are involved, in which the combination of LEO and GEO is the most common case. The inherent high-speed movement of LEO satellites causes a high Doppler shift, frequent beam switching and handover occurrences, and extra transmission loss and signaling overhead. On the other hand, GEO satellites have a larger coverage with fewer handover occurrences but a longer transmission delay. With the ability of reliable links, wide coverage, broadcasting and stationarity to the ground, GEO satellites are suitable as the control plane. To manage the massive LEO satellites, the SDN controller can be deployed in either the ground station or the GEO satellite, with different considerations.

In [53], the SDN controller is placed in GEO satellites, which obtains the status of LEO satellites and deploys an adaptive routing algorithm with a variety of QoS requirements. The LEO satellites constitute the data plane and perform data-forwarding tasks based on the distributed flow tables.

The SDN controller could also be placed in the

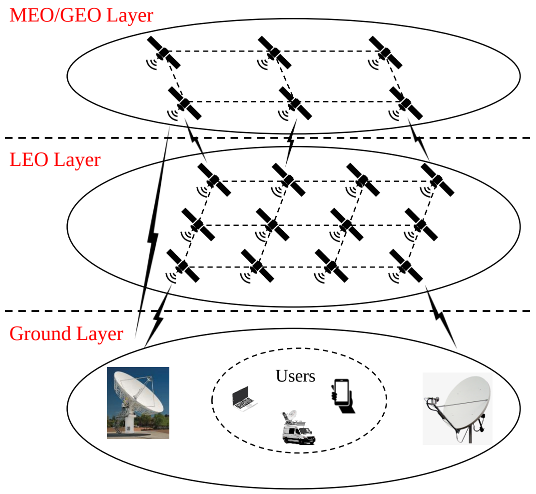

Fig. 5: The two-layer structure.

ground station and both the GEO and LEO satellites are used as the data plane. This structure is adopted in FRBSN [35] and the corresponding network resource management problems are handled in the ground segment.

The third case is that the SDN controllers are placed both in the ground station and satellites, as in the multi-layer hierarchical control architecture proposed in [43]. The ground station is the super controller to facilitate the entire network control. GEO satellites are the master controllers to control and manage LEO satellites. Several LEO satellites are slave controllers that make up the limited orbit without polar area coverage of GEO satellites.

Another case is that the SDN controllers are placed both in the satellite, aerial, and terrestrial networks. A cross-domain SDN architecture is proposed in ML-STIN [54] for multi-layered space-terrestrial integrated networks, in which the main controller is deployed in the terrestrial network and other controllers are deployed in both GEO satellites and High Altitude Platforms (HAPs). The data plane includes LEO satellites, Low Altitude Platforms (LAPs), and terrestrial networks. The cross-domain SDN architecture is proven effective for enhancing the system compatibility and scalability and reducing the overhead of configuration updates and decision-making control significantly.

4.2.3. *Three-layer Structures*

In a three-layer structure as shown in Fig. 6, all three types of LEO, MEO and GEO satellites are involved. While LEO satellites are often used as the data plane in the two-layer structure, the increasing applications are putting forward higher requirements, which may be beyond the service ability of LEO satellites, e.g., the frequent handover operations caused by the high-speed movement of LEO satellites could introduce a heavy overhead that damages the overall performance. MEO satellites are introduced in the three-layer structure, which can act as a substitute role in the control plane for sub-network management or an add-on role in the data plane for data transmission and backhauling.

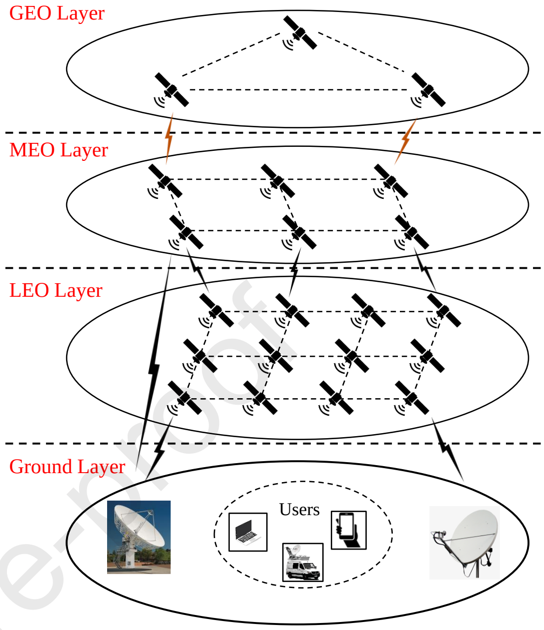

Fig. 6: The three-layer structure.

OpenSAN [55] is a classical framework that first introduces the SDN concept into a multi-layered satellite infrastructure. The data plane consists of the satellite infrastructure including GEO, MEO and LEO satellites, and the control plane consists of the GEO satellite group, with at least three GEO satellites to cover the whole data plane. The data plane runs the flow table “match-action” protocol and focuses on packet forwarding, while the GEO satellites perform the control and management tasks and the number of ground stations can be reduced.

The satellite-terrestrial integrated network with SDN is further considered in [56]. The SDN controllers are deployed in different places, including GEO satellites, data centers and satellite gateways, which are further managed by the Satellite Network Management Center (SNMC) to collect the whole network information and design routing strategies. The data plane contains both the LEO and MEO satellites, as well as the ground segment including satellite gateways, switches and routers in the terrestrial network. The whole satellite-terrestrial integrated network is under centralized management, with fine-grained QoS guarantees and network performance optimization.

In [57], master controllers are deployed in GEO satellites to manage LEO satellites and assistant controllers are deployed in MEO satellites to reduce the burden of the master controller and improve the robustness of the network. More specifically, the master controller is responsible for routing strategy calculation, caching strategy update, mobility management, etc. The LEO satellites are used in the data plane, along with the terrestrial network. An effective co-operative content retrieval scheme is further proposed for the content retrieval application, which adopts co-operative caching and coded caching for traffic saving.

Instead of deploying the SDN controller in GEO satellites, SDN-SatArc [58] deploys the SDN controller in ground stations, which controls the data transmission in the cross-layer infrastructure consisting of GEO, MEO and LEO satellites. A similar idea of placing the SDN controller in the ground is adopted in HetNet [59], which is a flexible architecture for heterogeneous satellite-terrestrial networks, and both satellite and terrestrial networks are used as the data plane. Different network protocols are used in different domains, and cross-domain data transmission is enabled and managed with a unified identification scheme, e.g., an identifier and a locator. This locator/ID split achieves a series of benefits, including heterogeneous network convergence, routing scalability alleviation, mobility support, traffic engineering, and efficient content delivery. However, the system complexity is also greatly increased with the newly introduced function of service resolution.

The deployment of the SDN controller is not limited to fixed ground stations. In the software defined naval network [60], SDN controllers are deployed in ships with satellite terminals, which rely on satellite communication as the primary communication service. However, new problems arise when multiple SDN controllers are deployed in ships. The east-west control overhead cost among different SDN controllers is negligible in the ground terminal case, when the data can be transported via high speed terrestrial links. The control message propagation delay must be taken into consideration in a software defined naval network and a Multi-Path Transmission Control Protocol (MPTCP) is proposed to cooperate with the existing SDN tools for the goal of an agile, bandwidth efficient, robust naval network [60].

SD-STIN [61] is proposed for solving the time-varying network topology, satellite mobility and network scalability problems, which integrates various satellite systems, mobile networks, and the Internet backbone by transparent protocol translation. The SDN controller is deployed in the terrestrial network, and the data plane contains both satellite systems and the terrestrial network. Mobile edge computing is further incorporated into SD-STIN to provide diverse communication services. Potential solutions with SD-STIN are discussed for problems including resource management, routing, and forwarding strategies.

In [62], super SDN controllers are deployed in GEO satellites and terrestrial networks, and normal controllers are deployed in MEO satellites and terrestrial networks. The LEO satellites and the ground network equipment constitute the data plane. The OpenFlow protocol is extended and enhanced to handle the highly dynamic satellite network, with heterogeneous controller management and integrated scheduling of resources under heterogeneous networks. A novel routing algorithm is further proposed and validated in an NS3 simulation system, in which multiple paths are used to achieve link load balancing for data transmission.

As a summary, the control and data planes used in the studies discussed in this section are summarized in Table 4.

5. Software Defined Satellite Network Key Techniques

In this section, some key techniques, as well as the corresponding problems and challenges, are discussed with the surveyed studies.

5.1. SDN Controller Placement

The first technique to consider is SDN controller placement, which has been widely considered in terrestrial networks. For an SDN network, the proper deployment of the SDN controller is critical to ensure the communication reliability between the control plane and the data plane, reduce deployment costs, and minimize the communication delay from the controller to the SDN switches. Many solutions have been proposed in the literature for the optimal placement of SDN controllers in terrestrial networks with different optimization objectives, e.g., transmission delay minimization, reliability maximization, and deployment cost minimization.

SDN controller placement is also very important in a software defined satellite network. To ensure the normal operation of SDN-based protocols and equipment in the satellite network, reliable communication between the controller and the switches must be ensured, especially in the out-of-band control mode, e.g., the GEO network as the control plane and the LEO network as the data plane. To improve the SDN network reliability, potential link and node failures should also be considered. Otherwise, the switches would be misguided by the outdated information from the controller caused by the long transmission delay or forwarding rule update failure. This concern also arises when the SDN controller is deployed in the ground station, which relies on direct transmission only when the satellite is visible or indirect transmission with inter-satellite links and a longer transmission delay.

The optimal SDN controller placement problem becomes more complex in satellite networks than in terrestrial networks, in which the optimization problem is single objective. In the satellite network or the satellite-terrestrial integrated network, the SDN nodes are more diverse, with routers and switches in the ground and the satellites in the space. Joint optimization with satellite gateway placement is non-negligible, when the SDN command transmits through

Table 4: A summary of the software defined satellite network architectures discussed in Section 4.

Study	Control Plane	Data Plane	Satellite-terrestrial Integrated
Single-layer Structures			
[49]	Data Center	LEO	Yes
[50]	Ground Station	LEO	No
SoftLEO [51]	LEO	LEO	No
[52]	LEO	LEO	No
Two-layer Structures			
[53]	GEO	LEO	No
FRBSN [35]	Ground Station	GEO, LEO	Yes
[43]	Ground Station, GEO, LEO	LEO, Satellite Gateway	No
MLSTIN [54]	GEO, HAP, Terrestrial Network	LEO, LAP, Terrestrial Network	Yes
Three-layer Structures			
OpenSAN [55]	GEO	GEO, MEO, LEO	No
SERvICE [56]	GEO, Data Center, Satellite Gateway	MEO, LEO, Router, Switch, Satellite Gateway	Yes
[57]	GEO, MEO	LEO, Terrestrial Network	Yes
SDN-SatArc [58]	Ground Station	GEO, MEO, LEO, Switch	Yes
HetNet [59]	Ground Station	GEO, MEO, LEO, Satellite Gateway, Switch, Router	Yes
SDB-SAT [60]	Ships	Satellites	No
SD-STIN [61]	Terrestrial Network	GEO, MEO, LEO, Terrestrial Network	Yes
[62]	GEO, MEO, Terrestrial Network	LEO, Terrestrial Network	Yes

the satellite gateway, making the optimization problem multi-objective. For example, minimizing the flow setup time is an important objective that measures the time required for the installation of a forwarding rule. The gateway placement problem is formulated as a network reliability maximization problem under the constraint of propagation latency and an intelligent gateway placement algorithm based on the discrete particle swarm optimization method is proposed as the solution [63].

The existing solutions for SDN controller placement in software-defined satellite networks can be roughly divided into two categories: single-layer and multi-layer hierarchical control architectures. As shown in Table 4, the SDN controller can either be put in a single domain (i.e., the single-layer control architecture) or put in multiple domains (i.e., the multi-layer hierarchical control architecture). In both categories, multiple SDN controllers can be deployed either in a peer-to-peer mode or a master-slave mode, and connected with the east-west bound interfaces. In the peer-to-peer mode, the functions of different SDN controllers are the same, and each controller has the whole network topology information. In the master-slave mode, the priority or control ability of the master or super controller is higher or stronger than that of the slave controller. The whole network topology is only possessed by the master or super controller, and the slave controller is only aware of a sub-network. There is no communication between different slave controllers, which are governed by the master or super controller only.

The common evaluation metrics for evaluating SDN controller placement algorithms include flow setup time, network reliability, network latency, switch-controller latency, and load balancing.

