

Received December 6, 2019, accepted December 20, 2019, date of publication December 31, 2019, date of current version January 9, 2020.

Digital Object Identifier 10.1109/ACCESS.2019.2963223

Convergence of Satellite and Terrestrial Networks: A Comprehensive Survey

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This work was supported in part by the National Science Foundation of China (NSFC) under Grant 61771065, Grant 61901048, Grant 61631005, and Grant 61801177, and in part by the Beijing Municipal Science and Technology Commission Research under Project Z181100003218015.

ABSTRACT The explosive growth of various services boosts the innovation and development in terrestrial communication systems for the implementation of the next generation mobile communication networks. However, simply utilizing limited resources in terrestrial communication networks is difficult to support the massive quality of service (QoS) aware requirements and it is hard to guarantee seamless coverage in far remote regions. Leveraging the intrinsic merits of high altitude and the ability of multicasting or broadcasting, satellite communication systems provide an opportunity for novel mobile communication networks with its tight interaction and complementary characteristics to traditional terrestrial networks. It is believed that the convergence of satellite and terrestrial networks can solve the problems existing in current mobile communication systems and make a profound effect on global information dissemination. In this paper, we make a comprehensive survey on the convergence of satellite and terrestrial networks. First, motivations and requirements of satellite-terrestrial network convergence are identified. Then, we summarize related architectures of existing literature, classify the taxonomy of researches on satellite-terrestrial networks, and present the performance evaluation works in different satellite-terrestrial networks. After that, the state-of-the-art of standardization, projects and the key application areas of satellite-terrestrial networks are also reviewed. Finally, we conclude the survey by highlighting the open issues and future directions.

INDEX TERMS Satellite-terrestrial networks, resource allocation, mobility management, access control, security, performance evaluation, survey.

I. INTRODUCTION

Last decades have witnessed a sprout of demands and new applications in the communication industry, innovations are breaking the bottleneck of restrictions and consolidating the procedure of constructing the ubiquitous reliable networks for the next generation. As more and more humans and machines access to networks, the increasing requirements for quality-guaranteed services pressurize the network performance in terms of efficiency and productivity. The current network has already been faced these challenges, requiring a new

communication architecture that could make a breakthrough in traditional information exchanging restrictions. Compared with the fourth generation (4G) long term evolution advanced (LTE-A) systems, the fifth generation (5G) networks have the requirements of massive devices connection ability, higher traffic flow capacity, and customized user services experience [1]. Various applications and customized requirements entitle a new communication evolution with the ability of low latency, high throughput, intensive computing performance and artificial intelligence. It can be noted that these service demands explode beyond imagination, and triggered the development of different technologies influenced people's everyday life. Service providers enhance the user experience

The associate editor coordinating the review of this manuscript and approving it for publication was Giacomo Verticale¹.

through new technologies like virtual reality (VR), augmented reality (AR), and high definition (HD) videos, which drive the increasing growth of applications on mobile devices. Distributed communication infrastructure to be connected and massive data to be delivered motivate the development of an integrated network taking full advantages of communication resource from different dimensions.

In order to meet the requirements of next generation networks, numerous new technologies are developed and applied. Terrestrial networks are now introduced to massive novel mobile technologies to face unprecedented challenges like accommodating skyrocketing traffic flow with the spectrum scarcity, amount escalation of the Internet of Things (IoT) and transformation for an all-IP environment network. The function of networks is no longer simply to transmit information. For now, newly emerging applications incur network operators to redefine the function of communication systems as caching, computing and retrieving resources with intelligence regarding context around users, which could help provide a more efficient communication system with combined innovations. Although decades of developments have yielded a wealth of technologies to enhance terrestrial networks, some challenges involved in enhancing the performance of current networks must be confronted:

- 1) Due to the economical and geographical reasons, service areas of cellular networks usually cannot reach 100% coverage of the globe [7], [35]. For areas with very low-density population, unnecessary communication entities would result in high average cost per person. And in mountainous regions, it is difficult to deploy infrastructure.
- 2) Nature disasters like earthquake, tsunami and forest fire would destroy the communication entities and result in a completely damage for backhaul networks [203], [259]. In this circumstance, it is vital to enhance the robustness of the whole system to make a quick response for rescue.
- 3) Short range communication technologies like device to device (D2D) can help information dissemination in terrestrial networks, however, when the requirements of the cellular on the ground is overloaded, service ability is constraint to the limited local resources like spectrum, power or cache capacity [104]. A global awareness of large areas or networks is essential to help achieve a more balanced resource allocation.

Traditionally, some problems mentioned above have been alleviated by enlarging the scale with more terrestrial communication nodes. However, sometimes merely increasing the scalability of these entities may cause redundancy and bring about more complex problems. Besides, some regions even have no qualification for construction of terrestrial communication infrastructures.

Breaking the geographical restrictions from traditional ground networks to space dimension, satellite networks have attracted unprecedented attention in recent years, and many

innovations have been developed to enhance network flexibility [2]. Compared with terrestrial communication networks, satellites are more suitable for large-scale communications. Due to the ubiquitous service footprint and robust multi-link transmission ability, satellites provide flexible access schemes and high-speed connectivity around the world [3]. Typically, what satellite provides is coverage extension to small cell urban 5G. The booming of new satellite payloads for geostationary earth orbit (GEO) satellite platforms and constellations comprised of low earth orbit (LEO) satellites have forged the integration of satellite and terrestrial networks into an essential network foundation to achieve the quality of service that cannot have by leveraging either of two networks independently. Although this has been expensive, recent moves in very high throughput GEO and LEO constellations are changing the business cases in this respect [21], [23], [77], [78].

The ideology of satellite and terrestrial network convergence has led the communication industry to rethink the communication architecture, especially the role and function of satellite networks and terrestrial networks in the integrated system. In fact, 5G opens up the prospect of real integration between the satellite and the mobile world, but this means a real change in the business models for mobile network operator (MNO) and satellite network operator (SNO). Moreover, optimum solutions for challenges and key technical enablers need to be defined for the contribution of standardization of the features enabling the integration of satcom solutions in 5G at European telecommunications standards institute (ETSI) and the 3rd generation partnership project (3GPP) [4].

ETSI has defined two satellite-terrestrial network deployment concepts, the integrated and the hybrid satellite and terrestrial communication networks [5]. These two deployments are proposed for the delivery of fixed satellite services (FSS), broadcasting satellite service (BSS) or mobile satellite services (MSS) [5]. Integrated satellite-terrestrial networks usually employ satellite components and ground components where the ground components are complementary to the satellite components, while hybrid satellite-terrestrial systems employ satellite and terrestrial communication network infrastructures where the satellite and ground communication components are interconnected, but operate independently. From the definition, the way to distinguish the two satellite-terrestrial networks is that whether the space and ground communication infrastructures exist in a unified network utilizing the shared spectrum.

Some articles and surveys on satellite-terrestrial networks have been published in the last few years [6]–[15]. Mainly focusing on the integration of geostationary satellites and terrestrial networks, reference [6] provided a survey of converged networks from the perspective of end user quality-of-experience (QoE). The article identified four factors, i.e. traffic requirement identification, the link characteristics identification, as well as the traffic engineering and the execution cost, to get a QoE-guaranteed traffic distribution schemes. Wang *et al.* [7] explore the key technologies

like radio resource management and handover schemes in Hybrid satellite-aerial-terrestrial networks, as the authors aim to present the network is an effective solution to natural disaster or large-scale unexpected events, content distribution schemes and security problems is not involved.

Architecture, resource management, and optimization of the space-air-ground integrated network (SAGIN) are explored in [8] and [9]. In particular, authors in [8] make a comprehensive study on space-air-ground integrated network and they are the first to present research works concerning the network design and allocations. But related knowledge for industrial implementation like research and development researches and standardization is not presented. Airborne communication networks which are comprised of satellites, high-altitude platforms (HAPs), and low-altitude platforms (LAPs) have received considerable attention in [9]. Still, key technologies and a taxonomy are needed for a broad view.

Other reviews like [10]–[15] only dive deep in single aspects of satellite-terrestrial networks. Authors in [10] makes an investigation on spectrum sharing in satellite communication systems. Specifically, they confined their discussions on spectrum database method. Reference [11] concludes resource allocation challenges and related solutions to deal with spectrum coexistence issues, beam correlation problems and cross-layer power allocation problems. In [12], challenges and solutions of optical space communication are presented. Links between satellite and ground are easily affected by absorption, scatter, and turbulence. The survey provides a detailed interference mitigation solution. Reference [13] and [14] review MIMO technologies utilized in satellite-terrestrial networks. Ranging from single-input multiple-output system to dual-satellite multiple-input single-output systems, [13] gives measurement results of the system channel and characterized the radio environments of land mobile systems in outdoor scenarios. While [14] presents a broad view on two satellite MIMO systems: fixed satellite systems and mobile systems. The paper also considers the application and future perspectives of the system. It is worth to mention that with the increase in the demand for HD TV, video-on-demand and mobile TV services, standards of satellite and terrestrial broadcasting is summarized in [15].

Although works on satellite-terrestrial networks have already been published, a detailed investigation to describe the up-to-date findings and current industrial implementation is not currently available in the open technical literature. This article attempts to provide a comprehensive survey of satellite and terrestrial network convergence, which covers developments in integrated and hybrid satellite-terrestrial networks. We outline the motivation and requirement of satellite-terrestrial network structure, the existing researches on the integration of satellite and terrestrial networks are classified and future research directions are also identified. In summary, the contributions of the paper are as follows:

- The motivations and requirements of satellite and terrestrial network integration are identified.

- Innovations in satellite network that may have a profound influence on the convergence of satellite and terrestrial networks are summarized.
- A general architecture of converge satellite-terrestrial networks is provided and related existing architectures leveraging varied technologies are surveyed.
- A taxonomy of researches on satellite-terrestrial networks is summarized.
- A review of performance evaluation and simulation platforms is summarized, meanwhile standardization and existing related projects are surveyed.
- Key application areas for satellite-terrestrial networks are summarized, challenges and open issues for the future exploration of satellite and terrestrial networks convergence are identified.

A list of acronyms used throughout the paper is presented in Table 1. As illustrated in Figure 1, the rest of the paper is organized as follows:

Section II identifies the motivations and requirements of satellite-terrestrial networking convergence.

Section III aims to summarize innovations impacting satellite communication networks in recent years and these technologies help implement the convergence of satellite and terrestrial networks.

Section IV-VI survey the architecture of satellite-terrestrial network convergence, and provide a taxonomy of the researches on satellite-terrestrial networks and classify the performance evaluation works.

Section VII-IX provide standards and key application areas of satellite-terrestrial networks.

Section X discusses the challenges and open issues and Section XI concludes the paper.

II. MOTIVATIONS AND REQUIREMENTS OF THE SATELLITE-TERRESTRIAL NETWORK CONVERGENCE

Since 5G Public Private Partnership (5GPPP) provides a concrete perspective on the emerging technical directions for network architecture, massive requirements of data delivery and mobile broadband have accelerated the service to integrate computing and storage infrastructures into a sophisticated communication network system [16]. The network operates in a complex environment characterized as a heterogeneous one because of the co-existence of various access technologies. More complexity is added to the envision of the next generation networks since devices are developed for various services and interaction modes such as human to human or machine to machine communication. The access of massive devices and users results in that much more spectrum is required to deliver information with higher data rates [17]. More importantly, such circumstance urges 5G communication networks to provide consistent and quality-guaranteed services with the consideration of time and space [18]. The need to increase the performance and capacity while enabling the QoS provisioning still remains a great challenge. Considering the resources available but uncooperatively and

TABLE 1. Summary of abbreviations.

| | |
|--------------|---|
| 3GPP | 3rd generation partnership project |
| 4G | fourth generation |
| 5G | fifth generation |
| 5GPPPP | 5G Infrastructure Public Private Partnership |
| ADSL | asymmetric digital subscriber line |
| AF | amplify and forward |
| AI | artificial intelligence |
| AR | augment reality |
| ASER | average symbol error rate |
| BER | bit error ratio |
| BS | base station |
| BSS | broadcasting satellite service |
| CAPEX | capital expenditures |
| CCI | co-channel interference |
| CCN | content centric network |
| CDN | content delivery network |
| CR | cognitive radio |
| CSI | channel state information |
| CSTN | cognitive satellite-terrestrial networks |
| D2D | device to device |
| DoS | denial of service |
| DVB | digital video broadcasting |
| eMBB | enhance mobile broadband |
| ETSI | European Telecommunication Standards Institute |
| FSS | fixed satellite service |
| GEO | geostationary earth orbit |
| HAP | high altitude platform |
| HD | high definition |
| HTS | high throughput satellite |
| HSTCS | hybrid satellite-terrestrial cooperative system |
| HSTRN | hybrid satellite-terrestrial relay network |
| ICN | information centric network |
| IoT | internet of things |
| ISL | inter-satellite link |
| ISP | Internet service provider |
| LAP | low altitude platform |
| LEO | low earth orbit |
| LTE-A | long term evolution advanced |
| M2M | machine to machine |
| MEO | medium earth orbit |
| MIMO | multiple input multiple output |
| ML | machine learning |
| MMSE | minimum mean squared error |
| MMF | max-min fair |
| mMTC | massive machine type of communication |
| MNO | mobile network operator |
| MSS | mobile satellite service |
| N3IWF | non-3GPP interworking function |
| NB-IoT | narrowband Internet of things |
| NDN | named data networking |
| NFV | network functions virtualization |
| NGMN | next generation mobile networks |
| NTN | non terrestrial network |
| NSP | near space platform |
| NR | new radio |
| ONF | Open Networking Foundation |
| OP | outage probability |
| OPEX | operational expenditures |
| PLS | physical layer security |
| QoE | quality of experience |
| QoS | quality of service |
| RTT | round trip time |
| SAGIN | space-air-ground integrated network |
| Sat-CloudRAN | satellite cloud radio access network |
| SDN | software defined networking |
| SER | symbol error rate |
| SINR | signal to interference plus noise ratio |
| SNO | satellite network operator |
| SNR | signal to noise ratio |
| UAV | unmanned aerial vehicle |
| URLLC | ultra-reliable low latency communications |
| VAST | very small aperture terminal |
| VR | virtual reality |

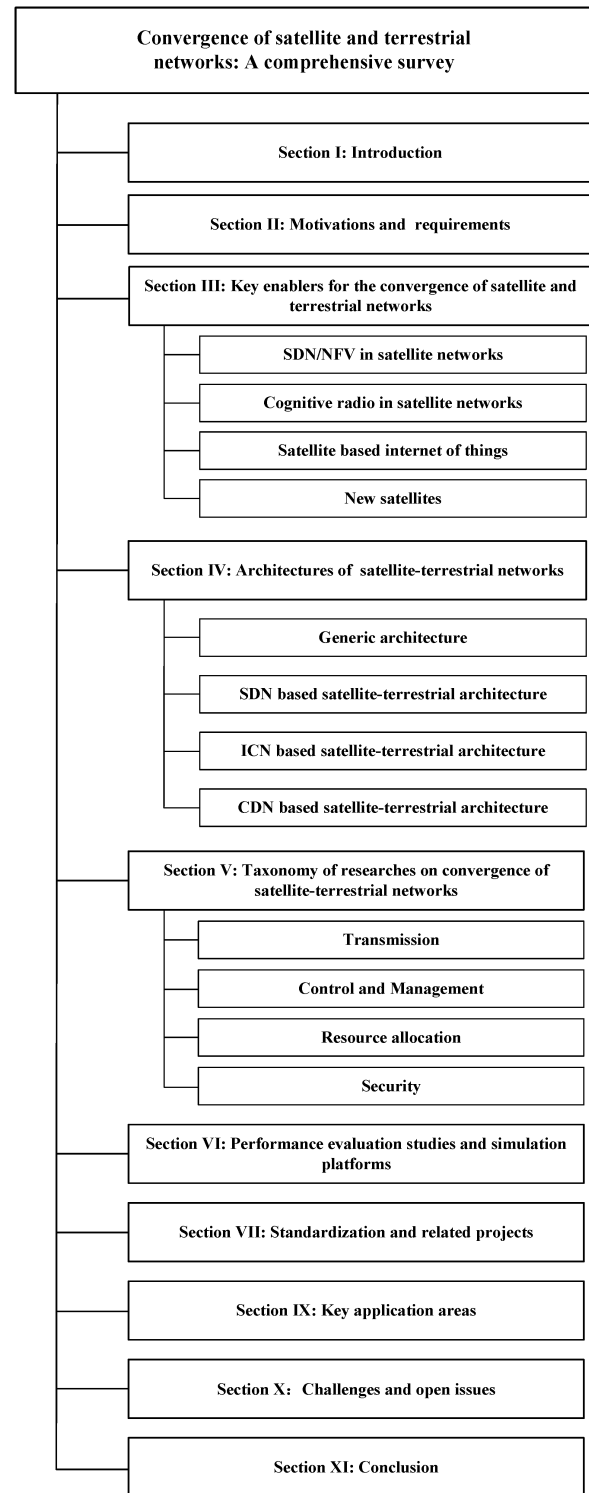


FIGURE 1. Section structure of the paper.

and discuss the motivations and requirements of the satellite-terrestrial network convergence.

A. MOTIVATIONS

Next generation communication networks focus on an architecture with high throughput, low latency, multi-access

independently distributed in satellite networks and terrestrial networks, researchers need to seek appropriate solutions for effective networking integration. In this section, we analyze

ability, flexible and resilient transmission ability, especially when it is asked to handle circumstances with massive fluctuating traffic flow and complex computational tasks [1], [4]. Toward a trend for enabling a completely wireless and connected society, it is essential to propose a novel network of integrating the ground and space communication networks.

The plethora of recent advances in technologies also make it possible to merge the satellite communication systems and terrestrial networks, such as software defined networks, Internet of things, cognitive radio and high throughput satellites. Although D2D communications and ultra-dense small cell on the ground can alleviate the pressure caused by growing number of massive requirements, the limits of the terrestrial systems to meet the 5G envision are apparently [104]. For example, communication systems on the ground with D2D technology need delicate frequency allocation scheme, and in places where users may be blocked by buildings, performance of D2D schemes would be degraded. At the same time, ultra-dense small cell schemes need to deal with complex backhaul management strategies and interference caused by other users and cells [104]. It is time for terrestrial networks to seek help from satellite networks because the converged networks can bring more benefits than drawbacks.

On the one hand, satellites in the converged networks can enhance the service coverage and capacity of communications. First, they provide direct links to the users, with the merits of MIMO, satellites can also provide a high capacity transmission links [14]. Second, for moving platforms, satellite-terrestrial networks aim to provide a reliable transmission with diverse technologies. Satellites can facilitate fast moving platforms with less handover scheme. In particular, the convergence also enlarges the service areas to the air. For instance, satellite can not only broadcast common information to terrestrial vehicles, but also unmanned aerial vehicles (UAV) and airplanes [9]. Without the broadcast ability of satellite, interference will be increasing and need additional allocation. Third, in far remote or rural areas where deploying terrestrial infrastructure is geographically challenging or undeserved, satellites play vital roles for information transmission [7], [11].

On the other hand, the converged satellite-terrestrial networks provide reliable and on-demand wireless communications to target areas. When natural disasters like snow storm, earthquake, or tsunami happen, communication infrastructures on the ground are significantly destroyed. In the circumstance, satellites in the network can be utilized for connectivity. What's more, in some regions where ceremonies or sports games take places, base stations on the ground are usually overload [200]. Satellite in the networks can help assist the terrestrial networks and offload tasks to alleviate the pressure.

In addition, satellite networks offer an efficient way of dealing with delivering content to the edge of communication networks. By broadcasting or multicasting information to the ground, satellites can solve the problems caused by frequent requirements of the same content in terrestrial

networks [134]. This is in contrast to conventional terrestrial networks. Utilizing user-centric information such as content request distribution, satellite can push the content more accurately and effectively to base stations.

From an implementation perspective, some recent key satellite projects have already laid the foundation of the satellite-terrestrial network convergence. Megaconstellation satellite networks composed of LEO satellites, such as SpaceX, OneWeb, LeoSat, Kuiper Amazon and Google systems, have already been proposed to implement the space networks [21]–[23]. As a matter of fact, these very low LEO constellations with only few millisecond-latencies will play vital roles in 5G networks as they are time efficient and flexible to deploy. Also, compared with GEO satellite networks, the signal loss of LEO constellation to the ground would be smaller relatively due to shorter propagation distance, which decreases uncertainty of the link state and helps the terminal on the ground to reach the ideal pattern.

Toward a trend for enabling a completely wireless and connected society, it is essential to propose a novel network of integrating the ground and space communication networks. To implement the convergence of satellite and terrestrial networks, the resource management of satellite networks should be flexible and adaptive to application requirements. From the view of implementation, prevalent standards for integration with terrestrial communication systems restrict the seamless service providing ability [4], [25], [225]. Besides, the problem to date is that satellite and terrestrial networks have been designed separately, a novel management structure which can orchestrate the separated resources should be investigated and developed for the truly integrated information communication system [17].

In summary, the motivations to converge satellite and terrestrial networks are:

- Extending the coverage of service area and providing QoS guaranteed services
- Balancing inefficient communication resource allocation
- Delivering content to the edge of the network

B. REQUIREMENTS

While the convergence of satellite-terrestrial networks aims at providing a network that can support anybody anywhere anytime communications, it is necessary to conquer various challenges. For the purpose that the network can operate effectively as a reliable and ubiquitous wireless service environment, researchers should consider the following requirements:

- 1) A WIDE VARIETY OF SERVICES SUPPORTING ABILITY
Satellite-terrestrial networks in the next generation communication should retain massive applications in satellite networks and terrestrial networks as much as possible. In other words, the new network should integrate communication systems, navigation systems, and remote sensing systems, at the same time, it can provide survivable services, protected services,

narrowband tactical services, assured services and commercial services [24]. It should cater to customized services with varied priorities thus satisfying the requirement of 5G scenarios: massive machine type of communication (mMTC), ultra-reliable low latency communications (URLLC) and enhance mobile broadband (eMBB) [25].

To implement the ability for supporting varied services, three problems should be considered: spectrum sharing, multiple access and resource allocation [11]. First, in the future, new bands of frequency will be utilized to increase the capacity and millimeter wave bands will be applied to satellite-terrestrial networks, under this circumstance, interference from the ground will affect the satellite uplink performance deeply [26]. To protect the primary signal in the system, spectrum sharing is a basic problem laid in the convergence process. Second, satellite-terrestrial networks aim to provide a ubiquitous service to massive users and terminals, new satellites tend to enhance the transmission rate by narrow spotbeams that can be formed to users' directions. While the performance of multiple access is improved by beamforming techniques, sometimes spatial correlation between users or terminals in terrestrial networks and satellite networks make it hard to distinguish [42]. Third, more resources in satellite and terrestrial networks will be available as also more interference will be introduced. The QoS of customized services should be guaranteed in space or on the ground, regarding characteristics of the networks respectively. The fixed resource allocation schemes are not suitable as it wastes resources (like bandwidth, power, space) and more dynamic management ability should be introduced [6], [27].

2) SEAMLESS SERVICE COVERAGE

Here the seamless service ability has double-fold meanings: On one hand, satellite networks and terrestrial networks coexist in the service coverage. This indicates that when traffic flow in the terrestrial networks is over the capacity, satellite networks can provide a supplement to cope with the data transmission demand. More specifically, in this scenario, satellite networks act as a relay node or part of backhaul networks [28], [159]. The satellite links should provide an alternative path rather than a simple connection. With this regard, information flow needs to be distributed properly onto the terrestrial and the satellite network [6], unfortunately, related information offload schemes in this multilink backhaul scenario are still lack of investigations till now. On the other hand, for areas lack terrestrial infrastructures like mountainous or rural regions, satellite networks play main roles in these remote areas as accessing terminals. In fact, satellites in this scenario can reinforce the reliability by providing continuous service of moving platforms and also enable the scalability by multicasting the data to network edges [28]. However, the access of high mobility platforms and handover schemes should gain special attention as LEO satellites move fast in the area causing Doppler shifts or GEO satellite at high altitude resulting in delayed channel state information (CSI). In satellite-terrestrial networks, two

types of handover schemes should be taken into consideration [29]: horizontal handover and vertical handover. Horizontal handover means the handover scheme happens between satellites beams and vertical handover take action when terrestrial networks need to mitigate the task to satellite or vice versa [158], [168], [169]. What's more, it should also be considered that the service time in space is discontinuous, according to [30], although constellations are designed to maximize the coverage area, it is a complicated task to deploy appropriate populated satellite that can guarantee one hundred percent coverage rate, as the settlement of total satellite number is a multi-objective problem.

3) INTEGRATED NETWORK MANAGEMENT

It is expected that in the converged system, a network management scheme should be proposed to improve the efficiency of communication. The heterogeneous communication architecture with complex merits needs a unified management scheme which contains a set of interfaces and protocols compatible with flexible internetworking concept. It is dumb to upgrade the software of the traditional satellite payload since the new technology is time-consuming [31]. The configurations are completed manually, which will be in need of high maintenance costs and bring inflexibility of the network management. Besides, the case that different operators develop their infrastructures while no standards have been developed leads to an environment that is too complicated to manage [32]. One way to solve the problem is to consider an evolving way to converge the independent networks. The core problem to be solved here is an issue as to who controls what—is it the MNOs taking control of the SNOs or the other way around. For instance, in the satellite and terrestrial network for 5G (SaT5G) project a broker that allows them to make decisions are proposed [33]. Another way to solve the problem is to develop a novel architecture with the technologies of software defined network (SDN) and network function virtualization (NFV), SDN release the control plane from the physical infrastructures, thus systems can be programmed with specific functions. The unified interface standards provide a way for the integration. NFV provides improvement in the utilization of physical resources by allowing multiple instances of the same or different VNFs to coexist over a common pool of compute, network and storage resources. As SDN and NFV are crucial, it is a promising approach for management orchestration in satellite-terrestrial networks. The details will be explored in chapter III and chapter IV.