5.1.1. Single-layer Control Architecture

In the single-layer control architecture, the SDN controller is often placed in the ground station or a single type of satellite. Three deployment cases are discussed, namely, in the ground station, in the GEO satellite, and in the LEO satellite. The first case is the deployment in the ground station. The ground station is equipped with stronger computation and storage abilities, which improves the satellite network management level and enables more complex network functions [39]. The multiple SDN controllers deployed in different ground stations can be connected with high speed terrestrial links with a negligible communication delay. The second case is deployment in the GEO satellite. The GEO satellite has a wide range of coverage and three proper GEO satellites would be enough to cover an LEO constellation. The third case is the deployment in the LEO satellite. The LEO satellite has a smaller transmission delay to the ground than the MEO and GEO satellites. Some LEO satellites can be chosen as the SDN controllers, to manage the whole LEO constellation as the in-band control mode. While the low latency property is properly leveraged, it is necessary to select a large number of satellite nodes as controllers to meet the associated coverage of the SDN switches. It would be difficult to maintain the real-time global network topology considering the size of large-scale LEO constellations and the inherent high-speed movement of LEO satellites. Last, a large amount of signaling overhead between massive nodes will increase the network transmission delay, which still fails to meet the low delay requirements in cases of emergency tasks.

The dynamic controller placement problem in the LEO constellation with time-varying traffic demands is considered in [64], with an Integer Linear Programming (ILP) formulation that is solved by the Gurobi solver [22]. The optimization objective is the average flow setup time minimization, with respect to the traffic dynamics. The dynamic solution is proven more effective than the static approach.

The joint placement of controllers and gateways in the terrestrial switches of the satellite-terrestrial integrated network is considered in [65], with the goal of maximizing the network reliability while satisfying the average latency constraint. Compared with the optimal enumeration algorithm with an extremely long running time, the proposed Simulated Annealing and Clustering hybrid Algorithm (SACA) can achieve an approximate optimal performance with much lower computational complexity.

The joint controller and gateway placement problem is also considered in [66, 67], in which the optimization objective is network reliability maximization, with network latency as the constraint. A network partition scheme is adopted and a Simulated Annealing Partition-based K-Means (SAPKM) algorithm is proposed, which achieves a near-optimal performance on network reliability, propagation latency, and much lower computational complexity, e.g., the inter-plane latency costs less than 2 ms to converge.

The joint controller and gateway placement optimization problem is formulated as an integer linear programming problem in [68], to maximize the average network reliability while satisfying the latency constraint. A double simulated annealing algorithm is proposed as the solution, in which the inner part finds the optimal controller placement with the given set of satellite gateways and the outer part loops over many sets of satellite gateways to obtain the overall near-optimal controller and gateway placements. Numerical experiments are conducted for hyper-parameter tuning and performance evaluation, which demonstrates that the proposed method outperforms the baseline heuristic algorithms with better precision and faster computation time, e.g., a 300% decrease in running time.

The controller placement problem in LEO satellite networks is formulated as a mixed integer programming model in [69]. A Static Placement with Dynamic Assignment (SPDA) method is proposed as the solution, in which the controllers are placed statically on certain nodes and then switches are dynamically assigned to them. The evaluation based on two satellite constellations shows that the proposed method reduces the switch-controller latency in both average and worst cases.

Multi-agents deep Q-learning is adopted in [70] for solving the tangled problems of multiple controller position decisions and controller-switch mappings. Compare with K-means, the Q-learning approach increase the link switch number and load balance by 48.25% and 30.92%.

[22] https://www.gurobi.com/

A non-convex integer programming formulation is built for the controller provisioning problem in software-defined LEO satellite networks. An approximate algorithm named AROA based on regularization and randomized rounding is firstly proposed as a theoretically competitive solution and a more efficient heuristic algorithm named HROA is further proposed for practical implementation consideration in [71]. Compared with existing solutions, the proposed methods improve the control overhead and network scalability, while avoiding frequent switch migration.

There are still some disadvantages of the single-layer control architecture in the literature. The characteristics of satellites at various orbital levels cannot be comprehensively utilized, e.g., wide coverage and low latency cannot meet simultaneously in the single-layer control architecture with only GEO or LEO satellites.

5.1.2. Multi-layer Control Architecture

In the multi-layer hierarchical control architecture, SDN controllers are often placed in both GEO and LEO satellites, so that both advantages can be leveraged from these satellites, e.g., the wide coverage of GEO satellites and the low latency between LEO satellites and ground stations. However, the increase in controller nodes also makes it more difficult to synchronize the global network topology among different SDN controllers, with an inevitably increased delay. The multi-layer hierarchical control architecture can also be placed in the LEO network only, by assigning different LEO satellites as super, master and slave controllers.

Considering the controllers deployed in LEO, MEO, GEO or on the ground, both dynamic and static controller placement problems are considered in [72], with the objective of minimizing the controller placement cost. In the dynamic scenario, many backup controllers are placed throughout the network and invoked by changing the on-off status according to highly dynamic network conditions. In the static scenario, the controller is deployed only once. An Accelerate Particle Swarm Optimization (APSO) algorithm is further proposed for solving the optimization problems, which improves the overall performance.

A three-layer control architecture is considered in [73], in which the super controller is placed in the Network Operations Control Center (NOCC), the domain controller is placed in the GEO satellite and the slave controller is placed in the LEO satellite. A greedy slave controller selection strategy is further proposed to facilitate cost reduction and stability enhancement, in which the LEO satellite has the lowest latitude and a longer communication time window is selected.

The dynamic controller placement problem is formulated as a mixed non-integer linear programming problem in [74], which is further proven to be NP-hard. An efficient Dynamic Controller Placement and Adjustment (DCPA) algorithm is proposed to solve the problem with the objective of minimizing the placement and management costs including latency, handover, reliability and load balancing expense. An NS3-based simulation is carried out, which demonstrates the superiority of the proposed DCPA algorithm in terms of average response time and load balancing.

To improve the networking response latency of the distributed satellite subnet is considered in [75], and the dynamic controller placement problem is formulated as a capacitated facility location problem. An on-demand dynamic approximation algorithm is further proposed for effectively optimizing the network latency, which is reduced by approximately 15%.

Considering the frequent network topology variation caused by constellation movement and communication link failure under the in-band control mode for LEO mega-constellations, a novel dual-layer SDN in-band control framework is proposed in [48], in which an upper-layer control plane is used to provide reliable in-band control paths for control traffic generated/received by the lower-layer control plane. By performing the logarithmic treatment for reliability and assigning a weight function to each edge and each vertex, it is demonstrated that the reliability of a path can be measured by the shortest path algorithm and a redundant path routing algorithm is further proposed as the solution, to maximize the network reliability. The experiments show that the proposed framework possesses fewer inaccessible satellites when multiple link failures occur in a mega-constellation scenario.

The hierarchical SDN controller placement problem in the satellite-terrestrial integrated network is formulated as a Mixed Integer Linear Programming (MILP) problem in [76, 77], with the weighted objective of average controller-to-gateway latency minimization and average control path reliability maximization. In a sub-modular optimization-based approach, a linear-time algorithm with a theoretical performance guarantee is proposed, which achieves a near-optimal solution compared with the exact MILP solution.

Taking the highly dynamic topology and randomly fluctuating load of LEO satellite networks into consideration, the multi-layer hierarchical SDN control placement problem is considered in [78]. An NP-hard Adaptive Controller Placement and Assignment (ACPA) formulation is built and a control relation graph based heuristic solution is proposed for management cost minimization. A lookahead-based improvement algorithm is further designed to decrease the management cost with the predicted topology and estimated traffic load. The superiority of the proposed algorithm is validated with response time and load balancing.

The simulated annealing algorithm is adopted to design a hierarchical multi-controller deployment strategy for SDN-enabled space–air–ground integrated networks in [79]. Then a switch migration strategy is designed for load balancing. The proposed scheme achieves a 7.71% increase in terms of the controller load, compared with OCLDS in simulations.

There are still some disadvantages of the multi-layer hierarchical control architecture in the literature. The processing delay of the controller is often ignored and only the propagation delay is considered, which neglects the difference in processing capabilities among different controllers and takes the processing time of all data packets as the same. In practice, the processing delay also has a non-negligible impact on the network performance, especially when the on-board processing ability is limited.

A summary of the relevant studies for SDN controller placement is presented in Table 5. While most of the surveyed studies focus on the SDN controller placement problem in the establishment stage or the SDN controller selection problem from the previously deployed candidate controllers in the operation stage, the controller placement update problem with the minimum cost when a satellite network is expanded is further considered in [80]. A virtual topology approach is leveraged to formulate this problem and a heuristic controller update algorithm is further proposed and validated.

Most of the studies listed in Table 5 rely on numerical experiments for performance evaluation, while the theoretical analysis is rare in the literature. An analytical model with M/M/1/m priority-based queueing theory is built in [81] for performance modeling and evaluation of the in-band control mode in software-defined satellite networks.

Instead of SDN controller placement, the control link selection problem is also considered in the surveyed studies [82, 83]. A new cross-layer SDN control link problem in the software-defined LEO satellite network is introduced and studied in [82], which minimizes the expected latency as a function of propagation delay and gateway power. A power-efficient control link algorithm is proposed, which establishes low latency control links with reduced power consumption and achieves low latency and high reliability in numerical experiments. The constraint of limited cross-layer links between the GEO control plane and LEO data plane is also considered in [83], and a switching-aware dynamic control path planning scheme is proposed to select the control link based on a particle swarm optimization-based algorithm, with the multiple objectives of minimizing the control path latency and maximizing the load balancing index.

Another relevant problem is efficient flow table management, with two specific challenges in software defined satellite networks. The first challenge is that Ternary Content Addressable Memory (TCAM) space is limited on satellites so that the flow table size cannot be too large. The second challenge is

Table 5: A summary of the relevant studies for SDN controller placement.

Study	Optimization Objective	Problem Formulation	Proposed Solution	Limitation
Single-layer Control Structure				
[64]	Flow setup time minimization	Integer linear programming formulation	Gurobi solver	The proposed solution is based on an existing solver and the evaluation metrics are not comprehensive
[65]	Network reliability maximization	Joint controller and gateway placement optimization	Simulated annealing and clustering hybrid algorithm	The experiment is based on terrestrial network topologies
[66, 67]	Network reliability maximization	Joint controller and gateway placement optimization	Simulated annealing partition-based K-Means algorithm	The experiment is based on terrestrial network topologies
[68]	Network reliability maximization	Joint controller and gateway placement optimization	Double simulated annealing algorithm	The experiment is based on terrestrial network topologies
[69]	Switch-controller latency minimization	Mixed integer programming formulation	Static placement with dynamic assignment method	The evaluation metrics are not comprehensive
[70]	Link switch number and load maximization	Joint controller placement and controller-switch mapping	Multi-agents deep Q-learning	The evaluation metrics are not comprehensive
[71]	Total control overhead minimization	Non-convex integer programming formulation	Approximate and heuristic algorithms	The evaluation metrics are not comprehensive
Multi-layer Control Structure				
[72]	Placement cost minimization	Dynamic and static controller placement optimization	Accelerate particle swarm optimization algorithm	The evaluation metrics are not comprehensive
[73]	Cost reduction and stability enhancement	Slave controller selection optimization	Greedy slave controller selection strategy	The evaluation metrics are not comprehensive and the greedy solution is sub-optimal
[74]	Placement and management cost minimization	Mixed non-integer linear programming formulation	Heuristic algorithm	The evaluation metrics are not comprehensive
[75]	Network response latency minimization	Capacitated facility location problem formulation	On-demand dynamic approximate algorithm	The evaluation metrics are not comprehensive
[48]	Network reliability maximization	Graph-based optimization formulation	Redundant path routing algorithm	The evaluation metrics are not comprehensive
[76, 77]	Latency minimization and reliability maximization	Mixed integer linear programming formulation	Sub-modular optimization-based algorithm	The experiment is based on terrestrial network topologies
[78]	Management cost minimization	Adaptive controller placement and assignment formulation	Control relation graph based approximation algorithm	The evaluation metrics are not comprehensive
[79]	Control load maximization	Multi-objective optimization problem formulation	The simulated annealing algorithm	The evaluation metrics are not comprehensive

the flow table size increase caused by frequent handovers. Several solutions have been discussed in the literature. A multi-strategy flow table management method called SAT-FLOW is proposed in [84], based on two heuristic algorithms, namely, the Dynamic Classified Timeout (DCT) algorithm for flow table size reduction and the Timeout Strategy-based Mobility Management (TSMM) algorithm for drop flow reduction during handovers. In another solution proposed in [85], an Intelligent Dynamic Timeout (IDT) algorithm is proposed to predict dynamic timeout for the eviction of unused flow entries, with the purposes of reducing the size of the flow table, drop flow rate and number of table miss packets. Considering the memory shortage challenge of flow tables in software defined satellite networks, an expanded-field search algorithm is proposed for flow table storage compression in [86]. Compared with the global optimization algorithm, the proposed algorithm achieves a comparable storage compression efficiency with a run time saving of 1-2 orders of magnitude. The proposed algorithm also reduces the search cost by over 64% compared with baselines.