4) RELIABLE SECURITY

The satellite-terrestrial network is such a complex communication environment that it is comprised of space crafts in different orbit planes and terrestrial infrastructures. Telecommunication, remote sensing and navigation transfer information through wireless satellite intra or inter links and satellite-terrestrial channels for accurate information acquirement and effective processing. Satellite communications are

delicate to security violation risks and eavesdropping threats, as the wireless channel of broadcasting is open to anyone who has the corresponding receiver. The inherent transmission agenda results in a delicate security system especially for the circumstances that eavesdrop exists. Besides, for some commercial satellites in the space, there is a need for segregation as they are used by both military and domestic civil living, so it is asked for a rigid resilient and security-guaranteed information interaction network for threats and attacks.

Thus, methods of confidentiality shall be employed to prevent the unauthorized data disclosure. As a complex system supporting tasks, all the interconnected devices have the potentials to suffer the vulnerability. These security threats can be classified as two types [34]: active and passive. Active threats are caused by unauthorized access and software vulnerabilities result from malicious software such as viruses. With no or weak access controls in place, the result might be unauthorized access to systems. It is also possible that users or administrators install unauthorized software, which might contain bugs, viruses, spyware, or which might simply result in system instability. Passive threats are mainly not from a threat source, for example, tapping of the system will lead to the confidential loss, link evaluation or performance analysis need to collect information. In scientific research, threats of security mainly deal with active threats, as satellites operate at a high level and is visible to ground nodes, GEO satellites would have a relatively large downlink beam width resulting in a much more easily intercepted signal. A strong authentication access control scheme and protection of traffic via encryption are necessary.

III. KEY ENABLERS FOR THE CONVERGENCE OF SATELLITE AND TERRESTRIAL NETWORKS

Long-distance transmission and wide service coverage are the most remarkable characteristics that separate satellite networks from other communication systems. Although the idea that satellites would play more important roles has been confirmed at the beginning of the advanced proposals for personal satellite services many years ago, it is very difficult to integrate the independent networks into a seamless one providing customized services [35], [36]. While the terrestrial telecommunication network has embraced the boost of the technology, satellites entitled capabilities that can deeply affect the communication networks are proposed to provide a wide range of services these years. For example, the “other 3 billion” (O3b) constellation deployed in medium earth orbit provide an optimized Internet service [280]. Similarly, others like Intelsat, SES global also support this type of service [2]. The Orbcomm, a leading solution provider for remotely track, monitor, and control fixed and mobile assets, develops an IoT and M2M system comprised of a low earth orbit constellation, which benefits from its small size and minimal transmission delay. The main technologies behind the different applications are very similar in both terrestrial and space systems [37], but as two systems developed separately, the technical gap and differences still remain in the innovation

of satellite networks. For that innovations in the terrestrial network have been extensively surveyed while few articles summaries the counterparts in satellite, in this chapter, we list these key enablers for convergence of satellite and terrestrial networks.

A. SDN/NFV IN SATELLITE NETWORKS

The technologies of SDN and NFV have been widely deployed in terrestrial networks. Providing applications in complicated scenarios, satellite networks are required to implement an effective communication paradigm for customized services. The requirement should be supported by a sophisticated network management strategy in which SDN and NFV concepts are helpful to achieve full network convergence and flexible management [38].

SDN aims at providing a dynamic and programmable network structure to break the lock of physical equipment limitations. The open networking foundation (ONF) [39], an organization dedicated to the promotion and adoption of SDN, defines SDN as a programmable network where the control plane is separated from the data plane. The separation releases the tight interconnection of signaling and data, it simplifies the management that usually full of stringent requirements. For better understanding the principles of SDN, we list the main idea of it [40], [41]: (i) the decouple of control plane from data plane, (ii) the flexible architecture making decisions based on whole network states, and (iii) the logical control and management part abstracted from physical infrastructures. High mobility and limited onboard processing ability of satellite networks make the effective and optimal management a challenging task. The newly emerging studies on SDN/NFV-enabled satellite networks mainly aim at the softwarization and virtualization in the ground segment. It is also worth mentioning that while SDN in terrestrial networks has been studied a lot, as the bottleneck of the cooperative network, satellite networks have already been paid increasing attention to in the process of softwarization.

For satellite communication networks, the architecture is simpler, GEO and other satellite controllers are usually taken as the control plane, MEO and LEO satellites form the data plane, and manage centers located in space or on ground are taken as the management plane. Some researches try to deploy the idea of SDN to transform the satellite networks [27], [31], [42]–[44]. A new software-defined architecture for next-generation satellite networks, called SoftSpace, is presented in [31]. The authors mainly focus on the network management using proposed architecture. With this regard, multi-layer controller, cooperative traffic classification, and network virtualization are involved. Furthermore, they identified challenges of the architecture, which are QoS-aware routing, fault recovery mechanism and mobility management. Unfortunately, a more specific analysis of solutions dealing with challenge should be presented and the implementation should be taken into consideration. Thus reference [42] proposes an SDN scheme aiming at segment control, and authors analyze controlling overhead and showed that SDN scheme

with segment control technique can scale down the overhead. However, it is vital to point out that more works shall be done in efficient cross-layer resources allocation algorithm and distributed control schemes.

Focusing on digital video broadcasting satellite system, authors in [27] visualize satellite terminals and consider the split and placement of virtualized and nonvirtualized functions. In the proposed framework, Satellite Cloud Radio Access Network (Sat-CloudRAN), part of the satellite gateway functionalities can be delivered and the flexible control can be achieved. The main contribution of the paper is that they fill the gap in satellite gateway virtualization and present how to manage the virtualized satellite ground infrastructure using SDN technology, the SDN control of satellite core networks is also investigated. However, the implementation of the transportation network in the satellite network is not involved. Also, a proof-of-concept prototype should be designed to determine the functionalities proposed in this paper.

It is vital to point out that recently LEO satellite networks, which are suitable for the delay-sensitive data, have been explored to adopt the SDN technology. For instance, reliable control links associated from the SDN controller to all the LEO satellites is the basis of the architecture, however unstable wireless channel and Doppler effect would have influence on the links between LEO satellite and terrestrial terminals, Cho *et al.* propose a power-efficient control link algorithm according to the power control analysis [43]. The solution help satellites establish low latency control links with reduced power consumption. The paper shed light on the feasibility of the software-defined LEO satellite network.

Focusing on LEO satellites' rapid mobility and the limited controller process ability on board, Papa *et al.* propose a solution for controller placement problem of SDN-based LEO satellite networks [44]. They develop a dynamic controller placement on the LEO satellites, and find a method considering spatial and temporal user traffic requirements. Though the method is more promising, a further investigation on migration cost and communication overhead is essential.

Some researchers have already considered more practical SDN-based architectures comprised of LEO satellites and terrestrial networks. In [45], authors elaborate on the architecture of an SDN-based LEO satellite and terrestrial networks, they model the data flow and proposed a plastic path with the consideration of latency, capacity, wavelength fragmentation, and load balancing. It shows that LEO networks can help the networks performs better with a slight disadvantage in latency when the service requirements are overload. There exist some paper dealing with transportation problems in this aspect. For instance, in [46], a dynamic routing protocol based on software defined satellite networks have been studied for large LEO systems. Overlapping footprints, fast changing of inter satellite link (ISL) states are identified as challenges in the system. However, routing in the spotbeams is not investigated and the model of ISL should be more accurate.

At the same time, application of SDN based satellite networks have already been investigated. For example, Nazari *et al.* analysis an SDN framework to a fleet of naval ships that relies on constellations for onboard communication [47]. They solve the sharing and load balancing problems in satellite links by leveraging multipath transmission control protocol (MPTCP). Ships are taken as SDN switch management and classification of MPTCP subflows are handled by a remote SDN controller. The frame work enhance the network throughput and reliability.

As described in [48], NFV is a network abstraction technology. Using the NFV technology, network functions that used for dedicated hardware are implemented in the form of software. Therefore, the new software function can enable operations on top of general-purpose hardware. The main benefits of NFV are [49]: (i) creating customized network services with the inherent flexible edibility as network functions can be assembled and allocated according to service requirements, (ii) the central servers in NFV framework liberate capital expenditures (CAPEX) and operational expenditures (OPEX) from additional hardware cost when new services are required, (iii) breaking the physical restrictions and provide a global management foundation for software-based networks. In satellite networks, NFV elaborates resources from physical devices, systems in the air benefit from redefining architecture logic as what it brings terrestrial networks. Usually SDN and NFV technologies introduce flexibility to SNOs, the technologies work together to reduce costs in deploying and managing.

Reference [50] investigates the applicability of the NFV technologies to satellite communications platforms and identify the associated challenges and considerations. In the article, authors outline that core satellite gateway, radio front-end functions, on board functions of the satellite payload and customized functions like firewalling and traffic inspection. Specifically, the authors point out that availability and performance should be taken into account and NFV resilience mechanisms should be exploited such as live VNF migration to failover server units. At the same time, they consider security issues, since visualization are implemented by software, bugs or misconfigurations in satellite gateway may make the system delicate and be attacked by malicious codes. Finally, NFV resource signaling overhead should be optimized since hundreds or thousands of VNFs remotely over the satellite link would cause massive overhead. In particular, [51] mainly concentrate on satellite gateways and show the possibility of responding to customized requirements through the implementation of virtualized satellite network functions. They provide a general procedure for customer request and prove the feasibility by demonstrating satcom services like virtual private network services, hybrid access and WAN optimizations.

In fact, it is clear that SDN and NFV are promising technologies to enhance the satellite networks, more agile and flexible management can be made in an SDN-based satellite

networks and it can facilitate the orchestration across space and ground communication nodes.

B. COGNITIVE RADIO IN SATELLITE NETWORKS

Cognitive radio (CR) is a technology for other users to utilize the same frequency band allocated to incumbent users based on prior knowledge of current spectrum use [52], the limited bandwidth can be utilized efficiently by introducing CR. As terrestrial systems have already been developed for many years, CR based satellite ground terminals need to orchestrate with varied terrestrial networks by sharing the same spectrum, time and spatial resources [53].

In 5G proposals published by International Telecommunication Union (ITU), the requirement of high spectrum and energy efficiency is clarified. Aiming to achieve higher capacity and improving coverage, satellite networks are introduced to form network structures with different scales ranging from ground station cells to wide area coverage. To implement the integrated satellite-terrestrial network and provide a seamless communication system, how to share the radio resources is an urgent problem [225]. In integrated satellite-terrestrial networks, satellite and terrestrial communication infrastructure share the same radio frequency. Without cognitive radio technology, satellite networks and the ground node operating at the same band simultaneously would be interference to each other. Reasonable spectrum allocation for limited bandwidth can provide a better QoS. Moreover, with the channel and radio resource are changing rapidly, cognitive radio helps the entities in satellite networks access in the whole network efficiently [227]. Thus, more attention should be paid on Increasing the bandwidth usage for future-generation satellite networks without interfering with incumbent services.

In the perspective of spectrum sharing, the coexistence of satellite and terrestrial networks can be classified as two typical scenarios [225]–[227]: (i) satellites take the role as the primary user (PU), while communication systems on the ground is the second user (SU) that should utilize the spectrum when the spectrum is temporal available. And (ii) satellite is SU and accessing the channel when PU, i.e. the ground network, is detected as not in transmission state.

Reference [54] gives three possible scenarios for satellite networks operating at the Ka band: (i) the cognitive wireless channel is from the GEO satellite to the fixed satellite service (FSS) terminal, and the incumbent user is from the broadcasting satellite service (BSS) feeder link to another GEO satellite which is utilized for broadcasting. (ii) a cognitive FSS downlink scheme operates in the 17.7–19.7 GHz band. In the scenario, the incumbent users are fixed service (FS) links which serve communication between FS terminals. (iii) The cognitive wireless channel is from the FSS Earth terminal to the GEO satellite, and the FSS terminal provides cognitive uplink communication with the band 27.5–29.5 GHz where FS links are the incumbent users.

However, there exist several issues in the co-existence of the systems. One of the problems is that satellite systems

usually have long-distance propagation links, leading a delay which is not compatible with terrestrial networks. Moreover, the long propagation paths usually make the signals weak at the receiving stations on the ground. A method for the related receiver to get the signal successfully, which usually rely on the adequate signal-to-interference-plus-noise ratio (SINR), is critical [262]–[264].