5.2. Mobility Management

In satellite networks, satellite movement has a much higher speed than mobile network nodes in the terrestrial networks. In a satellite-terrestrial integrated network, the connection status between a satellite node and a ground node is constantly changing. The users previously covered by a satellite would need to be served by another satellite with greater signal strength and better communication service, which is accomplished by the handover mechanism. The frequent handover of satellite-to-earth links will increase the network management overhead and the problem of designing better mobility management and handover strategies to minimize handover frequency and overhead has been an important research direction in satellite networks. The frequently adopted evaluation metrics for evaluating mobility management algorithms include handover latency, throughput, and user qual-

Table 6: A summary of the relevant studies for mobility management.

Study	Proposed Solution	Limitation
[87]	A seamless handover mechanism based on link selection with the strongest signal	The proposed solution is sub-optimal
[88]	A heuristic timeout strategy-based mobility management algorithm	The proposed solution is sub-optimal
[89]	A new distributed mobile management scheme for traffic redirection	The distributed solution is not globally optimal
[90]	A potential game based handover strategy	The game theory approach is difficult to implement in practice
[91]	A smart gateway diversity management logic and handover control procedure based on different signal-to-noise ratio thresholds	The threshold values are difficult to determine in practice
[92]	A Wardrop game based handover strategy	The game theory approach is difficult to implement in practice

ity of experience. A summary of the relevant studies for mobility management is presented in Table 6.

Both hard and soft handover schemes are proposed for satellite networks. In a hard handover scheme, the current link is released before the next link is established, with the benefit of saving channel resources. In a soft handover scheme, the current link is not released before the next link is established. For example, the MEO constellation O3b uses a make-before-break mechanism to ensure seamless handovers, in which a ground terminal temporarily enjoys a simultaneous connection to two satellites [93].

In traditional satellite networks without using SDN tools, mobility management is often based on a predictive approach. Each satellite operates in a fixed orbit, so that the movement trajectory and connection links are regular and predictable. Since the ground station can determine the whole network topology at any time with a strong computation ability, the flow table can be calculated and sent in advance, before the handover procedure. After the handover happens, the satellite can directly forward data with the updated forwarding rules, without the waiting time caused by the flow table transmission between the satellite and ground station.

While the predictive approach is effective in most cases, it is not flexible for emergency situations. In addition to the satellite trajectory and topology, the handover scheme design also depends on the user demand request and link resource availability, which is time-varying and cannot be known ahead. The handover in satellite-terrestrial integrated networks is further modeled as a multi-objective optimization problem and an intelligent handover algorithm based on Improved Discrete Binary Particle Swarm Optimization (IBPSO-HO) is designed with the goals of both achievable rate and load balance [94]. In software-defined satellite networks, the SDN controller is used to collect real-time network status information and design more efficient handover mechanisms.

A seamless handover mechanism based on software defined satellite network is proposed in [87], in which the unified collection and centralized control of network status information is performed by the ground controller and LEO satellites only act as switches. The user terminal can connect to multiple satellites at the same time and selects the link with the strongest signal as the main communication link. The strength of signals received by different satellites is periodically measured and the main communication link can be changed before handover occurs. This change would be reported and updated to the controller. Through physical layer simulations, the proposed handover protocol outperforms both the existing hard and hybrid handover schemes, in terms of handover latency, throughput and user quality of experience.

The flow entry drop problem due to the limited flow table space and frequent handovers is considered in [88] for the software defined satellite network. A heuristic timeout strategy-based mobility management algorithm is proposed as the solution, which takes the limited flow table space and satellite link handover into consideration during handover and reduces drop flows. The transmission quality improvement, drop-flow rate decrease, and flow table size decrease are validated for the proposed algorithm in the experiments, in which the drop-flow rate decreases by 8.2%-9.9% and the flow table size decreases by 6.9%-11.18% during the handover.

The traffic redirection problem during handover is considered in [89] with SDN techniques. A new distributed mobile management scheme is proposed, which implements location management and address handover with SDN controllers. When the satellite or ground mobile node moves to a new location, the registration information is sent to the nearest gateway, and the SDN controller synchronizes and updates the location information in all gateways. The new proposed scheme manages to achieve packet forwarding path optimization and management cost reduction, compared with the traditional schemes.

A game theory-based approach is adopted in [90] for handover strategy design in software defined LEO satellite networks, which is formulated in a bipartite graph framework to model the connection relations between LEO satellites and mobile terminals. The potential game is used to design a handover algorithm, which maximizes the benefits of mobile terminals who are computing for the satellites and available channels as resources with Nash equilibrium. A terminal random-access algorithm is further proposed for the target of user space maximization, by allocating the load to maximize the feasible area of the subsequent access terminals.

For extremely high-frequency satellite networks with SDN switches, a smart gateway diversity management logic and handover control procedure is proposed in [91], which considers link degradation and triggers traffic reallocation by different signal-to-noise ratio thresholds. Only a portion of the groups of user beams is reallocated in the handover procedure, so that the number of user beams that are reallocated is minimized. The performance of the proposed solution is evaluated with real link data measured during the Alphasat experiment of the Italian Space Agency and the proposed solution achieves a gain of 40% in terms of aggregated capacity.

The queued gamed theory model is used when considering the transmission control problem in software defined space-air-ground integrated networks and the optimal handover strategy is the solution to the system social welfare maximization problem in [92]. Compared with the Wardrop scheme which uses response time as the reference value for traffic control, the proposed solution achieves a higher throughput and the maximum social welfare with a lower delay.

5.3. Routing

Routing is to find the optimal path from a source node to a destination node and has been extensively studied in terrestrial networks. The problem becomes more challenging in satellite networks, due to the high-speed movement, time-varying topology, and limited on-board processing ability. Various problems are encountered, such as unstable communication link status, unbalanced network traffic distribution and network congestion, making satellite communication less reliable than terrestrial networks. With the increase in the number of satellites and the expansion of the network scale, e.g., large-scale LEO constellations, satellite networks would have various services with different QoS requirements and higher requirements for energy consumption and fault recovery capabilities. The metrics used for routing performance evaluation include packet drop rate, end-to-end delay and throughput. A summary of the relevant studies for routing is presented in Table 7.

Traditional satellite network routing algorithms can be roughly classified into three categories, namely, virtual node based routing, virtual topology-based routing and adaptive routing. Both virtual node and virtual topology routing schemes bypass the troubles caused by dynamic topology changes. The adaptive routing schemes obtain the whole network topology information to calculate a better routing table based on the periodic exchange of network information between satellite nodes. However, adaptive routing has a higher requirement for on-board processing ability. Most of the adaptive routing schemes based on terrestrial routing algorithms are impractical, without fully considering the satellite link characteristics and limited processing ability.

In software defined satellite networks, the SDN controller has the ability to obtain the link information of all satellite nodes in real time, making the basis for designing more efficient routing schemes. The routing scheme can also be adjusted in real time, based on the time-varying topology and link status. Some studies have focused on improving traditional satellite network routing schemes with the SDN architecture. For example, a Virtual Node Matrix Routing algorithm (VNMR) is designed in [109], through the features of the periodicity and predictability of the satellite network, the separation of forwarding and controlling by the SDN architecture and the response speed improvement of content requests by the Information-Centric Networking (ICN) idea. The Dijkstra algorithm is implemented in each time slice to determine the optimal path, based on the virtual node topology. A virtual topology strategy is also adopted to shield the dynamics of satellite motion in [110], and an interval-type-2 fuzzy set routing algorithm is proposed that manages to reduce the average delay, increase the total throughput and reduce the packet drop rate.

More surveyed studies are designing routing algorithms for software-defined satellite networks from scratch with different types of objectives, e.g., load balancing, link utilization maximization, packet loss rate minimization, energy saving, fault tolerance, congestion, congestion avoidance and control, etc. Inter-satellite link attributes are leveraged in [95], which proposes a dynamic routing algorithm for software defined LEO satellite networks and chooses the optimal routing path with the highest path utility. The proposed algorithm demonstrates 35%, 10%, and 20% improvements in terms of packet drop rate, end-to-end delay and throughput in the simulations.

Load balancing is one of the major objectives in the surveyed studies, when the uneven distribution of users is often seen in satellite networks. Load balancing is also tightly aligned to the goal of congestion avoidance and control, which are often together considered. The existing algorithms are leveraged to design new routing solutions for load balancing and congestion avoidance. The depth-first-search and Dijkstra algorithms are combined to design new routing algorithms for software-defined satellite networks in [96, 97]. Based on the time slice division method, the satellite network topology is seen as static in each time slice [96] and the combined routing algorithm improves the computational efficiency and reliability. The time slice division strategy is further improved in [97], with better computational efficiency. The pre-

Table 7: A summary of the relevant studies for routing.

Study	Proposed Solution	Limitation
[95]	A dynamic routing algorithm with the highest path utility	The proposed solution is sub-optimal
[96]	New routing algorithms based on the depth-first-search and Dijkstra algorithms	The dynamic satellite network topology is regarded as a static topology in each time slice
[97]	The time slice division strategy	The dynamic satellite network topology is regarded as a static topology in each time slice
[98]	A novel QoS-aware routing algorithm based on Bresenham and Dijkstra algorithms	The proposed solution is sub-optimal
[99]	A load balancing optimization algorithm based on the Viterbi algorithm	The proposed solution is sub-optimal
[100]	A heuristic service-oriented end-to-end fragment-aware routing algorithm based on the ant colony-based heuristic algorithm	The proposed solution is sub-optimal
[101]	A routing algorithm based on the improved genetic algorithm	The dynamic satellite network topology is regarded as a static topology in each time slice
[102]	A load and shared bottleneck aware subflow route selection algorithm and adjust algorithm	The proposed solution is sub-optimal
[103]	A MPTCP based load balancing mechanism	The proposed solution is sub-optimal
[104]	A fault-tolerant routing algorithm	The proposed solution is sub-optimal
[105]	An energy-saving routing scheme	The proposed solution is sub-optimal
[106]	An online intra-domain segment routing framework	The proposed solution is sub-optimal
[107]	A MPTCP path selection scheme	The dynamic satellite network topology is regarded as a static topology in each time slice
[108]	A load balancing strategy with total congested links minimization	The proposed solution is sub-optimal

requisite node is defined and used to avoid the link congestion problem by selecting the node with a small load to pass through.

A novel QoS-aware routing algorithm called fybrrLink is proposed in [98], based on the Bresenham and Dijkstra algorithms. The optimal path is found in a significantly reduced computation time. A score function is incorporated for each link for congestion avoidance during routing and quick re-routing during inter-satellite link congestion or satellite failure. A load balancing optimization algorithm based on the Viterbi algorithm for minimum migration cost is proposed in [99] when the network functions of the overloaded nodes are migrated to other suitable nodes with a migration cost function.

Various heuristic algorithms are often used too [100, 101]. A heuristic service-oriented end-to-end fragment-aware routing algorithm is proposed in [100] for elastic data flows in LEO satellite-terrestrial integrated networks. An ant colony-based heuristic algorithm is adopted to search for the optimum path. Through numerical experiments, the proposed algorithm is proven effective for reducing the wavelength fragmentation and bandwidth consumption, and has a better performance on load balancing. Specifically, the wavelength fragmentation decreases by 23.58% and 19.78% and the bandwidth decreases by 10.23% and 9.23%, compared with Dijkstra and SADR algorithms, respectively. An improved genetic algorithm is used in [101] to calculate the path with the minimum cost.

Multipath solutions with load awareness have also been designed in several studies [102, 103]. An SDN-cooperated Multi-Path Transmission Control Protocol (scMPTCP) is designed in [102], in which a load and shared bottleneck aware subflow route selection algorithm and adjust algorithm are proposed to select routes for new subflows, based on the available bandwidth of each route and the network load changes, to avoid the bottleneck of other subflows. A similar MPTCP based load balancing mechanism is proposed in [103], in which the flow is first divided into several subflows and k shortest paths are then selected, according to the cost of different paths.

Fault tolerance is another important objective when designing a robust routing scheme under the situations of inter-satellite link and satellite node failures. A fault-tolerant routing algorithm is designed in [104] based on the hierarchical routing method. The satellite nodes are classified into different types, i.e., faulty, deactivated, unsafe and active nodes, so that the data packet can pass through the active nodes with no faults. The proposed algorithm manages to achieve a better performance than the baselines with severe link and node failures, in terms of total routing delay and packet loss rate. In serious failure scenario, the proposed algorithm has a 3.99%-19.19% lower total routing delay, a 16.94%-37.95% lower packet loss rate than baselines.

Energy saving is another objective for designing routing algorithms in resource-limited satellite networks. An energy-saving routing scheme is designed in [105] when SDN controllers are placed in both the ground and GEO satellites. The combination of the ground and GEO controllers not only relieves the computational pressure on the satellite, but also makes up for the shortcomings of real-time monitoring difficulty in the ground station. Based on the user number and distribution, the ground control center builds a traffic request model to predict the on-board traffic demand,

and designs a pre-computed energy-saving routing algorithm based on the prediction results, which optimizes path choices while reducing network energy consumption.