Another problem is related to the beam coverage of a satellite, the service area of a single beam is usually larger than a terrestrial cell [55], [56]. Massive cellular base stations operating in the shared spectrum band may raise interference that cannot be ignored. In the case of uplink band of satellite networks, the interference would be rather high that the satellite networks could hardly distinguish the wanted signal from the coverage area, thus uplink channel to the target satellite will be less interfered as high elevation will help the main beam from the ground physically point to the target satellite while low elevation will make the information affected by signals on the ground [55]. This circumstance is also similar in the case of the downlink band of satellite systems [56]. Besides, usually the channels in wireless terrestrial networks confront multipath propagation with frequency-selective fading. At the same time, channels in satellite systems are characterized by line-of-sight (LoS) transmission with occasional heavy shadowing.

To solve these problems, more optimized spectrum awareness techniques and spectrum database technologies are used in cognitive satellite communication networks [10], [57], [58]. In the context of cognitive satellite networks, resource allocation problems are concerned most [59]. It is worth to mention that recently some learning technologies like reinforcement learning are also used in cognitive satellite communication for better resource allocation [60].

C. SATELLITE BASED INTERNET OF THINGS

The 5G whitepaper clearly states the scenarios of eMTC, the advent of IoT and M2M in civil application enhance the performance of the intelligent electronic devices [1]. For example, Long-Range (LoRa) WAN [61] and Narrow-Band IoT (NB-IoT) [62] are developed to surveillance disaster area emergency and wearable devices monitoring health conditions.

Ensuring worldwide connectivity which is essential for sensors scattered in remote areas, satellite IoT communication networks can provide a breakthrough in geographical restriction because of the easy deployment merit and large coverage advantages [62]–[65]. Although the altitude nature of satellite can mitigate drawbacks of shadowing and blockage effects, satellite internet of things faces some challenges at the same time. IoT services are usually characterized as heterogenous. Different from terrestrial IoT networks, IoT or M2M nodes in satellite networks should pay more attention to reliability, uplink transmission rate, and guaranteed latency. For instance, satellites like LEO moves fast in space, antennas' mobility and atmosphere condition would affect the reliability of channel a lot. Besides, the ability provided

by large service can also bring problems, the information generated in large areas by massive IoT or M2M nodes ask the satellite provide a high uplink rate. Moreover, some nodes are deployed to respond for emergency and a real-time information allocation is necessary for saving lives. Thus, a guaranteed latency scheme is essential for satellite IoT systems.

Two fundamental problems in satellite based IoT make the innovation possible: ubiquitous access and effective backhaul. For ubiquitous access, two typical deployment schemes of the satellite IoT networks are identified [66]: direct access deployment scheme and indirect access deployment scheme. For some sensors with large power transmitters, the direct access deployment allows them to send information directly, while indirect access usually needs aggregation nodes to collect data from massive sensors and process the redundant information. Recently indirect access deployment gains more attention as it reduces the implementation cost with lesser satellite terminals compared with direct access deployment require every sensor to equip with a satellite terminal. There exist frameworks to analyze the performance of random access-based satellite channels under the application of IoT communication flow [67], which focuses on the interaction between the random-access scheme and the constrained application protocol (CoAP) to avoid congestion.

Using as backhaul, the system in [68] is presented for IoT sensors and controllers for commercial aircraft, satellite IoT networks are also utilized in power grid to monitor the power consumption and help allocate the power effectively [69]. Besides, some works shed light on the related design implications of improving satellite-based IoT is the spectrum efficiency by using constellation coding [70].

D. NEW SATELLITES

New satellites raise a revolution in space networks recently, and it is necessary to keep an eye on this area as it will change traditional satellite networks deeply. Here we mainly review two kinds of satellites: high throughput satellite (HTS) and nanosatellites.

High throughput satellites drastically increase capacity through frequency reuse and spatial separation. The satellites are suitable for next generation broadband satellites employing spot beams. Leveraging the improved modulation techniques and spotbeams of Ka-band as the frequency range 27-40GHz and Ku-band as the frequency range 12-18GHz frequency [71], [72], bandwidth efficiency of HTS can achieve an improvement evidently. It is critical to mention that the bandwidth efficiency of the multi-beam user link can be substantially increased by using quasi-orthogonal polarizations. The implementation can be done simultaneously within each beam, or alternatively in beams around [73]. To gain the optimal capacity of the network, the flexible multispot antenna configuration ability is deployed in the service area.

Usually multi-beam HTS system needs to employ a very high reuse efficiency over the coverage area [74].

The application of the multibeam concept with narrow beams and exploiting the frequency reuse principle result in a great leap in satellite systems' capacity. For example, typical HTSs like Eutelsats KaSat, Viasat 1 and SES-12, can get a stable network performance with the capacity up to 100Gbps [75]. The capacity of Viasat 2 now is 300Gbps [76] and Viasat 3 will be 1Tbps [77], and Eutelsat Konnect VHVS's capacity is up to 500Gbps [78]. Besides, combined with LEO satellites that operate at the altitude of 800-1000km, transmission latency can be reduced for quick response [79].

Recently HTS gain great attention on frequency resource allocation. Inadequate frequency management scheme may result in a malignant effect on systems, for example, it may lead to low throughput, current task failures, and requirements rejections [80]. Therefore, the next generation of HTSs need frequency flexibility according to different circumstances in communication [79], [81], digital channelizer is the typical solution to alleviate the challenge [82]–[84]. To cope with other problems like link outage caused by weather conditions, references [85], [86] propose schemes using diversity to keep the high capacity in satellite systems.

Another kind of new satellites in application is the nanosatellite because it is smaller and much more flexible. Nanosatellites usually weigh from 1 to 10kg and vary in dimensions [87], and they are a cost-effective solution for rural areas where don't have suitable information and communication technology (ICT) ground infrastructures [88]. With the characteristic of small volume and simple structure, nanosatellites usually have very limited energy supply on board. Thus they are in general used for small and dedicated missions rather than the larger constellations. For example, the nanosatellite CubeSat [89], which requires 0.1% of the cost of a classical LEO satellite, is utilized for Earth observation tasks. As we investigate in the literatures, there is a trend to operate more researches on nanosatellite networks. However, just as referred in [90], nanosatellites will not replace large satellites or small satellites, as their goals and issues are often different. In the next communication episode, it is believed that they will function together for a more efficient network.

IV. ARCHITECTURES OF SATELLITE-TERRESTRIAL NETWORKS

To get a general view of converged satellite-terrestrial networks, we begin this section by a generic architecture, and then we walk through some architectures which are suitable for innovations applied in satellite-terrestrial networks, these architectures offer benefits but also have limitations. When considering different challenges, it is necessary to prefer different architectures according to its characteristics.

A. GENERIC ARCHITECTURE

At present, the architectures of satellite-terrestrial networks are proposed with different peculiarities, but there exist common merits in these architectures. Integrated satellite-terrestrial communication systems are aiming at providing

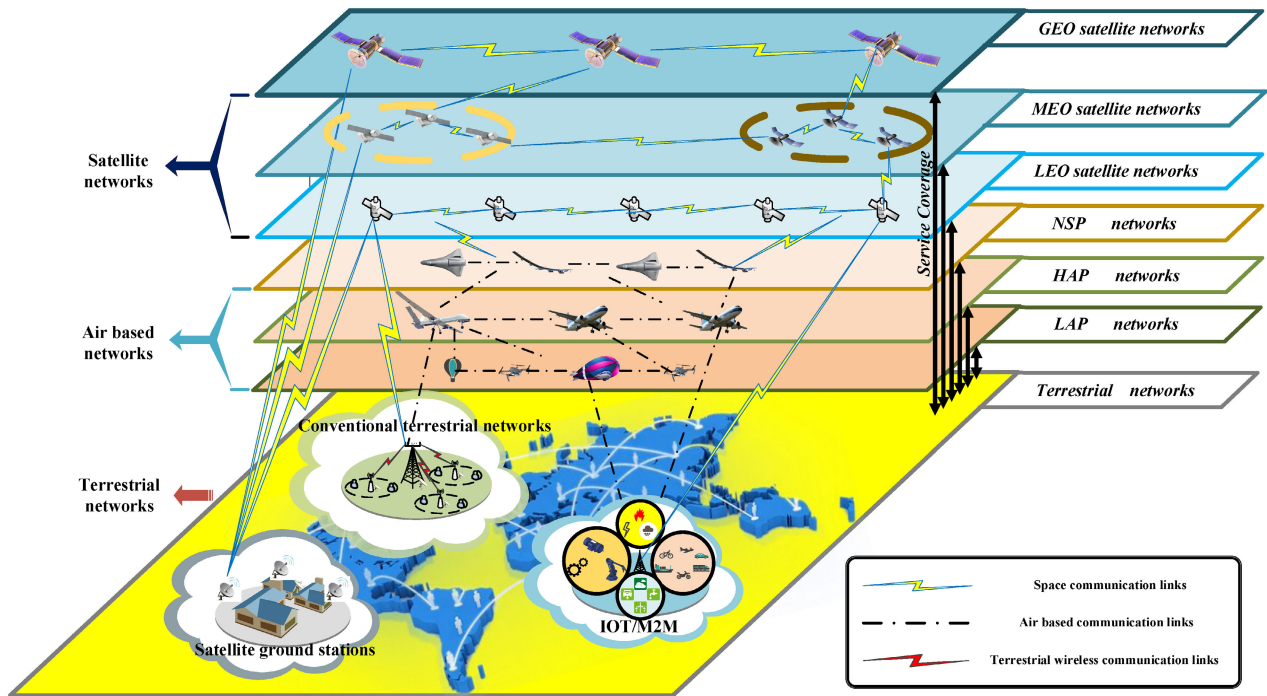


FIGURE 2. Generic architecture of satellite-terrestrial networks.

cooperation of heterogeneity networks. Resources orchestration is one of the main drives behind the implementation approach of converged satellite-terrestrial networks. Typically, exploiting resources distributed in space dimension achieve better performance because more infrastructures provide the potential of improved function ability. At the same time, to avoid redundancy resources in the communication procedure, integrated network components should be selected cooperatively as they have different constraints.

Figure 2 illustrates the generic architecture a complete integrated of satellite-terrestrial networks. We identify that the structure of the architecture can be divided into different layers: space networks, air-based networks and terrestrial networks.

1) SPACE NETWORKS

Multi-layer space networks are usually comprised of three categories, namely GEO, MEO, and LEO satellites, according to their orbital altitudes. GEO satellites operate at 36 000km orbits, MEO satellites function at the orbits from 10 000 to 20 000km, and LEO satellites work at the orbits between 500 and 1500km [91]. The cooperative communication of satellite network is based on wireless links in terms of microwave or laser.

Different satellite constellation needs to take different number of factors into consideration, such as: type of service, maximum transmission delay, minimum elevation angle, service quality and availability specifications [91]. GEO satellites provide large services area and thus can reduce handover times as minimum as possible. Unfortunately, the long propagation latency is not suitable for latency-sensitive services.

Compared with GEO satellites, LEO satellites are characterized as less free space attenuation and propagation delay. However, low altitude leads to a smaller coverage, to get a global service coverage, a greater number of satellites would be needed. Usually large constellations need a more complex frequency reuse. Besides, the higher speed of LEO satellites introduces larger Doppler effects, this also leads to frequent handover can cause transmission loss and signaling overhead. MEO satellites take a compromise with GEO and LEO satellite, and a typical use of it is to provide trunk transmission and backhaul services [92].

In all, the topology of the space-based network is dynamic. As the satellites in the system move, links between different satellite connected and intermitted frequently. Fortunately, the orbit trajectories are deterministic and the related topology is predictable. The communication resource of space-based network is constrained. Due to the volume and the number of satellite nodes, the power, cache and processing ability are constrained. Most satellites payload is custom designed and is utilized for unique mission.

2) AIR-BASED NETWORKS

Air-based networks use airship and high air flight vehicles as communication nodes, sometimes stratosphere balloon and plane are also utilized in this layer [93]. From the articles we surveyed, air-based networks can be divided into three categories: near-space platform (NSP) networks, high-altitude platform (HAP) networks, and low-altitude platform (LAP) networks.

Near-space platform Networks: NSPs operate at an altitude between 20-100km [94]. The platform is similar to an

artificial satellite while its cost is less expensive for implementation. They are more flexible when dealing with simple communication tasks and closer to the ground. That means weaker signals can be detected as the distance is much closer to the receivers [95].

High-altitude platform Networks: High-altitude platforms (HAPs) operate at an altitude between 17-22km [96]. Like near-space platforms, they are utilized as agile platforms to extend broadband wireless connectivity with strong signals and reduced implementation cost [94], [97]–[99].

Low-altitude platform Networks: Low-altitude platforms (LAPs) function at the altitude range from 200m to 11km [100], [101]. It can be balloons or even UAVs with communication payloads. It usually deploys for emergency scenarios in support of public protection [7], [102] and relief the pressure of massive data requirement in scenario of eMBB [103].

Usually, platforms in air-based networks play two roles in communication networks, one is base station and the other is user equipment [104]. Base stations mounted on these platforms can enhance the coverage and reliability of the cellular networks. As it is not economical to deploy extra communication entities on the ground for temporary use like festival parades or national sport games, air-based platforms are suitable to provide access. Unlike satellites, platforms in air-based networks can adjust the altitude for LoS transmission, it is a more flexible and cost-effective method for the burst service requirements.

For some platforms, they are used for delivery and monitoring the traffic, which is called cellular-connected drones as user equipment's. These type platforms usually need reliable connectivity to the cellular and high uplink speed. For instance, delivery platforms need a connection that is not intermittent until the mission is complete. A guaranteed connectivity should be ensured for that the delivery can be sent into the target area. Compared with LEO, platforms in this layer is nearer to the ground thus less transmission delay will be achieved [101]. When the platform is used for surveillance, the high definition image for emergency aid or information from massive sensors on the ground need adequate rate for the real-time processing and thus get a quick response to different requirements.

Though air-based platforms provide advantages and is a promising part of the converged satellite-terrestrial networks, some challenges also should be considered. For example, UAV is a kind of typical air-based platform and the energy of them is a limitation for long time period communication. The weights of these platforms range from 100g to 150kg, and the relative battery time ranges from 6min-1800min [104]. Obviously, the performance of this communication layer is significantly affected by energy consumptions. The 3D position and the optimal trajectory also bring problems to be solved. the 3D position made the channel model complex and it determine the performance of UAV-based wireless communications in terms of coverage and capacity [105]. Restricted to the limited energy, trajectory should be aware

of the obstacles and make a reliable path to maximum the efficiency of each flight.

3) TERRESTRIAL NETWORKS

Terrestrial networks locate at the bottom of the satellite-terrestrial network, it bears massive service requirements from multi-devices and multi-domains as the nature of hybrid and heterogeneous network structure, terrestrial networks in the architecture are the most complicated and critical part. Cooperating with satellite networks, networks on the ground are usually composed of mobile or wire communication networks, conventional satellite ground stations equipped with very small aperture terminals (VSATs). Formed as self organized networks, sensors or IoT nodes are usually deployed in the rural or far remote areas enable the function as a monitor of the critical area for an emergency.

Taken as backhaul networks, nowadays satellite networks provide IP-based services to users by using gateways with very small aperture terminals (VSATs). However, except these satellite terminals on the ground, the various satellite and terrestrial transports have traditionally employed distinct and incompatible designs for multi-layer communication functions [106]. Terrestrial networks are experiencing revolutionary changes these years. Innovations make spectacular advances in improving the performance and user experience [107]: For example, in the scenario of enhanced mobile broadband, advances in MIMO and new waveform make the high data rate and spectral efficiency possible. Software Defined Networking (SDN), Network Function Virtualization (NFV), Network Slicing, and Cloud RAN make terrestrial networks more flexible and MEC push the computing resource to the edge thus both reliability and latency can make adoption to the requirement of URLLC. New structure for NR has already proposed for mMTC from subcarrier spacing, cyclic prefix and transmission time interval length to deal with a family of applications [108].

Specifically, millions of IoT nodes connected to the network ask the network operator to consider factors in terms of data traffic volume, peak rates and latency [109]. Compared with other services like video conference, the transmission rate is relatively low and the scalability is more important in the IoT networks. Massive nodes in IoT networks need to get access in the network to transmit the information, it is essential to suppress the signaling for spectrum efficiency. When the nodes need to transmit the information to terrestrial networks or space networks, the nodes should wake up and complete the packet transmission task as fast as possible, after that the nodes should be set to sleep mode and make the spectrum available for other nodes. Usually mMTC terminals can be classified into three categories with specific user needs: alarm devices, telemetry and tracking devices, and traffic aggregators [109]. Each category has its own characteristics, for instance, the alarm devices need low latency and high reliability for emergency, while Telemetry and tracking devices need Scheduled transmissions, they are usually utilized in Environmental monitoring. And traffic

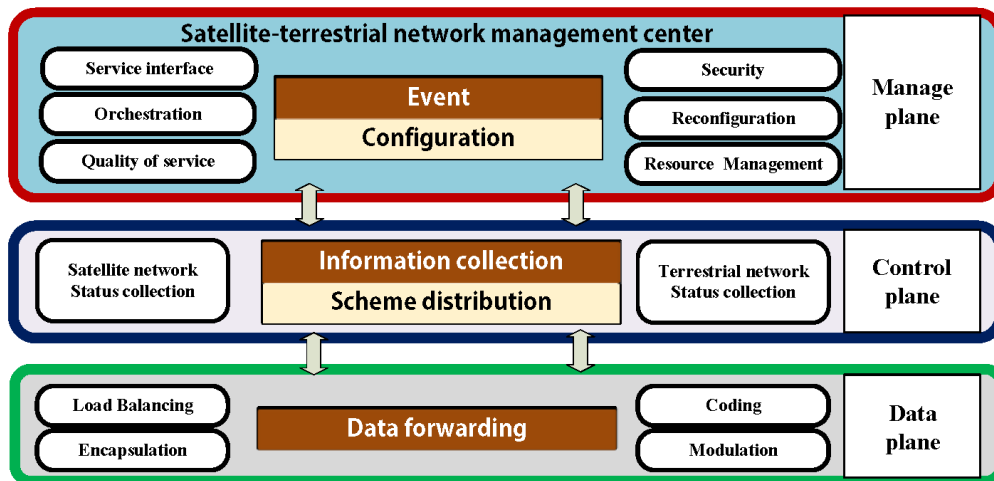


FIGURE 3. Functional architecture of SDN based satellite-terrestrial networks.

aggregator are developed for aggregating traffic from low-end sensors, as they are used for traffic, they have relatively high aggregated data rates.

In general, satellite-terrestrial networks make full use of communication resources distributed in satellite networks, terrestrial networks and space platforms. The architecture provides a converged 5G system and it is changing the communication ecosystem and transmission scheme for the function of (i) ubiquitous access, (ii) global connectivity, (iii) massive traffic pressure relief, (iv) intelligent content caching and delivery, and (v) reliable and quick emergency response.

B. SDN BASED SATELLITE-TERRESTRIAL ARCHITECTURE

Conventional communication networks suffer from cumbersome operating discipline and physical restricted resources [110], [111]. For instance, infrastructures are tightly related to its service function and the cycle for updating of the whole network is usually too long. In the convergence of satellite and terrestrial networks, designing an efficient and flexible architecture is more challenging. To integrate satellite and terrestrial networks, one problem that network operators must be confronted is how to achieve flexibility and orchestrate the resources of the heterogeneous network. In fact, infrastructures of different networks lack of standards and it is very hard to manage when they operate together.

Compared with terrestrial networks, satellite-terrestrial networks need to deal with connectivity block brought by high mobility of users or satellites [168], [177]. The intermittent connection is rather harmful to some delay-sensitive services. Moreover, in the system, the huge amount of entities is unquestionably bringing pressure on efficient resource allocation ability. Also, as many network innovations will be introduced into the satellite-terrestrial networks, it is vital to upgrade communication nodes in the system. Currently most hardware in the networks is designed for customized services and it is time-consuming and costly to upgrade the

infrastructure with new technologies. Besides, satellite networks usually have specific settings due to its operation environment. A transparent manner like routing, QoS, security, management and connectivity are essential for the applicability with terrestrial networks.

SDN/NFV is taken as a key enabler towards more flexible and agile integration of satellite and terrestrial networks [32]. As a general SDN architecture adopted system, SDN-based satellite-terrestrial networks separate the data plane and control plane. Based on the information collected from the networks, controllers of the satellite-terrestrial network can decide efficiently the path to transmit the flow and guarantee the QoS. While nodes on the data plane merely abide by the rules from controllers, which can emit flexibility by the programmable devices. The network is built on the top of standard open interfaces like Openflow [112], which provide a convenient approach for configuration and interoperation between different entities on planes. As shown in Figure 3, the functional architecture of SDN based satellite-terrestrial network is composed of data plane, control plane and manage plane.

Data plane is comprised of switches distributed in satellite and terrestrial networks, the switches are responsible for packet transmission according to the flow table. Related communication infrastructures are connected by wireless radios or cables. Physical entities on the data plane bear the function of data forwarding [45], [51]. To be specific, load balancing is implemented by the physical infrastructures on the plane. Carriers, gateways and access technologies are applied for load sharing [35]. In MAC layer, encapsulations, coding, modulation and multiplexing are also presented in this plane.

Control and management plane are consisted of controllers and managers. Controllers are located in satellite earth stations and terrestrial communication systems and collect the network status. Controls for routing, handover, network operating system and network status collections can be done in control plane [45], [51]. Control plane charges for information collection and distribute the scheme made by

manage plane. And it can also deal with physical parameters. For operators, to make the satellite-terrestrial network orchestration, synchronization both in time and frequency domain needs to be guaranteed. For user terminals, it is necessary to gather information of resources for access and capacity to login. Besides, admission control should also be embedded in the plane, authentication can avoid some illegal user accessing the network.

Taking care of the whole visualized satellite-terrestrial system, manage plane is charge for network management functions. Managers provide service interface and here typical applications can be radio resource management which allocate the bandwidth of satellite links or terrestrial links dynamically and adaptive coding modulation according to different link quality [31], [155]. In the plane, network composition can be implemented by multi-domain federated orchestration, this orchestration manager partitions the end to end services in to each domain and guarantee the QoS of service quality. Different security strategy can be managed according to different service requirements [31], [105], [155]. Also, required resources can be calculated and configured according to monitored satellite and terrestrial network status.

In the articles we surveyed, satellite networks can be utilized as forwarding nodes in data plane or controllers in control plane. For instance, in [155], satellite infrastructures (like GEO, MEO and LEO satellites) and terminal routers are formed data plane. GEO satellites, with the reliable link state, are formed as group to cover the data plane and transmit rules from manage plane to data plane. In [31], satellites are organized in the constellation and support routing, access control, and spotbeam management. The authors identify that each satellite should have: (i) SDR, which enable programmable MAC and physical-layer functions to support radio reconfiguration and remote upgrade. (ii) A flow table guide the satellite to transmit the packet. The flow table can be modified by the controller through southbound interface. (iii) Wireless hypervisor can create virtual satellite according to system requirement. And (iv) several satellite front ends which support different communication satellite links. Moreover, some LEOs in the architecture is utilized for data forwarding and network statement collecting, GEOs are taken as controllers of the space networks. As the limited number of GEOs, polar area cannot be covered and frequency interaction would increase the workload. Other LEOs can be employed as slave controllers to solve the problem that caused by limited GEO satellites. Similar to systems proposed in [31], authors in [105] place controllers on GEO satellites considering the global view of the whole network, compare with frameworks mentioned above, the data plane comprised of two parts, one is the entities in space networks, including MEO satellites and LEO satellites, the other is the entities in terrestrial networks. For the reason that resources on the satellite are usually limited, management plane often located on the ground. Satellite networks in SDN-based networks play roles as data plane and partial control plane, it requires more breakthrough in

on-board processing aspect to operate management ability and enhance various kinds of new services.

SDN based satellite-terrestrial networks also face a lot of challenges. In the architecture, the location of controller and satellite gateways poses significant challenges to provide the robust transmission performance due to the innate characteristics of satellite channel and terrestrial nodes failures [113], [114]. The joint placement deployment can be formulated to a multi-objective optimization problem with regard to reliability, latency and QoS guaranteed traffic flow [115]. Other challenges stick to the problem that how to adjust management to in a complex and rapidly changeable mobile communication environment: (i) QoS guaranteed service communication networks. Traffic engineering and fine-grained QoS are guaranteed as entities in the network can be redefined according to services requirements. Multi-domain orchestrators cooperation with network resources to guarantee reliable end-to-end service quality [116], [117]. (ii) Robust and efficient data delivery networks. Flexible reconfiguration of physical resources supports efficient and robust data delivery [118]–[121]. In this aspect, the robust multipath transfer scheme with load awareness can be achieved by cooperation [118]. Authors in [119] evaluate the performance when the system serves a new data delivery requirement, particularly it investigates the latency for the service response including the time consuming of transferring corresponding control actions. The reconfigurable ability of satellite antenna enables the adjustable beamforming coverage and make optimized resource allocation possible [120], the interruptions of transmission during handover can also be prevented thanks to the programmable beam tracking capability [121].

C. ICN BASED SATELLITE-TERRESTRIAL ARCHITECTURE

Information-centric network (ICN) architectures decouple the content and the service storage location by location independent naming [122], [123]. While the addressing space faced the problem that IPV4 address is becoming exhausted, in the future IPV6 may face the same challenges. Compared with traditional TCP/IP network architecture, ICN models are based on naming the content to alleviate the address-space scarcity. The architecture promotes a publish/subscribe information model and complete the transmission process after the content negotiation.