Segment Routing (SR) is introduced to minimize the control traffic, for example, an online intra-domain SR framework based on SDN for CubeSats is introduced in [106] with an online algorithm for near-optimal route computation. The proposed framework achieves a higher level of demand satisfaction but also provides a significant reduction in control traffic, along with load balancing. Segment control technology is applied in [107], and an MPTCP path selection scheme is designed to meet the low delay requirements of delay-sensitive traffic flow, improve bandwidth utilization, and ensure more efficient and reliable data transmission.

The SDN router placement and routing problems are jointly considered in [108], and a load balancing strategy is designed to distribute traffic among networks optimally and minimize the total congested links, in which the congestion estimation of inter-links is first introduced and then the allocation solution is computed for each flow. The proposed strategy improves the packet loss rate by 4.4%-6.5% and the throughput by 8.3%-11.6%.

5.4. Virtual Network Embedding

Enabled with SDN techniques, network virtualization has become a significant technology for future network development, both in space and on the ground. Virtual networks can be built by mapping Virtual Network Functions (VNFs) to physical network devices and links, in the process of Virtual Network Embedding (VNE). A similar concept often used in the literature is Service Function Chaining (SFC), which aims to allow various service functions to be connected to each to form a service enabling carriers from the virtualized software defined infrastructure. Different from terrestrial networks, the time-varying network topology, intermittent inter-satellite links, and limited network resources lead to larger challenges for VNE and SFC problems in software-defined satellite networks. The evaluation metrics for virtual network embedding algorithms include average resource utilization, algorithm convergence speed, end-to-end delay, and service mapping success rate. A summary of the relevant studies for virtual network embedding is presented in Table 8.

Topology dynamics, quality of service requirements, and resource constraints are considered in [111] and a two-step multi-constraint virtual network embedding algorithm is proposed, in which the node is embedded with the greedy algorithm and the link is embedded with the k shortest path algorithm. With another objective of energy saving of satellite networks, a two-step virtual network embedding algorithm is proposed in [112] based on the greedy algorithm for node mapping and the shortest path algorithm for link mapping. The experiments show that the proposed algorithm reduces the number of link establishments in the mapping of virtual links compared with baselines. The VNE problem is formulated as an integer linear programming problem in [113, 114] to minimize satellite network resource consumption. A branch-and-price algorithm is designed by combining Dantzig-Wolfe decomposition, column generation, and branch-and-bound as an effective solution. For practical usage, an approximation algorithm with beam search is proposed to obtain a faster solution. A horizontal-based multi-domain service function chaining orchestration framework is proposed in [115] for SDN-enabled satellite networks. A heuristic SFC mapping algorithm is further proposed with a cooperative inter-domain path calculation method to map service function chains to infrastructures in a cooperative approach that masters multi-domain orchestrator and intra-domain orchestrator coordinates to select proper inter-domain links.

Virtual network embedding and routing are often jointly considered in the surveyed studies [116, 117, 118]. The joint optimization of VNF deployment and routing is considered in [116], in which VNF deployment and routing are matched to fulfill the requirements of traffic flows. A software defined time evolving graph is introduced to describe the time-varying network topology, and a multi-slot integer linear programming problem is formulated to minimize cost. Based on the formulation, a time-slot decoupled algorithm is proposed and validated through simulation results, which makes an optimization strategy each time slot based on the predictable and deterministic mobility of LEO satellites. The joint problem of virtual network embedding and service data routing is also considered in [117], in which an NP-hard integer nonlinear programming problem is formulated. A heuristic greedy algorithm is proposed, which leverages different features of aerial and ground nodes and balances the resource consumption. The communication-computation tradeoff is evaluated with a newly introduced metric, i.e., the aggregation ratio, and the proposed algorithm manages to achieve a higher aggregation ratio than baselines. The problem of VNF placement and routing traffic is formulated as an integer nonlinear programming problem with the objective of minimizing the link resource utilization and the number of servers used in [118], which is proven NP-hard. Based on the greedy idea and IBM CPLEX solver, a location-aware resource allocation algorithm is further proposed as the solution, which performs better than baselines and can effectively decrease the average resource utilization by 12.62%-15.34% in different settings.

Considering the inevitable observation errors and transmission delays caused by the constantly changing satellite network topology, the partial observation

Table 8: A summary of the relevant studies for virtual network embedding.

Study	Proposed Solution	Limitation
[111]	A two-step multi-constraint VNE algorithm based on the greedy and k shortest path algorithms	The greedy solution is sub-optimal
[112]	A two-step VNE algorithm based on the greedy and shortest path algorithms	The greedy solution is sub-optimal
[113, 114]	A branch-and-price algorithm and an approximation algorithm with beam search	The proposed solution is sub-optimal
[115]	A heuristic SFC mapping algorithm	The considered scenario is static and the proposed solution is sub-optimal
[116]	A time-slot decoupled algorithm	The considered scenario is static and the proposed solution is sub-optimal
[117]	A heuristic greedy algorithm	The greedy solution is sub-optimal
[118]	A greedy algorithm and IBM CPLEX solver	The greedy solution is sub-optimal
[119]	A partial observation Markov decision process solution	The proposed solution is sub-optimal
[120]	A SFC mapping algorithm with the lowest predicted delay	The proposed solution is sub-optimal
[121]	An on-demand network slicing solution based on a mathematical program and an online algorithm	The proposed solution is sub-optimal
[122]	An improved adaptive satellite-5G downlink scheduler	The proposed solution is sub-optimal

Markov decision process is adopted in [119] for designing service function chain deployment plan. The influence of different factors including the length of service function chain and the number of service requests is evaluate in the simulations, in terms of the algorithm convergence speed, end-to-end delay, service request mapping success rate, and running time. Compared with three different baselines, the proposed method manages to increase the convergence speed by 65.75%, 35.89% and 59.02%, and the service mapping success rate by 11.54%, 26.09% and 36.79% with the lowest end-to-end delay. Based on delay predictions of the potential deployment paths, a service function chain mapping algorithm selects the path with the lowest predicted delay in [120]. Compared with the traditional scheme, the prediction-based algorithm increases the CPU resource utilization rate, the link resource utilization rate, and the service acceptance rate by 27.8%, 22.7% and 21.5%, respectively, with a 25.2% reduced total resource consumption.

Network slicing is another relevant concept that provides logically isolated network transmission tunnels using shared physical network resources to support increasing and heterogeneous network service requirements, e.g., the various user scenarios in 5G. Network slicing with the satellite network incorporated is also considered in the surveyed studies [121, 123, 122]. To provide flexible service chaining and provisioning with diversified service requirements, an on-demand network slicing solution based on a mathematical program combined with an online algorithm is proposed in [121], which aims to minimize resource consumption while meeting the end-to-end delay requirement. Slice isolation is used to boost the effectiveness of radio resource management in [122] and an improved adaptive satellite-5G downlink scheduler is proposed to reduce the packet loss ratio under different network conditions and traffic types.

6. Simulation Tools of Software Defined Satellite Networks

In this section, we present the first and most comprehensive summary of simulation tools used in the relevant studies about software defined satellite networks, as shown in Table 9. The purpose of this section is to create a reference manual for newcomers in this research area as guidance. This manual does not aim to cover all relevant tools, but those frequently used in the surveyed studies. These simulation tools are divided into the following types:

- Network simulators, which are used to simulate the network topology, network protocols and network functions. The often used network simulators include Network Simulator NS3 [23], NS2 (an older version of NS3) [24], Mininet [25] and EXata [26]. Various real-world satellite constellations are used to build the satellite network topology, including LEO constellations, e.g., Iridium, Starlink, Globalstar, Celestri, and MEO constellations, e.g., MAGSS-14. For the terrestrial part in the satellite-terrestrial integrated network, the Internet Topology Zoo [27] records many real-world network topologies, e.g., the China Education and Research Network (CERNET) used in [100, 115]. Synthetic topologies are also generated and used with the network topology generators, e.g., GT-ITM used in [99].

- Satellite tools, which are used to calculate the satellite orbit parameters, simulate inter-satellite links and satellite network topology, analyze the

[23] `https://www.nsnam.org/`
[24] `http://nsnam.sourceforge.net/wiki/index.php/User_Information#The_Network_Simulator_-_ns-2`
[25] `http://mininet.org/`
[26] `https://www.ncs-in.com/product/exata-network-emulator/`
[27] `http://www.topology-zoo.org/`

global or regional coverage, etc. Satellite Tool Kit (STK) is the primary choice, which provides link accessibility, link distance, and satellite ephemeris.

- SDN tools, which mainly include the SDN controller and APIs, as introduced in Section 2. The often used SDN controllers in the surveyed studies include Ryu, ONOS, and POX. OpenFlow is the primary southbound API and Open vSwitch is the primary virtual switch.

Table 9: A summary of the simulation tools for software defined satellite networks.

Tool	Relevant Studies
Network Simulator	
NS3	[50, 62, 74, 98]
NS2	[97, 110]
Mininet	[87, 60, 78, 103, 104, 124]
EXata	[72, 80, 125]
Satellite Tool	
STK	[51, 53, 56, 52, 72, 73, 69, 89, 90, 96, 125, 104, 105, 116, 113, 114]
Satellite Topology	
Iridium	[51, 52, 72, 90, 96, 108, 125, 110, 100]
Starlink	[83, 69]
Globalstar	[62]
Celestri	[69]
MAGSS-14	[62]
SDN Controller	
Ryu	[91, 102, 103, 104]
Floodlight	[60]
ONOS	[78]
POX	[56, 88]
OVS	[124]
SDN Protocol	
OpenFlow	[56, 58, 59, 60, 43, 54, 46, 62, 64, 88, 89, 91, 103, 124]
SDN Switch	
Open vSwitch	[60, 124]

While not listed in Table 9, MATLAB is the most popular programming language in relevant studies (e.g., at least used in [53, 35, 65, 72, 73, 80, 68, 83, 69, 99, 100, 116, 113, 114]), both for its powerful modeling ability and flexibility and its compatibility with other simulation tools. In addition to MATLAB, Python and Java are often used in the surveyed studies.

7. Challenges and Opportunities

To inspire follow-up studies, research challenges and opportunities are identified in this section. Some of them have already been considered in the surveyed studies but with no perfect solutions found, while the others are still in a preliminary stage without being given full consideration. The challenges are briefly discussed first. Then, some opportunities are proposed as potential solutions to solve these challenges.

7.1. Challenges

7.1.1. Management Challenge

While the introduction of SDN helps to improve the management ability of satellite networks, the management challenge still exists for the following reasons. First, the dramatic satellite number increase in LEO constellations requires an efficient hierarchical and multi-domain SDN satellite network architecture with network scalability. For large-scale constellations, effective network monitoring and management tools are required, which can realize the fine configuration of network resources and can also react quickly to node or link failures. In addition, spectrum coexistence issues, beam correlation problems and cross-layer power allocation problems in satellite-terrestrial integrated networks require cooperation among different network operators to achieve an integrated and efficient spectrum management scheme. Finally, there are various services with different QoS requirements and higher requirements for energy consumption and fault recovery capabilities. Potential solutions include priority-based resource allocation and scheduling mechanisms [81], heuristic algorithm-based management schemes [78, 80, 84, 100, 101] and AI-powered management solutions [126, 127].

7.1.2. Migration Challenge

Migration challenges occur in satellite networks when researchers migrate the existing SDN protocols and tools from terrestrial networks to satellite networks, as in many surveyed studies. However, there are still many differences between these two types of networks, making migration not as easy as assumed. Some efforts have been made with integration with terrestrial networks, e.g., a virtual data-plane addressing scheme by leveraging IP addresses to represent virtual switches is proposed in [124], to fulfill the seamless integration of the fixed control plane on the ground and the mobile data plane. However, most of the existing network protocols are not applicable in space when the satellite network has frequent handovers and large transmission delays. Potential solutions include the efforts of migrating existing terrestrial network protocols (e.g., TCP/IP protocols) to satellite networks or designing new network protocols with the consideration for satellite network features, e.g., the delay-tolerant routing protocol [128].

7.1.3. Security Challenge

Compared with terrestrial networks, satellite networks have wide coverage. However, this advantage also brings more security challenges, e.g., it is easier to eavesdrop anywhere in a wide area. In addition, the limited on-board processing ability of satellites makes them less capable of fighting against potential cyber attacks. For software-defined satellite networks, new security issues arise in the communication between the SDN controller and switches in the data plane, when the signaling information may be forged, encrypted and eavesdropped during handovers [61]. To ensure handover robustness, efficient physical-layer security measures should be considered. However, due to the complexity and variability of satellite network nodes, the establishment of a satellite network security key management system is still a very difficult task. Potential solutions include anti-jamming techniques, secure routing algorithms, secure handover schemes, secure key management methods, intrusion detection systems, etc [12]. Recently, blockchain-based security services are also proposed to deal with the security threats in satellite networks and improve the security and privacy of satellite based IoT applications [13]. Dynamic Bayesian game is also used to design DDoS defense method in software defined space-air-ground networks [129].

7.2. Opportunities

7.2.1. Joint Optimization of Networking, Caching, and Computing

The joint optimization of networking, caching, and computing has been proposed as an effective approach to increase the satellite network management efficiency in recent years, which could improve the system performance and user experience [130, 131]. In [130], the joint optimization problem is described as a Markov decision process. The state space includes the angle state, networking state, caching state, and computing state. The action space includes user allocation, content caching action and computation task offloading. The reward function is defined as the ratio between the charging fee of using the resource and the paid fee of having the resource. A novel deep Q-learning approach is proposed as the solution to learn the optimal resource allocation strategies. In [131], the joint computing and communication resource management problem is considered to minimize the execution latency of computation-intensive applications, and the joint computing and communication resource allocation problem is formulated as a mixed-integer programming problem. A game-theoretic and many-to-one matching theory-based scheme with low complexity is proposed, which achieves an approximate optimal solution that has almost the same weight-sum latency as the brute-force method.

Mobile edge computing has been proposed as a specific approach for realizing the joint optimization of networking, caching, and computing in software defined satellite networks [132]. The basic idea is to extend cloud computing in servers to network edges or even user terminals so that hierarchical and heterogeneous computing resources are available from any location. Mobile edge computing has been widely considered in terrestrial networks, in which edge servers can be deployed in base stations. In satellite networks, it is difficult to deploy edge servers in satellites with limited computation ability. In most studies, edge servers are deployed in satellite gateways or ground stations with stronger computation ability, with optimization objectives including delay minimization, energy saving and QoS maximization [133, 134, 135, 136]. For satellite image processing tasks in IoT applications, a 5G/6G-oriented satellite IoT edge computing architecture is proposed in [134], which leverages edge computing and deep learning for satellite IoT image data target detection. Simulation results show that edge computing can effectively reduce the amount of data transmitted by satellites, data processing and communication delays, improve the link bandwidth utilization of inter-satellite links, and reduce the data processing burden on satellite ground stations. In [136], a computational offloading strategy based on an improved ant colony algorithm is proposed, which reduces the cost of the local system through the allocation of local equipment resources while finding the optimal queuing order of offloading tasks to reduce the cost of the satellite system. A reduction of 28% system cost can be achieved by the proposed strategy. In addition, game theory is leveraged to design better computational offloading and resource allocation schemes in satellite-based edge computing [137, 138], which is worth further consideration.

7.2.2. Application of Artificial Intelligence

With the satellite number increase in large-scale LEO constellations and more potential link or node failures, an increasing requirement for fast and efficient management abilities is required, which is beyond the capabilities of traditional solutions. AI has been considered a promising solution for management challenges due to its automatic planning and fast response abilities. Represented by deep neural networks, artificial intelligence has been successful in a series of problems in recent years [139, 140, 141, 142]. Different artificial intelligence techniques are introduced to design routing and VNE algorithms in software-defined satellite networks, e.g., supervised learning and reinforcement learning. For example, Chebyshev neural networks are leveraged to update the flow tables [125]. In the intelligent QoS routing scheme proposed in [143], the ensemble support vector regression is used to design the controller cooperation strategy. Deep reinforcement learning is leveraged for building a cross-domain VNE algorithm for heterogeneous resource orchestration in satellite-terrestrial networks [126]. As a specific family of neural networks, graph neural networks have been proposed and validated as new effective tools to design routing schemes in satellite networks [127, 144].

The application of AI in software-defined satellite networks is still in an early stage, with many challenges unsolved yet. The small amount of satellite traffic data makes it difficult to collect real-world data to train AI models. Simulation data are used as an alternative. The robustness of artificial intelligence algorithms is another concern, especially for deep learning models that are criticized as black boxes. The satellite network topology changes periodically, and the inter-satellite links have the characteristics of short link establishment time and dynamic distance change. Thus, an adaptive and scalable AI model is required to perform properly in unseen cases. In the case of SDN controllers in satellites, the computational complexity of AI models is also a concern. Thus, a lightweight, high-efficiency and low-complexity AI model is preferred in satellite networks.

7.2.3. Development of Satellite-Oriented SDN Tools

Most of the network simulators listed in Table 9 are designed for terrestrial networks or general simulation purposes, without consideration of satellite link characteristics. More recently, some efforts have been made for satellite-specific simulation tools, e.g., Large-scale Satellite Network Simulator (LSNS) [145] which is publicly available [28], SImulator for Large LEO-Satellite Communication NetworkS (SILLEO-SCNS) [146] which is publicly available [29], OpenSAND [30] and Trunks [31]. Some simulation platforms are also designed for software defined optical satellite networks in the literature [147, 148]. Some relevant commercial products are also available, e.g., the Satellite and Aerospace Channel Emulation Toolset provided by Keysight Technologies [32]. In addition to the simulation tools, some real-world satellite systems are built to carry out in-orbit tests and verification and validate the abilities of deploying SDN and other networking tools in satellite networks, e.g., the Tiansuan constellation [149] and Satellite Intelligence Service Platform in China SpaceTY Satellite used in [150].

However, most of the studies are still in the stage of proposing only prototypes, and to the best of our knowledge, no specific SDN protocols are finalized for satellite networks. In these prototypes, SDN APIs and controllers are adopted from the terrestrial network, with little or no modifications, which may be impractical for the satellite network. It is necessary to develop specific and universal SDN tools for satellite networks, to solve the migration challenge, even though the development cost is huge. A small step has been made in [151], in which a redesigned southbound interface based on OpenFlow is built to reduce the protocol complexity in heterogeneous software defined satellite networks, and there is still much room to explore.

7.2.4. Development of Security Tools

Two approaches are adopted in the literature for satellite network communication security, namely, physical-layer security and cryptography schemes [152]. In the physical layer, existing security issues include spoofing, which disguises a communication from an unknown source as being from a known source, and jamming, which injects intentional interference into the wireless channel to disrupt the operations of a legitimate communication channel. Cryptography techniques are proposed in the literature to secure satellite links, e.g., identity authentication schemes and key agreement protocols.

However, few security tools have been developed for software-defined satellite networks. Some preliminary efforts have been made to increase the software defined satellite network communication security [153, 154], and there are still many opportunities for developing SDN-enabled security tools for satellite networks. In [153], the secure communication of a cognitive satellite terrestrial network with software defined architecture is investigated and two beamforming schemes are proposed with the utilization of the interference from the terrestrial network as a green source to enhance the physical-layer security. In [154], a novel access authentication architecture is proposed for software defined satellite-terrestrial integrated networks with an access point decision algorithm and detailed access rules. Distributed Denial of Service (DDoS) attacks are considered in [155] for satellite networks and a DDoS attack detection method is proposed based on the combination of artificial intelligence models, i.e., LSTM and SVM.

7.2.5. Integration of Terrestrial-UAV-Satellite Networks

UAV networks have been used in a broad range of applications, including disaster management, data collection from the ground sensor network, surveillance, logistic support, etc [156]. UAVs can be easily deployed as a part of communication facilities and make up for site scarcity problems of both terrestrial base stations and satellites, with a wider coverage and better channels [157]. Terrestrial-UAV-satellite networks are further proposed, in which UAV is employed as a relay to assist the satellite signal delivery [158]. The challenge of improving system energy efficiency in terrestrial-UAV-satellite networks is considered in [159] and an iterative algorithm which leverages coordinate ascent and Lagrangian dual decomposition methods is proposed as the solution to obtain the optimal relay selection and power allocation decisions.

While UAV has been proposed as a component in terrestrial-UAV-satellite integrated networks, the combination of UAV networks with software defined satellite networks has been touched before to the best of our knowledge and is proposed as a promising research direction. Another opportunity is to further combine the AI capacities in software defined terrestrial-UAV-satellite networks, e.g., improvement of network reliability and data transmission rate with reinforcement

[28] `http://github.com/infonetlijian/ONE-Extended-Simulator`
[29] `https://github.com/Ben-Kempton/SILLEO-SCNS`
[30] `https://github.com/CNES/opensand`
[31] `https://github.com/shynuu/trunks`
[32] `https://www.keysight.com/us/en/product/S8825A/propsim-channel-emulation-aerospace-testing.html`

learning [160, 161].

7.2.6. Combination with Emerging Innovations

Besides the above discussion, more opportunities arise when emerging innovations are introduced into software-defined satellite networks, e.g., digital twins, blockchain, and zero-touch network management. While some of these emerging techniques are not mature yet, they have a great chance of reshaping existing information and communication infrastructure in the near future.

Digital twin is a promising solution for simulating and enabling software defined satellite networks. Digital twin is based on the digital replica of physical objects, places, system, people and devices, e.g., the physical satellite and ground facilities. It consists of three main parts, namely, physical product, virtual product and data transmission between them [162]. Digital twin has been proposed to model the health management data from satellites and help to improve the safety and reliability. Digital twin can be further combined with satellite networks by providing software-defined solutions to design and validate various applications, e.g., autonomous management and monitoring, software-driven transformation, end-to-end service orchestration, and network/service automation of complex satellite networks, instead of relying on physical satellites [7]. It is a relatively new idea of introducing digital twins to software-defined satellite networks and there are still some challenges, e.g., data privacy and information misuse threat.

Another potential opportunity is the combination of blockchains with software-defined satellite networks [13]. Blockchain is a decentralized, tamper-resistant, and publicly shared ledger that records transactions and tracks assets in a secure way [163, 164]. There are already some relevant studies applying blockchains in satellite networks, including access control protocols [165, 166, 167], reputation systems [168], and cyber attack detection methodologies [169]. It is worth further consideration for a joint design of blockchain and SDN techniques for future satellite networks, e.g., enhancing the network security.

The third opportunity is the combination with the zero-touch network management concept, which enables an autonomous network system with features of self-configuration, self-monitoring, self-healing, and self-optimization based on service-level policies and rules without human intervention [170]. SDN is one of the key enablers for the zero-touch network management solution, which helps to mange the entire network in a global manner and allows network configuration and monitoring in a dynamic and programmed manner [171]. Zero-touch network management is more attractive in satellte networks than terrestrial networks, because of the high maintence cost for satellite nodes in space. While some preliminary attempts have been made for introducing zero-touch network management into satellite networks [172], it is still in an early stage and requires a further investigation.

8. Conclusion

In recent years, SDN has been proposed as a new direction for the development of future satellite networks and there is considerable literature for relevant studies. In this survey, a comprehensive summary of the key techniques, existing solutions, challenges and opportunities and a practical guide of the simulation tools of software defined satellite networks are presented. Compared with existing surveys, this survey makes the following main contributions: (1) this survey reviews the latest progress of key techniques and solutions in software defined satellite networks in an up-to-date SDN-oriented approach; (2) this survey summarizes existing challenges, new research opportunities and publicly available simulation tools for inspiring follow-up studies; (3) this survey makes the first effort of building a public repository to track new results on relevant topics.

Currently, the application of SDN in satellite networks is still in an early exploration stage with no mature solutions or protocols. There are no off-the-shelf SDN controllers or switches designed for satellite networks. In other words, there is still a long way to go on the road of realizing a practical software defined satellite network.

References

[1] J. Garrity, A. Garba, The last-mile internet connectivity solutions guide sustainable connectivity options for unconnected sites, `https://www.itu.int/pub/D-TND-01`, 2020 (accessed 12 January 2023).

[2] N. McKeown, T. Anderson, H. Balakrishnan, G. Parulkar, L. Peterson, J. Rexford, S. Shenker, J. Turner, Openflow: enabling innovation in campus networks, ACM SIGCOMM computer communication review 38 (2) (2008) 69–74.

[3] R. Ferrús, H. Koumaras, O. Sallent, G. Agapiou, T. Rasheed, M.-A. Kourtis, C. Boustie, P. Gélard, T. Ahmed, Sdn/nfv-enabled satellite communications networks: Opportunities, scenarios and challenges, Physical Communication 18 (2016) 95–112.

[4] Y. Miao, Z. Cheng, W. Li, H. Ma, X. Liu, Z. Cui, Software defined integrated satellite-terrestrial network: A survey, in: International conference on space information network, Springer, 2016, pp. 16–25.

[5] Y. Peng, T. Dong, R. Gu, Q. Guo, J. Yin, Z. Liu, T. Zhang, Y. Ji, A review of dynamic resource allocation in integrated satellite and terrestrial networks, in: 2018 international conference on networking and network applications (NaNA), IEEE, pp. 127–132.

[6] A. Guidotti, S. Cioni, G. Colavolpe, M. Conti, T. Foggi, A. Mengali, G. Montorsi, A. Piemontese, A. Vanelli-Coralli, Architectures, standardisation, and procedures for 5g satellite communications: A survey, Computer Networks 183 (2020) 107588.

[7] O. Kodheli, E. Lagunas, N. Maturo, S. K. Sharma, B. Shankar, J. F. M. Montoya, J. C. M. Duncan, D. Spano, S. Chatzinotas, S. Kisseleff, et al., Satellite communications in the new space era: A survey and future challenges, IEEE Communications Surveys & Tutorials 23 (1) (2021) 70–109.