Many ICN architectures are proposed in the past ten years. Among them, content centric networks (CCNs) or name-defined networks (NDNs) is the prevailing approach among other ICN-based proposed architectures [124]. Figure 4 shows a typical architecture of ICN based satellite-terrestrial networks.

In the architecture, satellite provide content broadcast ability and terrestrial ICN provide multi-resource multi-path transferring ability. End hosts publish their interest, which is subscription, in receiving information object to the network but also inform to provide their information objects, which is publication. Name server charges for naming resolution

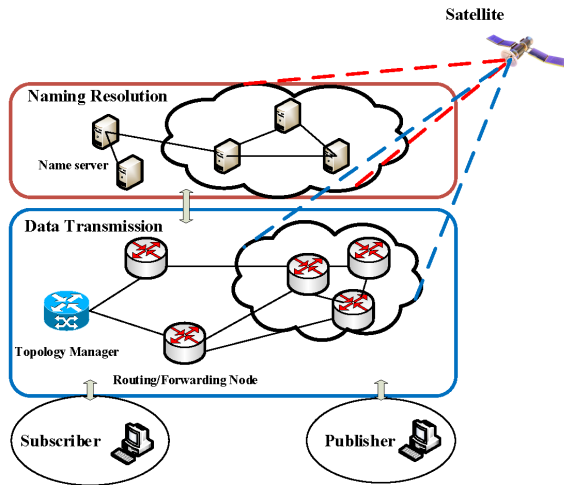


FIGURE 4. Architecture of ICN based satellite-terrestrial networks.

and topology manager help find the optimal path for data forwarding. The networks match interests to publishers and subscription to information objects.

When subscribers access the terrestrial network, terrestrial ICN is in utilization. When the subscriber connected to the satellite terminal, broadcast ability of satellite is utilized. Also, in the ICN based satellite-terrestrial architecture, selection of multiple communication path based on user preference and types of content can be performed for a load balancing [129]. Different caching updating rules can be implemented in satellite-terrestrial network nodes, or even in subscribers, the characteristics avoid the frequency transmission of the same content and improve the content delivery efficiency.

In the ICN based satellite-terrestrial networks, satellite can broadcast the caches simultaneously and reduce the additional time and transmission cost. The links and caching ability in the space and on the ground enhance robustness to transmission failures. At the same time, the application of satellite can bring seamless service ability in horizontal and vertical handovers. As a receiver-driven networks, the connectionless information request can help avoid complex inter satellite routing protocols and handovers. Last but not the least, in ICN networks, content cached in any nodes of the network, this means that the congestion control can be operated hop by hop, the characteristics address the long propagation delays of satellite links and provide a unified frame work for delay tolerate networking [126].

The researches of ICN based satellite-terrestrial architecture mainly focus on: mobility support [125], in-network caching [126]–[128], context-aware traffic management [129], congestion control [130] and security problems [131].

D. CDN BASED SATELLITE-TERRESTRIAL ARCHITECTURE

It is considered that content delivery networks (CDNs) are pivotal technical foundation for broadband services like video flow distribution on the Internet. A CDN is a collaborative set of network elements distributed over the Internet, with

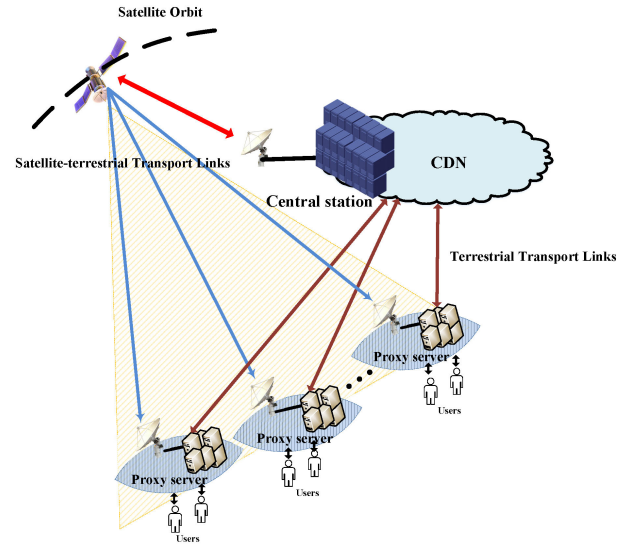


FIGURE 5. Architecture of CDN based satellite-terrestrial networks.

the aim to support content replication across several mirrored servers/caches [135].

A typical architecture of CDN based satellite-terrestrial networks is shown in Figure 5. In the architecture, a set of satellite terminals with proxy server is located on the ground, these proxies periodically send to the central station about the requests they collected from their local clients. The central station usually plays the role as an manage part computing the result of the desired content in the near future. Satellite receive the content and “push” them by broadcasting or multicasting.

Aiming at providing resources close to users, CDN servers locate in multiple ISPs for responding requirements as soon as possible. With the ever-increasing amount of broadband service requirements, CDN has to face several challenges [132], [133]. Among the challenge, what to cache and how to distribute the content efficiently are the key problems in CDN based satellite-terrestrial networks.

As many requests would point for the same popular content, satellites provide a way for efficient transmission by exploiting both multicast and large coverage features [134], [135]. Together with the satellite’s ability of multicasting, the CDN based architecture can take full advantage of caching and edge distribution networks using streaming technologies like MPEG-DASH which improve the performance and provide a satellite assisted terrestrial CDN network [136]. Most satellite-terrestrial networks focus on content delivery to the edge can be categorized as: (i) a delivery system using multicast over the satellite and converting to unicast after caching for final delivery and (ii) a delivery system using multi-linking with satellite and terrestrial components direct to the user.

The most important problem which draw the attention in academia is the intelligent routing problem due to the multi alternative paths in the interworking of space and ground [137]. The efficient routing decision can improve throughput

TABLE 2. Taxonomy of researches on satellite-terrestrial network convergence.

| Taxonomy of researches | | | Related works |
|--------------------------|--------------------------------|------------------------------------|-----------------------|
| Transmission | Content delivery | Satellite media content | [140]-[142] |
| | | Context-aware content | [143] |
| | | Service prioritization | [144][145] |
| | | Layered content delivery | [146] |
| | | Multi-group multicast delivery | [147] |
| | Traffic load balance | Backhaul networks | flexible backhaul |
| Optimized route protocol | | centralized scheme | [48][154][155][157] |
| | | Decentralized scheme | [158][159][162] |
| | | Schemes from global and local view | [161] |
| | | Qos-aware scheduling | [156] |
| Control and management | Access control | NOMA and beamforming | [164] |
| | | CoAP Protocol | [79][165] |
| | Mobility management | Mapping mechanism | [164][167] |
| | | SIP-based scheme | [168][170] |
| | | Spotbeam handover scheme | [177][178] |
| | | ISL handover scheme | [172] |
| Resource allocation | Packet scheduling schemes | | [180]-[183] |
| | Bandwidth allocation schemes | | [143][184][186]-[188] |
| Security | Datalink layer security method | | [189] |
| | Physical layer security method | | [186][190]-[198] |

and QoE. The merit of CDN can help the designer maximize the users’ QoE because the requested content size is known in the CDN based satellite-terrestrial network architecture.

V. TAXONOMY OF RESEARCHES ON CONVERGENCE OF SATELLITE-TERRESTRIAL NETWORKS

Satellite-terrestrial networks leverage various technologies to concrete the methodology of heterogeneous networks as seamless service coverage, robust service supporting ability and high-efficiency performance. As a long-term procedure for communication revolution, several main problems should be elaboratively considered:

- Uncertainty of the traffic flow and transmission demand of diverse services [143], [148], [154], [157], [161].
- Isolation access control and handover management in satellite and terrestrial networks [164], [166], [169]
- Mismatch between various service requirements and limited network resources [11], [180]–[183]
- Weak guarantee for information protection in the open electromagnetic environment [186], [189], [191]–[198]

In this section, we survey the existing researches on integrated satellite-terrestrial networks, for the classification of these papers, a taxonomy centered on challenges is proposed in Table 2. The surveyed research works are categorized into the following parts:

A. TRANSMISSION

When satellites and terrestrial networks get converged, users and devices distributed in the network would bring in the uncertainty of traffic flow and transmission demand of diversified services, which makes it hard for efficient transmission, thus transmission of the appropriate information efficiently will be a critical topic for researchers.

Indeed, some researches have already considered technical specifications to solve the problem. For instance,

the propagation delay and channel model have been identified for data transmission in satellite networks [138]. Moreover, some LTE communication technical protocols have already considered Doppler frequency shifts that would influence PHY/MAC procedures deeply [139]. But here we mainly focus on how to transmit data efficiently from a systemic view. Among the works we surveyed, it can be found that two aspects are investigated most:

1) CONTENT DELIVERY

Content delivery schemes mainly deal with what kind of information should be delivered and how to distribute the required content. Satellites that carry media content around the world have already enhanced the development of broadband services [140]. The mechanisms, i.e. unicast, broadcast and multicast, aim at transmitting content depending on the number of pieces of UEs receiving the same multimedia content from the same source simultaneously [141].

In the content delivery aspect, the trend of using satellite coupled with terrestrial networks will be influenced deeply in cooperative schemes, which should thoroughly take pros and cons of communication networks into consideration and reduce the abundant cost while guaranteeing the QoS within restrictions.

A system-level study of content delivery schemes in satellite networks to relieve the traffic on the ground is proposed in [142]. Appropriate scheduling entitles the satellite-terrestrial cognitive networks with the ability to handle dynamic context-aware demands, reference [143] proposes a cooperative scheme by guarantee different bandwidth requirements of services. Packet scheduling schemes with service prioritization algorithm for multimedia delivery is proposed in [144], [145]. In [144], the proposed scheme is related to queuing state, link variations, and current QoS satisfactions. And scheme in [145] is adaptive to applications’

QoS attributes like the priority and fairness among traffic flows and the physical layer data rate information.

Besides, a novel model for layered content delivery over satellite integrated cognitive radio network is provided in [146]. Unlike traditional cognitive networks, a cooperative multigroup multicast content delivery scheme is introduced in [147], it leverages beamforming and improves the satellite-terrestrial network performance by solving a weighted max-min fair problem. This method sheds light on how to improve network efficiency when multiuser exists and how to serve their various requirements with limited communication resources.

2) TRAFFIC LOAD BALANCE

As previously mentioned, an unprecedented boost of multimedia and varied services proliferate the increase of information in volume. Therefore, developing an interworking technique, such as load balancing, is necessary to achieve increased overall resource utilization in the various heterogeneous networks, particularly in hot-spot areas [148].

The procedure of satellite-terrestrial network integration also faces the challenges of traffic load balancing. On one hand, traffic in the terrestrial network usually distributed unevenly, it needs satellite to alleviate the local pressure. On the other hand, communication resources are still limited in space networks, the dynamic mobility and unstable connectivity make the system dedicate to traffic congestion. Hence, in order to fully exploit resources in satellite-terrestrial networks, researchers need to focus on how to balance the traffic in the networks.

a: BACKHAUL NETWORKS

Traffic load balancing is achieved by designing a flexible backhaul network for broadband connectivity with low cost and dynamic implementations in satellite-terrestrial networks [149], [150].

The design of backhaul networks should adhere to three key principles [151]: (i) together with conventional terrestrial backhaul networks, the satellite network transmit information as a critical part in the tight integration backhaul system, (ii) the topology of the terrestrial backhaul systems are adaptive to communication events and can be modified according to requirements, and (iii) satellite-terrestrial networks should be entitled the cognitive spectrum ability. In particular, it is worth to mention that ultra-dense LEO satellite networks with high frequency band and appropriate service coverage have been introduced into the architecture to achieve optimal backhaul capacity [152].

b: OPTIMAL ROUTE PROTOCOL

Selecting optimal routes is another way for efficient transmission. Many routing protocols are provided to avoid congestion resulting from satellites' unstable connectivity with their rapid mobility. The mobility of satellites leads to the dynamic state of the network topology. Besides, the density of users in the service area is usually non-uniformly distributed.

The situation will deteriorate the full loaded links and result in link congestion. It is essential to develop dynamic routing protocols adaptive to the characteristics of the networks. In this aspect, challenges are identified in [153], which are: (i) editable routing protocols which can adapt to the dynamic statement of satellites, (ii) methods to enhance the satellite channel efficiency, and (iii) methods to simplify control signaling and decrease the overheads. To alleviate the situation, many schemes are proposed. Among these schemes, the protocols aiming for load balance can be classified as centralized [48], [154]–[157] and decentralized [158]–[162]. Traditional centralized routing protocols usually need a control center that monitors the global traffic information, when there exist congestions, the control center makes new decisions to alleviate the traffic. But it brings additional signaling for communication and storage, thus usually the users experience a service response latency. While decentralized routing protocols entitles satellites to route independently according to local traffic state information.