[8] S. Kota, G. Giambene, 6g integrated non-terrestrial networks: Emerging technologies and challenges, in: 2021 IEEE International Conference on Communications Workshops (ICC Workshops), pp. 1–6.

[9] P. K. Donta, S. N. Srirama, T. Amgoth, C. S. R. Annavarapu, Survey on recent advances in iot application layer protocols and machine learning scope for research directions, Digital Communications and Networks 8 (5) (2022) 727–744.

[10] P. P. Ray, A review on 6g for space-air-ground integrated network: Key enablers, open challenges, and future direction, Journal of King Saud University-Computer and Information Sciences 34 (9) (2022) 6949–6976.

[11] M. Centenaro, C. E. Costa, F. Granelli, C. Sacchi, L. Vangelista, A survey on technologies, standards and open challenges in satellite iot, IEEE Communications Surveys & Tutorials 23 (3) (2021) 1693–1720.

[12] H. Guo, J. Li, J. Liu, N. Tian, N. Kato, A survey on space-air-ground-sea integrated network security in 6g, IEEE Communications Surveys & Tutorials 24 (1) (2022) 53–87.

[13] Y. Wang, Z. Su, J. Ni, N. Zhang, X. Shen, Blockchain-empowered space-air-ground integrated networks: Opportunities, challenges, and solutions, IEEE Communications Surveys & Tutorials 24 (1) (2022) 160–209.

[14] H. Cui, J. Zhang, Y. Geng, Z. Xiao, T. Sun, N. Zhang, J. Liu, Q. Wu, X. Cao, Space-air-ground integrated network (sagin) for 6g: Requirements, architecture and challenges, China Communications 19 (2) (2022) 90–108.

[15] H. Kim, N. Feamster, Improving network management with software defined networking, IEEE Communications Magazine 51 (2) (2013) 114–119.

[16] L. Zhu, M. M. Karim, K. Sharif, C. Xu, F. Li, X. Du, M. Guizani, Sdn controllers: A comprehensive analysis and performance evaluation study, ACM Computing Surveys (CSUR) 53 (6) (2020) 1–40.

[17] D. Kreutz, F. M. Ramos, P. E. Verissimo, C. E. Rothenberg, S. Azodolmolky, S. Uhlig, Software-defined networking: A comprehensive survey, Proceedings of the IEEE 103 (1) (2014) 14–76.

[18] A. Doria, J. H. Salim, R. Haas, H. M. Khosravi, W. Wang, L. Dong, R. Gopal, J. M. Halpern, Forwarding and control element separation (forces) protocol specification., RFC 5810 (2010) 1–124.

[19] H. Song, Protocol-oblivious forwarding: Unleash the power of sdn through a future-proof forwarding plane, in: Proceedings of the second ACM SIGCOMM workshop on Hot topics in software defined networking, 2013, pp. 127–132.

[20] N. Gude, T. Koponen, J. Pettit, B. Pfaff, M. Casado, N. McKeown, S. Shenker, Nox: towards an operating system for networks, ACM SIGCOMM computer communication review 38 (3) (2008) 105–110.

[21] J. Medved, R. Varga, A. Tkacik, K. Gray, Opendaylight: Towards a model-driven sdn controller architecture, in: Proceeding of IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks 2014, pp. 1–6.

[22] F. Tomonori, Introduction to ryu sdn framework, `https://ryu-sdn.org/slides/ONS2013-april-ryu-intro.pdf`, 2013 (accessed 12 January 2023).

[23] P. Berde, M. Gerola, J. Hart, Y. Higuchi, M. Kobayashi, T. Koide, B. Lantz, B. O'Connor, P. Radoslavov, W. Snow, et al., Onos: towards an open, distributed sdn os, in: Proceedings of the third workshop on Hot topics in software defined networking, 2014, pp. 1–6.

[24] S. Jain, A. Kumar, S. Mandal, J. Ong, L. Poutievski, A. Singh, S. Venkata, J. Wanderer, J. Zhou, M. Zhu, et al., B4: Experience with a globally-deployed software defined wan, ACM SIGCOMM Computer Communication Review 43 (4) (2013) 3–14.

[25] Z. Yang, Y. Cui, B. Li, Y. Liu, Y. Xu, Software-defined wide area network (sd-wan): Architecture, advances and opportunities, in: 2019 28th International Conference on Computer Communication and Networks (ICCCN), pp. 1–9.

[26] S. Azodolmolky, R. Nejabati, M. Pazouki, P. Wieder, R. Yahyapour, D. Simeonidou, An analytical model for software defined networking: A network calculus-based approach, in: 2013 IEEE Global Communications Conference (GLOBECOM), pp. 1397–1402.

[27] C. Lin, C. Wu, M. Huang, Z. Wen, Q. Zheng, Performance evaluation for sdn deployment: An approach based on stochastic network calculus, China Communications 13 (Supplement 1) (2016) 98–106.

[28] J. Ansell, W. K. Seah, B. Ng, S. Marshall, Making queueing theory more palatable to sdn/openflow-based network practitioners, in: NOMS 2016-2016 IEEE/IFIP Network Operations and Management Symposium, pp. 1119–1124.

[29] Y. Goto, B. Ng, W. K. Seah, Y. Takahashi, Queueing analysis of software defined network with realistic openflow–based switch model, Computer Networks 164 (2019) 106892.

[30] F. Riffel, R. Gould, Satellite ground station virtualization: Secure sharing of ground stations using software defined networking, in: 2016 Annual IEEE Systems Conference (SysCon), pp. 1–8.

[31] M. R. Maheshwarappa, M. D. Bowyer, C. P. Bridges, A reconfigurable sdr architecture for parallel satellite reception, IEEE Aerospace and Electronic Systems Magazine 33 (11) (2018) 40–53.

[32] X.-N. Yang, J.-L. Xu, C.-Y. Lou, Software-defined satellite: A new concept for space information system, in: 2012 Second International Conference on Instrumentation, Measurement, Computer, Communication and Control, pp. 586–589.

[33] G. Gardikis, S. Costicoglou, H. Koumaras, C. Sakkas, A. Kourtis, F. Arnal, L. M. Contreras, P. A. Gutierrez, M. Guta, Nfv applicability and use cases in satellite networks, in: 2016 European Conference on Networks and Communications (EuCNC), pp. 47–51.

[34] G. Agapiou, R. A. Ferrús Ferré, H. Koumaras, J. O. Sallent Roig, T. Rasheed, N. Kuhn, T. Ahmed, Sdn and nfv for satellite infrastructures, in: Proceedings of 2016 IEICE ICTF, Institute of Electronics, Information and Communications Engineers (IEICE), 2016, pp. 1–4.

[35] M. Sheng, Y. Wang, J. Li, R. Liu, D. Zhou, L. He, Toward a flexible and reconfigurable broadband satellite network: Resource management architecture and strategies, IEEE Wireless Communications 24 (4) (2017) 127–133.

[36] R. Ferrus, O. Sallent, T. Ahmed, R. Fedrizzi, Towards sdn/nfv-enabled satellite ground segment systems: End-to-end traffic engineering use case, in: 2017 IEEE International Conference on Communications Workshops (ICC Workshops), pp. 888–893.

[37] N. Yoshino, H. Oguma, S. Kameda, N. Suematsu, Feasibility study of expansion of openflow network using satellite communication to wide area, in: 2017 Ninth International Conference on Ubiquitous and Future Networks (ICUFN), pp. 647–651.

[38] P. Du, S. Nazari, J. Mena, R. Fan, M. Gerla, R. Gupta, Multipath tcp in sdn-enabled leo satellite networks, in: MILCOM 2016-2016 IEEE Military Communications Conference, pp. 354–359.

[39] L. Bertaux, S. Medjiah, P. Berthou, S. Abdellatif, A. Hakiri, P. Gelard, F. Planchou, M. Bruyere, Software defined networking and virtualization for broadband satellite networks, IEEE Communications Magazine 53 (3) (2015) 54–60.

[40] T. Ahmed, R. Ferrus, R. Fedrizzi, O. Sallent, N. Kuhn, E. Dubois, P. Gelard, Satellite gateway diversity in sdn/nfv-enabled satellite ground segment systems, in: 2017 IEEE International Conference on Communications Workshops (ICC Workshops), pp. 882–887.

[41] F. Mendoza, R. Ferrús, O. Sallent, Flexible capacity and traffic management for hybrid satellite-terrestrial mobile backhauling networks, in: 2016 International Symposium on Wireless Communication Systems (ISWCS), pp. 119–124.

[42] J. Zhang, B. Evans, M. A. Imran, X. Zhang, W. Wang, Performance analysis of c/u split hybrid satellite terrestrial network for 5g systems, in: 2015 IEEE 20th International Workshop on Computer Aided Modelling and Design of Communication Links and Networks (CAMAD), pp. 97–102.

[43] S. Xu, X.-W. Wang, M. Huang, Software-defined next-

generation satellite networks: Architecture, challenges, and solutions, IEEE Access 6 (2018) 4027–4041.
[44] C.-Q. Dai, S. Li, J. Wu, Q. Chen, Distributed user association with grouping in satellite–terrestrial integrated networks, IEEE Internet of Things Journal 9 (12) (2021) 10244–10256.
[45] C.-Q. Dai, J. Luo, S. Fu, J. Wu, Q. Chen, Dynamic user association for resilient backhauling in satellite–terrestrial integrated networks, IEEE Systems Journal 14 (4) (2020) 5025–5036.
[46] W.-C. Chien, C.-F. Lai, M. S. Hossain, G. Muhammad, Heterogeneous space and terrestrial integrated networks for iot: Architecture and challenges, IEEE Network 33 (1) (2019) 15–21.
[47] L. He, X. Zhang, Z. Cheng, Y. Jiang, Design and implementation of sdn/ip hybrid space information network prototype, in: 2016 IEEE/CIC International Conference on Communications in China (ICCC Workshops), pp. 1–6.
[48] W. Ningyuan, D. Chen, L. Liang, M. Wang, L. Bingyuan, An sdn based highly reliable in-band control framework for leo mega-constellations, in: 2021 IEEE 6th International Conference on Computer and Communication Systems (ICCCS), pp. 970–975.
[49] Z. Wang, G. Xu, T. Mai, L. Yang, Y. Gao, Design of leo satellite network resource management architecture based on ai, Information Technology and Network Security 37 (2) (2018) 20–22.
[50] Y. Zhu, L. Qian, L. Ding, F. Yang, C. Zhi, T. Song, Software defined routing algorithm in leo satellite networks, in: 2017 International Conference on Electrical Engineering and Informatics (ICELTICs), pp. 257–262.
[51] H. Hu, S. Zhang, B. Tang, Leo software defined networking based on onboard controller, in: 2018 IEEE Global Conference on Signal and Information Processing (GlobalSIP), pp. 1068–1071.
[52] A. Papa, T. De Cola, P. Vizarreta, M. He, C. Mas-Machuca, W. Kellerer, Design and evaluation of reconfigurable sdn leo constellations, IEEE Transactions on Network and Service Management 17 (3) (2020) 1432–1445.
[53] X. Shi, Y. Li, S. Zhao, W. Wang, X. Wang, Multi-qos objective optimization routing algorithm of satellite network based on sdn, Systems Engineering & Electronics 42 (6) (2020) 1395–1401.
[54] Y. Shi, Y. Cao, J. Liu, N. Kato, A cross-domain sdn architecture for multi-layered space-terrestrial integrated networks, IEEE Network 33 (1) (2019) 29–35.
[55] J. Bao, B. Zhao, W. Yu, Z. Feng, C. Wu, Z. Gong, Opensan: a software-defined satellite network architecture, ACM SIGCOMM Computer Communication Review 44 (4) (2014) 347–348.
[56] T. Li, H. Zhou, H. Luo, S. Yu, Service: A software defined framework for integrated space-terrestrial satellite communication, IEEE Transactions on Mobile Computing 17 (3) (2017) 703–716.
[57] J. Li, K. Xue, J. Liu, Y. Zhang, Y. Fang, An icn/sdn-based network architecture and efficient content retrieval for future satellite-terrestrial integrated networks, IEEE Network 34 (1) (2019) 188–195.
[58] J. Feng, L. Jiang, Y. Shen, W. Ma, M. Yin, A scheme for software defined ors satellite networking, in: 2014 IEEE Fourth International Conference on Big Data and Cloud Computing, pp. 716–721.
[59] B. Feng, H. Zhou, H. Zhang, G. Li, H. Li, S. Yu, H.-C. Chao, Hetnet: A flexible architecture for heterogeneous satellite-terrestrial networks, IEEE network 31 (6) (2017) 86–92.
[60] S. Nazari, P. Du, M. Gerla, C. Hoffmann, J. H. Kim, A. Capone, Software defined naval network for satellite communications (sdn-sat), in: MILCOM 2016-2016 IEEE Military Communications Conference, pp. 360–366.
[61] Y. Bi, G. Han, S. Xu, X. Wang, C. Lin, Z. Yu, P. Sun, Software defined space-terrestrial integrated networks: architecture, challenges, and solutions, IEEE Network 33 (1) (2019) 22–28.
[62] P. Dong, M. Gao, F. Tang, L. Cao, X. Zhang, P. Han, Y. Yang, W. Xu, X. Zhang, Multi-layer and heterogeneous resource management in sdn-based space-terrestrial integrated networks, in: 2020 IEEE 22nd International Conference on High Performance Computing and Communications; IEEE 18th International Conference on Smart City; IEEE 6th International Conference on Data Science and Systems (HPCC/SmartCity/DSS), pp. 377–384.
[63] C.-Q. Dai, Q. Yang, J. Wu, Q. Chen, Intelligent gateway placement in satellite-terrestrial integrated network, in: IEEE INFOCOM 2021-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), pp. 1–6.
[64] A. Papa, T. De Cola, P. Vizarreta, M. He, C. M. Machuca, W. Kellerer, Dynamic sdn controller placement in a leo constellation satellite network, in: 2018 IEEE Global Communications Conference (GLOBECOM), pp. 206–212.
[65] J. Liu, Y. Shi, L. Zhao, Y. Cao, W. Sun, N. Kato, Joint placement of controllers and gateways in sdn-enabled 5g-satellite integrated network, IEEE Journal on Selected Areas in Communications 36 (2) (2018) 221–232.
[66] K. Yang, B. Zhang, D. Guo, Controller and gateway partition placement in sdn-enabled integrated satellite-terrestrial network, in: 2019 IEEE International Conference on Communications Workshops (ICC Workshops), pp. 1–6.
[67] K. Yang, B. Zhang, D. Guo, Partition-based joint placement of gateway and controller in sdn-enabled integrated satellite-terrestrial networks, Sensors 19 (12) (2019) 2774.
[68] D. K. Luong, Y.-F. Hu, J.-P. Li, M. Ali, Metaheuristic approaches to the joint controller and gateway placement in 5g-satellite sdn networks, in: ICC 2020-2020 IEEE International Conference on Communications (ICC), pp. 1–6.
[69] J. Guo, L. Yang, D. Rincón, S. Sallent, C. Fan, Q. Chen, X. Li, Sdn controller placement in leo satellite networks based on dynamic topology, in: 2021 IEEE/CIC International Conference on Communications in China (ICCC), pp. 1083–1088.
[70] A. Wei, H. Yu, X. Lang, B. Yang, Dynamic controller placement for software-defined leo network using deep reinforcement learning, in: 2021 7th International Conference on Computer and Communications (ICCC), IEEE, 2021, pp. 1314–1320.
[71] X. Li, F. Tang, L. Fu, J. Yu, L. Chen, J. Liu, Y. Zhu, L. T. Yang, Optimized controller provisioning in software-defined leo satellite networks, IEEE Transactions on Mobile Computing (Early Access) (2022) 1–1.
[72] S. Wu, X. Chen, L. Yang, C. Fan, Y. Zhao, Dynamic and static controller placement in software-defined satellite networking, Acta Astronautica 152 (2018) 49–58.
[73] S. Xu, X. Wang, B. Gao, M. Zhang, M. Huang, Controller placement in software-defined satellite networks, in: 2018 14th International Conference on Mobile Ad-Hoc and Sensor Networks (MSN), pp. 146–151.
[74] X. Zhang, F. Tang, L. Cao, L. Chen, J. Yu, W. Xu, X. Zhang, J. Lei, Z. Wang, Dynamical controller placement among sdn space-terrestrial integrated networks, in: 2020 IEEE 22nd International Conference on High Performance Computing and Communications; IEEE 18th International Conference on Smart City; IEEE 6th International Conference on Data Science and Systems (HPCC/SmartCity/DSS), pp. 352–359.
[75] Z. Han, C. Xu, Z. Xiong, G. Zhao, S. Yu, On-demand dynamic controller placement in software defined satellite-terrestrial networking, IEEE Transactions on Network and Service Management 18 (3) (2021) 2915–2928.
[76] N. Torkzaban, J. S. Baras, Controller placement in sdn-enabled 5g satellite-terrestrial networks, in: GLOBECOM 2021-2021 IEEE Global Communications Conference, pp. 1–6.
[77] N. Torkzaban, J. S. Baras, Joint satellite gateway deployment & controller placement in software-defined 5g-satellite integrated networks, arXiv preprint arXiv:2103.08735.
[78] L. Chen, F. Tang, X. Li, Mobility-and load-adaptive controller placement and assignment in leo satellite networks, in: IEEE INFOCOM 2021-IEEE Conference on Computer

Communications, pp. 1–10.
[79] Z. Liao, C. Chen, Y. Ju, C. He, J. Jiang, Q. Pei, Multi-controller deployment in sdn-enabled 6g space–air–ground integrated network, Remote Sensing 14 (5) (2022) 1076.
[80] S. Wu, X. Liu, Q. Chen, J. Guo, L. Yang, Y. Zhao, C. Fan, Update method for controller placement problem in software-defined satellite networking, in: 2019 28th International Conference on Computer Communication and Networks (ICCCN), pp. 1–7.
[81] J. Guo, L. Yang, X. Liu, Q. Chen, C. Fan, X. Li, Performance modelling and evaluation of in-band control mode in software-defined satellite networks based on queuing theory, in: 2021 2nd International Conference on Computing, Networks and Internet of Things, 2021, pp. 1–6.
[82] W. Cho, J. P. Choi, Cross layer optimization of wireless control links in the software-defined leo satellite network, IEEE Access 7 (2019) 113534–113547.
[83] T. Zhang, F. Bai, T. Dong, J. Yin, Z. Liu, Y. Su, Switching-aware dynamic control path planning for software defined large-scale leo satellite networks with geo controllers, in: International Conference on Wireless and Satellite Systems, Springer, 2020, pp. 153–167.
[84] T. Li, H. Zhou, H. Luo, I. You, Q. Xu, Sat-flow: Multi-strategy flow table management for software defined satellite networks, IEEE Access 5 (2017) 14952–14965.
[85] S. Jan, Q. Guo, M. Jia, M. K. Khan, Intelligent dynamic timeout for efficient flow table management in software defined satellite network, in: International Conference on Wireless and Satellite Systems, Springer, 2019, pp. 59–68.
[86] S. Wang, K. Liu, C. Jiang, J. Yan, L. Kuang, Efs: Efficient storage optimization for multistage flow-table in software-defined satellite network, IEEE Access 10 (2021) 391–400.
[87] B. Yang, Y. Wu, X. Chu, G. Song, Seamless handover in software-defined satellite networking, IEEE Communications Letters 20 (9) (2016) 1768–1771.
[88] T. Li, H. Zhou, H. Luo, W. Quan, Q. Xu, G. Li, G. Li, Timeout strategy-based mobility management for software defined satellite networks, in: 2017 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), pp. 319–324.
[89] H. Li, C. Wang, W. Wang, J. Zhang, Research on distributed mobile management of satellite network based on software define network, Journal on Communications 38 (Z1) (2017) 143–150.
[90] Y. Wu, G. Hu, F. Jin, J. Zu, A satellite handover strategy based on the potential game in leo satellite networks, IEEE Access 7 (2019) 133641–133652.
[91] M. M. Aurizzi, T. Rossi, E. Raso, L. Funari, E. Cianca, An sdn-based traffic handover control procedure and sgd management logic for ehf satellite networks, Computer Networks 196 (2021) 108260.
[92] C. Guo, C. Gong, H. Xu, L. Zhang, Z. Han, A dynamic handover software-defined transmission control scheme in space-air-ground integrated networks, IEEE Transactions on Wireless Communications 21 (8) (2022) 6110–6124.
[93] M. Casoni, C. A. Grazia, M. Klapez, N. Patriciello, A. Amditis, E. Sdongos, Integration of satellite and lte for disaster recovery, IEEE Communications Magazine 53 (3) (2015) 47–53.
[94] C.-Q. Dai, J. Xu, J. Wu, Q. Chen, Multi-objective intelligent handover in satellite-terrestrial integrated networks, in: 2022 IEEE International Conference on Communications Workshops (ICC Workshops), pp. 367–372.
[95] Z. Han, G. Zhao, Y. Xing, N. Sun, C. Xu, S. Yu, Dynamic routing for software-defined leo satellite networks based on isl attributes, in: 2021 IEEE Global Communications Conference (GLOBECOM), pp. 1–6.
[96] M. Jia, S. Zhu, L. Wang, Q. Guo, H. Wang, Z. Liu, Routing algorithm with virtual topology toward to huge numbers of leo mobile satellite network based on sdn, Mobile Networks and Applications 23 (2) (2018) 285–300.
[97] W. Sun, J. Liang, N. Xiao, R. Ding, Y. Yan, Routing algorithm for space based network based on sdn and virtual topology, Transducer and Micro system Technology 39 (1) (2020) 125–128.
[98] P. Kumar, S. Bhushan, D. Halder, A. M. Baswade, fybrrlink: Efficient qos-aware routing in sdn enabled future satellite networks, IEEE Transactions on Network and Service Management 19 (3) (2022) 2107–2118.
[99] C. Pan, J. Shi, L. Yang, Z. Kong, Satellite network load balancing strategy for sdn/nfv collaborative deployment, in: 2019 IEEE SmartWorld, Ubiquitous Intelligence & Computing, Advanced & Trusted Computing, Scalable Computing & Communications, Cloud & Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI), pp. 1406–1411.
[100] Q. Guo, R. Gu, T. Dong, J. Yin, Z. Liu, L. Bai, Y. Ji, Sdn-based end-to-end fragment-aware routing for elastic data flows in leo satellite-terrestrial network, IEEE Access 7 (2018) 396–410.
[101] L. Yang, Q. Teng, Z. Kong, R. Cai, Design of spatial information network routing strategy based on sdn architecture, Spacecraft Engineering 28 (05) (2019) 54–61.
[102] Z. Jiang, Q. Wu, H. Li, J. Wu, scmptcp: Sdn cooperated multipath transfer for satellite network with load awareness, IEEE Access 6 (2018) 19823–19832.
[103] Z. Ma, X. Di, J. Li, L. Cong, P. Li, Mptcp based load balancing mechanism in software defined satellite networks, in: International Conference on Wireless and Satellite Systems, Springer, 2019, pp. 294–302.
[104] M. Jia, X. Wang, S. Zhang, B. Yi, M. Huang, Software defined network based fault tolerant routing mechanism for satellite networks, Journal of Computer Applications 39 (6) (2019) 1772–1779.
[105] Z. Liu, X. Wang, S. Xu, R. Zeng, Pre-computation based energy-saving routing for software defined satellite networks, Cyberspace Security 10 (11) (2019) 100–109.
[106] A. Kak, I. F. Akyildiz, Online intra-domain segment routing for software-defined cubesat networks, in: GLOBECOM 2020-2020 IEEE Global Communications Conference, pp. 1–6.
[107] M. Ouyang, X. Duan, J. Liu, R. Zhang, T. Huang, H. Lu, Multi-path transmission scheme based on segment control in low-earth-orbit satellite network, in: 2021 IEEE 22nd International Conference on High Performance Switching and Routing (HPSR), pp. 1–7.
[108] X. Tao, K. Ota, M. Dong, H. Qi, K. Li, Congestion-aware scheduling for software-defined sag networks, IEEE Transactions on Network Science and Engineering 8 (4) (2021) 2861–2871.
[109] Z. Liu, J. Zhu, J. Zhang, Q. Liu, Routing algorithm design of satellite network architecture based on sdn and icn, International Journal of Satellite Communications and Networking 38 (1) (2020) 1–15.
[110] Y. Wu, G. Hu, F. Jin, S. Tang, Multi-objective optimisation in multi-qos routing strategy for software-defined satellite network, Sensors 21 (19) (2021) 6356.
[111] D. Yang, J. Liu, R. Zhang, T. Huang, Multi-constraint virtual network embedding algorithm for satellite networks, in: GLOBECOM 2020-2020 IEEE Global Communications Conference, pp. 1–6.
[112] J. Liu, X. He, T. Chen, X. Wang, R. Luo, T. Huang, Sn-vne: A virtual network embedding algorithm for satellite networks, in: 2019 IEEE/CIC International Conference on Communications Workshops in China (ICCC Workshops), pp. 1–6.
[113] Z. Jia, M. Sheng, J. Li, Y. Zhu, W. Bai, Z. Han, Virtual network functions orchestration in software defined leo small satellite networks, in: ICC 2020-2020 IEEE International Conference on Communications (ICC), pp. 1–6.
[114] Z. Jia, M. Sheng, J. Li, D. Zhou, Z. Han, Vnf-based service provision in software defined leo satellite networks, IEEE Transactions on Wireless Communications 20 (9) (2021) 6139–6153.
[115] G. Li, H. Zhou, B. Feng, G. Li, Q. Xu, Horizontal-

based orchestration for multi-domain sfc in sdn/nfv-enabled satellite/terrestrial networks, China Communications 15 (5) (2018) 77–91.