Authors in [154] propose a routing scheme considering the link state. To alleviate the challenge caused by overhead and slow convergence time, the prediction of link delay and other uncertainty events (like queuing delay, node failures) should be handled in time. The result shows that the scheme reduces the overhead significantly compared with conventional flooding in satellite constellations like Celestri and Teledesic. It is worth to mention that SDN based architectures [48], [155], which can improve the efficiency in load balancing, draw a lot of attention for its highly efficient network route deployment ability. Authors in [155] make other approaches dealing with the problem. A software-defined architecture of satellite networks is proposed to help the network transmit information more efficiently. In [156], GEO group is taken as the control plane, satellite infrastructure and terminal router are taken as data plane. they argue that the back-up flow table and flexible path control simplifies the process of flow control, however more specific implementation details like the interaction between planes and different route protocols' performance are still needed. A new route protocol called contact plan design with prior knowledge is proposed based on the prediction of satellite location. Specifically, authors in [157] take the characteristics deep space system into consideration and explore the challenges to improve the routing schemes dealing with severe disruptions. They use contact plan computations to enhance the performance of delay tolerant networks, in the scheme, maximum contact time and contact assignment fairness are chosen as the path selection criteria. Unfortunately, in the future when the types of information considered increase, the complexity of the scheme will be a bottleneck.

Typically, reference [158] proposes an explicit exchange of information on congestion status among neighboring satellites: (i) At the beginning the target satellite broadcasts its congestion status to the satellites around. (ii) Then the neighboring satellites decrease forwarding communication rates to target satellite when receiving the notification

signaling message. (iii) After that, the neighboring satellites search for alternative available paths and transmit a part of data to guarantee the network performance as much as they can. The result identified that differentiated services architectures over satellite would be a promising area to implement the scheme and the aggregate performance of the proposed scheme is better in terms of queuing delays.

The fine-grained control over the carried data flows can provide flexible schemes for data flows dispatch over different links. Distributed traffic detour is a decentralized route protocol that satellites make the decisions independently to detour a part of traffic from a default route to an alternative route [159], [160], [162].

Authors in [159] design a scheme leveraging traffic lights rules for satellite IP networks. Combined with the current traffic load and pre-calculated plan, information is cut into packets for efficient transmission with multipath routing strategy. To avoid endless-loop, authors use records containing passed nodes, although the results show that the design avoids the unnecessary cost of resources, the multi-service type should be considered when implementation is made.

Schemes in [160] use prior topology information and long-distance traffic detour method to avoid cascade congestions. Speaker satellites in each orbit collect and broadcast information to identify the maximum hop distance, circuitous multipath calculation and detour are made for load balancing, also, unfortunately, it only considered single type services and the complexity path calculation is related to forwarding method.

There exist routing methods with consideration of global view and local view, routing schemes in [161] use global strategy for a prediction and deal with fluctuations using local strategies, the scheme holds a better performance, they also identify some challenges for implementation like packet reordering and real-world trace mobility.

Compared with [159]–[161], authors in [162] proposed a QoS guaranteed routes scheme for delay-sensitive flows, it outperforms traditional adaptive designs in terms of capacity and delay.

To emulate the routing solutions, J. A. Fraire [163] developed a tool to make the foundation of trials in satellite-terrestrial networks, it illustrates a scenario with DTN protocols and suitable results can be achieved using the tool, however, more simulation platforms or emulators needed to be developed in the future.

B. CONTROL AND MANAGEMENT

The integrated satellite-terrestrial network has a complex multi-layer communication structure that unified management is vital to guarantee high efficiency. The ability of management and control need to be flexible in reconfiguration, task allocation, and performance analysis.

Related researches mainly focus on access scheduling and mobility management. Works providing access schemes take up a part in management and control of satellite-terrestrial networks, innovations like massive M2M or IoT have brought

a bright future to a better lifestyle, so it is meaningful to research on access scheduling especially in M2M or IoT. Mobility management, especially the handover scheme is also one of the most critical issues in management and control problems. These handover schemes are mainly centered on cell selection and resource allocation schemes these years.

1) ACCESS CONTROL

5G communication systems are expected to relieve the pressure in providing services to massive users, meanwhile, M2M and IoT traffic sources push the terrestrial networks with a great access demand. As a promising part for the next generation communication networks, satellite-terrestrial networks should enable the ability to provide an efficient method for multiple access.

To alleviate the access problem, innovations like non-orthogonal multiple access (NOMA) and beamforming are introduced into integrated satellite-terrestrial networks to serve multiple users simultaneously. For example, authors in [164] propose a NOMA based satellite-terrestrial network in which base stations and satellites are equipped with multi-antennas. Using beamforming technologies and power allocation schemes, they optimize the capacity of the network with an interference temperature limit. The results show that the network can provide users access ability in the coverage area and better total system performance with other network architectures. It identifies the relationship between user fairness and total capacity. Besides, the traffic characteristic of traffic flow should also be considered, the data of M2M or IoT for transmission is usually generated irregularly and distributed unevenly, thus random access scheme is also suitable in satellite-terrestrial networks. For instance, CoAP protocol is a UDP-based lightweight application protocol and it is investigated in many kinds of literature. The low header overheads and the interaction procedure among application endpoints are suitable for satellite IoT systems. In [79], [165], they specify that CoAP is developed to interact with HTTP while meeting the multicast support.

2) MOBILITY MANAGEMENT

Seamless service ability relies on the flexible and fluent switch between satellite and terrestrial networks. The basic task for fluent service area switch is to develop efficient handover schemes. Usually, handover schemes in satellite-terrestrial network concern several problems as connection establishment, connection control, and connection transference. Unlike traditional handover schemes in terrestrial networks using signal strength or bit error rate (BER) as the threshold in handover decision, the signal strength received from space networks is much smaller than that on the ground. Besides, the boosting development of LEO satellite networks introduces high mobility which urge a suitable scheme for the seamless service providing ability.

To solve the problems, many different handover schemes between satellite and terrestrial networks are proposed over the past years. Considering multiple performance metrics

such as the radio quality link, QoS, BER and received signal strength (RSS), a fuzzer map each metric into a scale via a predefined function which can help make the decision adaptive to the complex circumstance in satellite-terrestrial networks. Foong [166] investigates the mobility management procedure of satellite-terrestrial networks, the author outlines the basic connection establishment scheme, transference scheme, reducing the procedure and "ping-pong" effect. The handover scheme takes multiple performance metrics into consideration, besides artificial neural networks is used for fuzzer to be compatible with different circumstance. The result shows that the softer mechanism is more promising in converged satellite-terrestrial networks. As the complexity is introduced by too many performance metrics, authors in [167] only take QoS as the criteria for the handoff scheme, the mechanism allows users to degrade their QoS requirements rather than deny them. Thus, the blocking probability will be lower than the conventional one. This undoubtedly adds workload for serving network to determine and select an appropriate cell. Some handover decisions take the characteristics of the signal from satellite as a criterion, authors in [168] make approach from the characteristic of the signal as the trigger for handover scheme, three signal strengths are proposed for the network to judge whether the handover scheme should be initiated. However, only the GEO satellite is analyzed. As 5G approaches, LEO constellations should also be investigated. Satellites have already been entitle with the ability of IP multimedia services, authors in [169] proposed a session initial protocol (SIP) based scheme for soft handoff. The result shows that the delay is less than 400ms. And it has significant meaning to design schemes for other services like urgent services. As the setup of the satellite link would take time, the handover is usually predicted in advance, wrong predictions will cost a waste of bandwidth. To deal with the problem, a handoff scheme is proposed in [170]. The results show that the scheme minimizes the delay and reduces the bandwidth cost.

Similar to [169], authors in [171] propose a SIP-based handover scheme with the concern of packet disorder and packet loss. The seamless handoff is done by extending the head of the packet and adjusting the jitter buffer. The results verify the continuity of the session and avoid handoff failure.

In [172], an adoptive hard handover scheme is proposed. Authors adapt the satellite mobile channel characteristics into the handover decision function and analysis the tradeoff between performance and overheads. As the MIMO technology is applied to satellite-terrestrial networks for enhancing the capacity and data rate, they investigate the handover scheme of the multi-antenna systems [173]. The Kalman filter is implemented for a better signal prediction to eliminate the complexity caused by satellite and terrestrial channels, though the prediction adds complexity in the implementation of the scheme, the notable performance shows a promising vision of this kind of architecture.

It is essential to mention that in the satellite communication system, there exist lots of handover schemes, the handover

procedures in space networks contain three handover types: satellite handover, spotbeam handover and inter-satellite link (ISL) handover [174], [175]. The handover criterions mainly focus on service time, elevation angle for receiving signals from satellite and available channel amount and so on.

There exist many satellite handover schemes, unfortunately, most of them are centralized, the management structure exposes defects like scalability problems and long latency problems. Thus, in [176], to eliminated scalability problems in LEO satellite networks, decentralized management architecture called distributed mobility management is proposed. Unfortunately, in the article, QoS should be considered and blocking probability should be analyzed. An adaptive spotbeam handover scheme is proposed in [177]. LEO satellites' high mobility brings frequency handover and it will result in service blocking. The scheme utilized a resource management method for shifting the wireless channels. It shows that the method improves the blocking probability and dropping ability. Compared with [177], authors in [178] proposed an analytical model with regard to service time correlation in spotbeams. They argue that temporally correlated channel has effect on transmissions and they derive a closed form method for correlated queue service. The result shows that the queue service correlation is critical when considering the spotbeam handover schemes.

ISL satellite handover problems arise as more and more LEO satellites are introduced in satellite communication systems. Most schemes are taken satellite links as a stable one while in fact the circumstance is complex. In [179], authors proposed a velocity-aware handover scheme to alleviate the drawback of traditional methods.

C. RESOURCE ALLOCATION

Although leveraging infrastructures in space networks improves the terrestrial network performance and provides a ubiquitous accessible environment, the explosion of data traffic with rapid developed high-end UEs puts pressure on QoS as communication resources available is limited. Thus, efficient resource allocation in frequency, time, and space is crucial in the future space and ground interworking.

Reference [11] provides a comprehensive study on the motivation, problem formulation, and research methodology on communication resource allocation schemes of satellite-terrestrial networks. The authors identify challenges in spectrum management, as: (i) radio resource allocation scheme between satellite systems and terrestrial systems, (ii) beamforming multiple access techniques and (iii) the strategy of resource allocation. Also, the paper explores bandwidth allocation, beam allocation schemes and cross-layer and power allocation and proposes future directions respectively.

The dynamic packet scheduling problem is quite critical in implementing an efficient utilization of the limited resources in satellite LTE networks [180]–[183], especially

for QoS guaranteed multimedia traffic scenarios. Authors in [181] proposed a cross-layer resource management with the constraint of QoS, furthermore, they consider the delay, data rate, and fairness as criteria for optimal resource management method [180], while most researches only consider the delay and data rate. They argue that the scheme can reach better throughput. Based on the works mentioned above, in [182] they modified user selection standards and add an exponential control parameter to settle the relationship between QoS and throughput. And in [183] they use the logarithmic function as the control parameter. However, the services they considered in the simulation only focus on multimedia service, more works should be done when the requirements are mixed services.

Considering more sophisticated factors that affect communication, context awareness can help communication networks achieve the users' perceived quality of service. More importantly, it also improves the utilization of cooperative satellite-terrestrial networks [143]. Authors in [184] proposed a resource allocation management considering the delay, they allocate the spectrum resources according to the users' distance. The allocation method is proposed for a burst access circumstance which is very meaningful as the quick response is critical when disaster happens. Similar to solve the spectrum allocation problem in satellite-terrestrial networks, the scheme proposed in [185] utilized a central controller to collect channel state information. The result shows that it can maximize the terrestrial network capacity and constrain the interference to the satellite system.

As presented in the former chapter, cognitive satellite-terrestrial networks (CSTN) is a promising architecture for future integrated satellite-terrestrial networks. There are some literature focus on resource allocations in CSTN [186]–[188]. As imperfect CSI should always be taken care of, authors in [186] analyze the effect and consider an efficient allocation method. Different from the architecture mentioned above, in the network, satellite is the primary user and terrestrial networks have the role of the second system. The method guarantees the outage probability and improves the whole system capacity. To reduce the complexity of channel state information acquisition in the spectrum sharing system, the scheme presented in [187] leverage the radio map. The scheme optimizes the power allocation and improves the data rate of the terrestrial network. It shows that the scheme can significantly improve the performance of satellite-terrestrial spectrum sharing networks. But it is essential to mention that the radio map method needs the knowledge from the geolocation database and the dynamic spectrum sensing results. It should solve the dilemma where radio perceiving measurements are hard to operate. None of the above methods take into account the resource management of security transmission, in [188], a resource allocation scheme concerning transmission power and information rate is presented. They formulate the problem to a transmission power minimizing question while keeping the satellite secrecy rate and data rate on the ground. It provides insights

for allocation problem when dealing with security transmission problems.

D. SECURITY

The inherent characteristics of broadcasting and vast coverage force challenges on the issues of security in integrated satellite-terrestrial networks. When satellites deliver information to terrestrial networks, it is delicate to be intercepted by eavesdroppers. New technologies and schemes must be robust against eavesdropping and malicious behavior. For example, in [189], security is enhanced in the network layer of the DVB-RCS satellite systems. The conventional method is utilized to provide datalink security and the authors of [189] also leverage IPsec to guarantee the security between hosts. To be more concrete, they add separate keys for multicast channels and develop a set of cryptographic methods for varied security profiles.

During the last decades, as multiple-input multiple-output (MIMO) antenna starts to play an important role in the communication system, physical layer security is becoming popular [190]. MIMO antenna, which can provide extra degrees of freedom, can adjust the steering orientation to make full use of directive gain and leakage little information around. The key ideology of physical layer security (PLS) is to exploit the difference between the service channel and eavesdropper's channel, in this context, there exist some open literature in [186], [191]–[199].

Authors in [191] firstly analyze the secrecy capacity of the satellite system. Authors provide a security method only with PLS and with a primary system model. More factors like CSI, power and interference should be considered in the scheme. Reference [192] provides insights on how to use imperfect CSI to extract information, and it explores the trade-off relationships between energy efficiency and spectrum efficiency.

Power constraint and beamforming method are two key approaches in PLS of satellite-terrestrial networks. For instance, under the security rate constraint, authors in [193] optimize power and the beamforming weights. They argue that the performance is related to antenna numbers, beam numbers, security requirement and CSI. Unfortunately, they take no considerations that the satellite channel has no perfect CSI. Reference [194] proposes a method to leverage interference for a precoding scheme which could minimize the power consumption. The design adapts the QoS constraints to the constructive interference, which is taken as useful transmit power. The method gives insights on how to make use of the interference in the PLS of satellite-terrestrial beamforming systems. In [195], the authors study the physical layer security scheme in satellite-terrestrial networks. They minimized transmit power and at the same time guarantee the users' security rate. The scheme not only explores the CSI of eavesdroppers, but also uses artificial noise as an extra degree of freedom for transmission protection. Authors in [196] consider the factors mentioned above, they use the interference as a source of transmission to enhance security performance.

And the scheme also analyzes the typical circumstances that whether CSI of eavesdropper is known to the satellite. The result validates the scheme but more works shall be done when satellite is employed with the multibeam.

More practical scenarios are considered in [197]. The authors investigate the security of satellite-terrestrial in the shadowed-Rician channel, unfortunately more methods dealing with imperfect CSI of the satellite should be proposed. Finally, authors in [198] propose the security scheme which addresses the spectrum scarcity problems in satellite-terrestrial networks. Aiming to make more accurate analysis of the scheme, they proposed a stochastic model to introduce the channel statement uncertainty, they demonstrate the scheme is effective for the outage probability.

E. DISCUSSION AND INSIGHTS

The heterogeneous networks bring challenges in terms of cooperative strategies in satellite and terrestrial networks. As presented in this section, a number of researches have been proposed, which can be summarized into four categories: (i) Transmission, (ii) Management and control, (iii) Resource allocation and (iv) Security. The extensive amount of scientific works mentioned above have made great contributions to the convergence of satellite and terrestrial networks, however, as wireless networks evolve, new challenges in terms of complex social relationships, service characteristics in specific areas, cumbersome signaling and malicious attacks, have increased as well.

In the first category, solutions are given to deliver content efficiently [140]–[147], some of these works focus the aim on how to improve the delivery efficiency under the constraint of QoS, others propose flexible backhaul networks strategies and optimal routing protocols for traffic loading balance, the use of LEO constellations bring insights for future networks as it has a low altitude [152] and the service delay will be small. When researchers design in designing optimal routing protocols, disruptions caused by uncertain events are the bottleneck that degrades the performance of the solution [158]–[162], more attention should be focused on the robust schemes as satellite communication environment is complex. Convergence time and performance are in a trade-off relationship in the satellite-terrestrial routing scheme. Thus, as [162] shows global and local view should be work together, for the global view would degrade efficiency in small regions and local view may cause congestions. Although the researches focus on transmission provide methods to improve the efficiency, few of them take users' social relationships into consideration. Social relationship and specific service regions may affect individual's content preference deeply. For example, it is investigated that social information of the networks can improve the multimedia content delivery by reducing the bandwidth cost [199]. Data requirements in specific regions tend to be regular, which can be used as guidance for traffic flow prediction [200]. Users access the cellular network where the SuperBowl takes

place and the traffic tends to show the theme that the sports information and related media flows.

In the second category, mobility management and access control are considered. Current scheduling stays in dealing with the maximum number of users accessed [163]–[165] and handover criteria problems [167]–[169]. More attention should be focused on spot beam handover schemes and ISL schemes. As SDN can split the control plane and data plane, it is meaningful to explore more detail in an SDN based satellite-terrestrial networks. Besides, the mobility and control of cruise ship, plane, and UAV should also be considered for their varied operational scale.

Resource allocation schemes are investigated in the third category, optimal schemes have been proposed to assign communication resources from the time domain, spectrum domain and space domain. The research focus on the QoS guaranteed resource management schemes considering delay, data rate, power consumption and fairness [180]–[188]. However, these resource allocation algorithms avoid considering tidal effect. In urban areas, traffic shows regular fluctuations with the variant of time. From the occupancy of communication resource point of view, within the constraint of limited resources, release resources can provide good results in performance.

The fourth category involves security problems in satellite-terrestrial networks. Utilizing MIMO systems, physical layer methods have been developed to help avoid information leakage to eavesdropper [190]–[198]. Here whether the system can get perfect CSI will be vital for secure transmission design [191]–[193]. Researches leverage interference on the ground to combat malicious eavesdrops, while it indeed affects the performance of satellite networks. Prediction methods, channel characteristics, and the delay are challenging the robust design. Although the solutions are promising, due to different innovations embedded in the networks, cross-layer design should be considered. For example, in SDN based architecture [201], application plane security challenges (fraudulent flow rules insertion and lack of authentication), control plane security challenges (denial of service (DoS) attacks), and data plane security challenges (TCP-level attacks, flooding attacks) cannot be solved simply in physical layer.

VI. PERFORMANCE EVALUATION STUDIES AND SIMULATION PLATFORMS

Performance evaluation is a set of methods to evaluate service quality transmitted in a proposed network [202]. Performance evaluation of integrated satellite-terrestrial network is usually performed via numerical simulations or mathematical analysis, from open literature that we review, most performance analysis focus on (i) Satellite-terrestrial backhaul networks, (ii) Hybrid satellite-terrestrial cooperative systems (HSTCS) and (iii) Cognitive hybrid satellite-terrestrial networks (CHSTN). There exist some other researches on SDN based satellite-terrestrial networks [118], [203], and related link budget [204]. Here we only focus on the

TABLE 3. Performance indicators in satellite-terrestrial cooperative systems.

| Performance indicators | Related works |
|--------------------------|-----------------------|
| OP | [208]-[212][216][222] |
| Symbol Error Probability | [208][209] |
| ASER | [212][213][217][222] |
| Ergodic Capacity | [214][216][218]-[220] |
| SINR | [215] |
| BER | [215] |
| SER | [215][223] |

evaluation of categories classified above. The performance indicators are summarized in Table 3.

A. BACKHAUL NETWORKS

The backhaul networks of satellite-terrestrial architecture aim at providing a resilient and flexible traffic offloading services. The service responding latency and the throughput will be a criterion for the backhaul network performance.

In [151], performance evaluation of TCP and UDP connections is presented. The flexibility of different backhaul routing method is based on the service merits. Traffic load, round trip time, and download time are taken as key performance indicators of the scheme. In [205], a satellite-terrestrial wireless network for the emergency is considered. In the network, satellites are considered as bentpipe connecting the Internet and terrestrial wireless networks. The performance evaluation of throughput and latency experienced by TCP connections is presented. Sharing the spectrum above 10 GHz, a cooperative satellite-terrestrial backhaul network using diversity theory is designed in [206]. Also, outage probability is calculated to evaluate the scheme, we think there remain lots of specific work to do when the millimeterwave is introduced in the network architecture.

B. HYBRID SATELLITE-TERRESTRIAL COOPERATIVE SYSTEMS

The hybrid satellite-terrestrial cooperative system (HSTCS) is proposed in [134] that the terrestrial relay nodes help to enhance the satellite transmission with diversity technology. Usually, in HSTCS satellite link is assumed as shadowed Rician distribution and terrestrial link the Nakagami- m distribution. The performance of hybrid satellite-terrestrial cooperative system has been studied in [207]–[223].

Various performance indicators of hybrid satellite-terrestrial relay networks under interference-limited scenarios, including outage probability (OP), average symbol error rate (ASER), and ergodic capacity, have been investigated for illustration in Table 3.

Implementing the selection of relay nodes or optimal relay selection strategy [207] and using the maximum ratio combining technique, OP and symbol error probability are evaluated [208], [209].

The decode-and-forward scheme with best relay selection is evaluated in [210] and the exact outage probability expression is formulated. It is worth to mention that the shadow

condition and elevation angle are also affect the network performance [211].

The average symbol error rate of the considered amplify-and-forward (AF) cooperative scheme is derived in [212], [213]. To be more complicated, authors in [214] consider a hybrid satellite-terrestrial relay system that employs a multi-antenna satellite to communicate with multiple users via multiple amplify-and-forward relays. With the opportunistic scheduling, the tight upper and lower bound for the ergodic capacity of the multiuser AF hybrid satellite-terrestrial relay network (HSTRN) is analyzed.

Consider the interference, reference [215] investigates the error performance of an AF relaying HSTCN with cochannel interference (CCI) and derive the approximate statistical distributions SINR. Some asymptotical bit error rate (BER) and symbol error rate (SER) results are also provided.

And authors in [216] study a multi-antenna multiuser HSTRN employing opportunistic user scheduling with outdated CSI and AF relaying with CCI. OP and ergodic capacity of the HSTRN is formulated, and the achievable diversity order is examined.

Reference [217] investigates the effect of CCI on a hybrid satellite-terrestrial cooperative relay network (HSTCN). The average symbol error rate (ASER) of the cooperative network is evaluated, the average and asymptotic capacity of the system are also derived by using the moment-generating function method.

Reference [218] investigates the performance of a multiuser AF hybrid satellite-terrestrial relay network (HSTRN) with opportunistic scheduling. The tight bounds for the ergodic capacity of the system are derived. [219] investigates the optimal capacity and minimum mean squared error (MMSE) capacity upper bound for the return link of HSTCSs under Rician fading. And [220] evaluated the ergodic capacity of the HSTCS with an AF cooperative protocol. Besides, some researches focus on the performance evaluation of AF-based hybrid satellite-terrestrial free-space optical (FSO) cooperative systems [221]. Others investigate the performance of the AF HSTRN, where the links of the two hops undergo shadowed-Rician and Rayleigh fading distributions, respectively. The analytical lower bound expression is also expressed to evaluate the OP and ASER of the system [222]. Reference [223] proposes a beamforming and combining scheme for a two-way AF-based transmission between two multi-antenna earth stations, while the satellite is taken as a relay node. The symbol error rate (SER) of the communication network is formulated based on the moment generating function of the signal-to-noise ratio (SNR) at the receiver.

C. COGNITIVE HYBRID SATELLITE-TERRESTRIAL NETWORKS

Cognitive hybrid satellite-terrestrial networks are designed to satisfy spectrum utilization requirements expected for the next generation 5G mobile networks [224]. A few researchers have investigated the performance of the cognitive hybrid

TABLE 4. Simulation and emulation platforms used in converged satellite-terrestrial networks.

| Simulation/emulation platform | Representative works |
|-------------------------------|----------------------------|
| MATLAB | [178][207][219][225][259] |
| OPNET | [165] |
| OMNET++ | [268] |
| NS2/NS3 | [152][157][163][175] |
| STK | [224] |
| Open SAND | [124][130]-[132][248][253] |

satellite-terrestrial network. Reference [225] investigates the performance of a cognitive hybrid satellite-terrestrial network. OP, which shows impact of system parameters, such as the interference temperature constraint, the fading severity of the SU link, and the shadowing severity of the satellite interference link, are evaluated in the article. Besides, in the article, considering that whether the interference temperature constraint at the PU is proportional or equal to the maximum available transmit power, the authors reveal the relationship among the asymptotic behaviors of the secondary terrestrial network, the diversity order and coding gain. Unlike [225], Sharma *et al.* [226] evaluate the OP of both primary and secondary networks, and examine their achievable diversity orders. Focusing on the selection of best secondary networks, the authors study the impact of partial secondary network selection and opportunistic secondary network selection on secondary cell coverage. Similarly, taken as an SU, the mobile communication network coexists with satellites under the acceptable interference constraint [227]. However, the difference here is that OP is evaluated in three secondary transmission schemes: (i) The transmit power of base station (BS) is limited by the interference constraint. (ii) Employing directional beamforming, the BSs point related signals to corresponding users. (iii) The BSs that do not satisfy