[116] Z. Jia, M. Sheng, J. Li, R. Liu, K. Guo, Y. Wang, D. Chen, R. Ding, Joint optimization of vnf deployment and routing in software defined satellite networks, in: 2018 IEEE 88th Vehicular Technology Conference (VTC-Fall), pp. 1–5.

[117] G. Wang, S. Zhou, S. Zhang, Z. Niu, X. Shen, Sfc-based service provisioning for reconfigurable space-air-ground integrated networks, IEEE Journal on Selected Areas in Communications 38 (7) (2020) 1478–1489.

[118] X. Gao, R. Liu, A. Kaushik, Service chaining placement based on satellite mission planning in ground station networks, IEEE Transactions on Network and Service Management 18 (3) (2021) 3049–3063.

[119] W. Qiao, X. Ni, Y. Lu, X. Li, D. Zhao, Y. Liu, A service function chain deployment scheme of the software defined satellite network, Mobile Information Systems 2022 (2022) 6402481.

[120] P. Zhang, P. Yang, N. Kumar, M. Guizani, Space-air-ground integrated network resource allocation based on service function chain, IEEE Transactions on Vehicular Technology 71 (7) (2022) 7730–7738.

[121] T. Ahmed, A. Alleg, R. Ferrus, R. Riggio, On-demand network slicing using sdn/nfv-enabled satellite ground segment systems, in: 2018 4th IEEE Conference on Network Softwarization and Workshops (NetSoft), pp. 242–246.

[122] S. Hendaoui, C. N. Zangarz, Leveraging sdn slicing isolation for improved adaptive satellite-5g downlink scheduler, in: 2021 International Symposium on Networks, Computers and Communications (ISNCC), pp. 1–5.

[123] C. Suzhi, W. Junyong, H. Hao, Z. Yi, Y. Shuling, Y. Lei, W. Shaojun, G. Yongsheng, Space edge cloud enabling network slicing for 5g satellite network, in: 2019 15th International Wireless Communications & Mobile Computing Conference (IWCMC), pp. 787–792.

[124] G. Zheng, N. Wang, R. Tafazolli, X. Wei, J. Yang, Virtual data-plane addressing for sdn-based space and terrestrial network integration, in: 2021 IEEE 22nd International Conference on High Performance Switching and Routing (HPSR), pp. 1–6.

[125] W. Sun, J. Liang, N. Xiao, R. Ding, Z. Zhang, Intelligent routing scheme for sdn satellite network based on neural network, in: IOP Conference Series: Materials Science and Engineering, Vol. 563, IOP Publishing, 2019, p. 052087.

[126] P. Zhang, C. Wang, N. Kumar, L. Liu, Space-air-ground integrated multi-domain network resource orchestration based on virtual network architecture: A drl method, IEEE Transactions on Intelligent Transportation Systems 23 (3) (2022) 2798–2808.

[127] M. Liu, J. Li, H. Lu, Routing in small satellite networks: A gnn-based learning approach, arXiv preprint arXiv:2108.08523.

[128] C. Caini, Delay-tolerant networks (dtns) for satellite communications, in: Advances in Delay-Tolerant Networks (DTNs), Elsevier, 2021, pp. 23–46.

[129] Z. Li, B. Yang, X. Zhang, C. Guo, Ddos defense method in software-defined space-air-ground network from dynamic bayesian game perspective, Security and Communication Networks 2022 (2022) 1886516.

[130] C. Qiu, H. Yao, F. R. Yu, F. Xu, C. Zhao, Deep q-learning aided networking, caching, and computing resources allocation in software-defined satellite-terrestrial networks, IEEE Transactions on Vehicular Technology 68 (6) (2019) 5871–5883.

[131] S. Zhang, G. Cui, Y. Long, W. Wang, Joint computing and communication resource allocation for satellite communication networks with edge computing, China Communications 18 (7) (2021) 236–252.

[132] T. Qinqin, X. Renchao, L. Xu, C. H. Yasheng ZHANG, L. Chengcheng, et al., Mec enabled satellite-terrestrial network: architecture, key technique and challenge, Journal on Communications 41 (4) (2020) 162.

[133] Z. Zhang, W. Zhang, F.-H. Tseng, Satellite mobile edge computing: Improving qos of high-speed satellite-terrestrial networks using edge computing techniques, IEEE network 33 (1) (2019) 70–76.

[134] J. Wei, S. Cao, Application of edge intelligent computing in satellite internet of things, in: 2019 IEEE International Conference on Smart Internet of Things (SmartIoT), pp. 85–91.

[135] N. Cheng, F. Lyu, W. Quan, C. Zhou, H. He, W. Shi, X. Shen, Space/aerial-assisted computing offloading for iot applications: A learning-based approach, IEEE Journal on Selected Areas in Communications 37 (5) (2019) 1117–1129.

[136] B. Wang, T. Feng, D. Huang, X. Li, Mobile edge computing for leo satellite: A computation offloading strategy based improved ant colony algorithm, in: Proceedings of the 11th International Conference on Computer Engineering and Networks, Springer, 2022, pp. 1664–1676.

[137] J. Du, C. Jiang, H. Zhang, Y. Ren, M. Guizani, Auction design and analysis for sdn-based traffic offloading in hybrid satellite-terrestrial networks, IEEE Journal on Selected Areas in Communications 36 (10) (2018) 2202–2217.

[138] H. Wang, H. Wang, J. An, Dynamic game-based computation offloading and resource allocation in leo-multiaccess edge computing, Wireless Communications and Mobile Computing 2021 (2021) 9486818.

[139] W. Jiang, L. Zhang, Geospatial data to images: A deep-learning framework for traffic forecasting, Tsinghua Science and Technology 24 (1) (2018) 52–64.

[140] W. Jiang, Applications of deep learning in stock market prediction: recent progress, Expert Systems with Applications 2021 (2021) 115537.

[141] W. Jiang, L. Zhang, Edge-siamnet and edge-triplenet: new deep learning models for handwritten numeral recognition, IEICE Transactions on Information and Systems 103 (3) (2020) 720–723.

[142] W. Jiang, J. Luo, Graph neural network for traffic forecasting: A survey, Expert Systems with Applications (2022) 117921.

[143] S. Wu, L. Yang, J. Guo, Q. Chen, X. Liu, C. Fan, Intelligent quality of service routing in software-defined satellite networking, IEEE Access 7 (2019) 155281–155298.

[144] W. Jiang, Graph-based deep learning for communication networks: A survey, Computer Communications 185 (2022) 40–54.

[145] M. Liu, Y. Gui, J. Li, H. Lu, Large-scale small satellite network simulator: Design and evaluation, in: 2020 3rd International Conference on Hot Information-Centric Networking (HotICN), pp. 194–199.

[146] B. Kempton, A. Riedl, Network simulator for large low earth orbit satellite networks, in: ICC 2021-IEEE International Conference on Communications, pp. 1–6.

[147] J. Qin, T. Dong, Q. Guo, J. Yin, R. Gu, Z. Liu, Y. Tan, T. Zhang, Y. Ji, Dynamic simulation platform for software defined optical satellite networking, in: Fiber Optic Sensing and Optical Communication, Vol. 10849, International Society for Optics and Photonics, 2018, pp. 230–235.

[148] J. Li, N. Hua, C. Zhao, K. Zhu, Y. Li, X. Zheng, Design and implementation of open optical satellite network emulation platform (oosn-ep) based on distributed multi-node system, in: Optoelectronics and Communications Conference, Optical Society of America, 2021, p. JS2A.7.

[149] S. Wang, Q. Li, M. Xu, X. Ma, A. Zhou, Q. Sun, Tiansuan constellation: An open research platform, in: 2021 IEEE International Conference on Edge Computing (EDGE).

[150] Y. Guo, Q. Li, Y. Li, N. Zhang, S. Wang, Service coordination in the space-air-ground integrated network, IEEE Network 35 (5) (2021) 168–173.

[151] X. Lang, L. Gui, Design of southbound interfaces in heterogeneous software-defined satellite networks, in: International Conference on Space Information Network, Springer, 2020, pp. 179–189.

[152] P. Tedeschi, S. Sciancalepore, R. Di Pietro, Satellite-based communications security: A survey on threats, solutions, and

research challenges, arXiv preprint arXiv:2112.11324.

[153] M. Lin, Z. Lin, W.-P. Zhu, J.-B. Wang, Joint beamforming for secure communication in cognitive satellite terrestrial networks, IEEE Journal on Selected Areas in Communications 36 (5) (2018) 1017–1029.

[154] Z. Hu, X. Du, L. Cao, One access authentication architecture and method for software defined space-ground integration network, Application Research of Computers 2019 (3) (2019) 873–877.

[155] J. Min, S. Yuejie, G. Qing, G. Zihe, X. Suofei, Ddos attack detection method for space-based network based on sdn architecture, ZTE Communications 18 (4) (2021) 18–25.

[156] M. Basharat, M. Naeem, Z. Qadir, A. Anpalagan, Resource optimization in uav-assisted wireless networks—a comprehensive survey, Transactions on Emerging Telecommunications Technologies (2022) e4464.

[157] M. Mozaffari, W. Saad, M. Bennis, Y.-H. Nam, M. Debbah, A tutorial on uavs for wireless networks: Applications, challenges, and open problems, IEEE communications surveys & tutorials 21 (3) (2019) 2334–2360.

[158] Q. Huang, M. Lin, J.-B. Wang, T. A. Tsiftsis, J. Wang, Energy efficient beamforming schemes for satellite-aerial-terrestrial networks, IEEE Transactions on Communications 68 (6) (2020) 3863–3875.

[159] Y. Shi, J. Wu, L. Liu, D. Lan, A. Taherkordi, Energy-aware relay optimization and power allocation in multiple unmanned aerial vehicles aided satellite-aerial-terrestrial network, IEEE Systems Journal 16 (4) (2022) 5293–5304.

[160] J.-H. Lee, J. Park, M. Bennis, Y.-C. Ko, Integrating leo satellite and uav relaying via reinforcement learning for non-terrestrial networks, in: GLOBECOM 2020-2020 IEEE Global Communications Conference, pp. 1–6.

[161] M. Ndong, M. Hayajneh, N. A. Ali, S. Alkobaisi, Towards a 3-tiered space-air-ground network with reinforcement learning, Journal of King Saud University-Computer and Information Sciences 34 (9) (2022) 7001–7013.

[162] M. Singh, E. Fuenmayor, E. P. Hinchy, Y. Qiao, N. Murray, D. Devine, Digital twin: Origin to future, Applied System Innovation 4 (2) (2021) 36.

[163] S. Zeadally, J. B. Abdo, Blockchain: Trends and future opportunities, Internet Technology Letters 2 (6) (2019) e130.

[164] S. B. Far, S. M. H. Bamakan, Blockchain-based reporting protocols as a collective monitoring mechanism in daos, Data Science and Management 5 (1) (2022) 11–12.

[165] S. Wei, S. Li, P. Liu, M. Liu, Bavp: blockchain-based access verification protocol in leo constellation using ibe keys, Security and Communication Networks 2018 (2018) 7202806.

[166] X. Deng, J. Shao, L. Chang, J. Liang, A blockchain-based authentication protocol using cryptocurrency technology in leo satellite networks, Electronics 10 (24) (2021) 3151.

[167] S. Cao, S. Dang, Y. Zhang, W. Wang, N. Cheng, A blockchain-based access control and intrusion detection framework for satellite communication systems, Computer Communications 172 (2021) 216–225.

[168] L. Clark, Y.-C. Tung, M. Clark, L. Zapanta, A blockchain-based reputation system for small satellite relay networks, in: 2020 IEEE Aerospace Conference, IEEE, 2020, pp. 1–8.

[169] M. Feng, H. Xu, Msnet-blockchain: A new framework for securing mobile satellite communication network, in: 2019 16th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON), pp. 1–9.

[170] M. Liyanage, Q.-V. Pham, K. Dev, S. Bhattacharya, P. K. R. Maddikunta, T. R. Gadekallu, G. Yenduri, A survey on zero touch network and service (zsm) management for 5g and beyond networks, Journal of Network and Computer Applications (2022) 103362.

[171] W. Kellerer, P. Kalmbach, A. Blenk, A. Basta, M. Reisslein, S. Schmid, Adaptable and data-driven softwarized networks: Review, opportunities, and challenges, Proceedings of the IEEE 107 (4) (2019) 711–731.

[172] A. Galli, P. Giardina, M. Guta, L. Lossi, A. Mancina, V. Moscato, F. Patrone, C. Roseti, S. P. Romano, G. Sperlí, et al., Ai for zero-touch management of satellite networks in b5g and 6g infrastructures, in: First International Workshop on Artificial Intelligence in beyond 5G and 6G Wireless Networks, 2022, pp. 1–9.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: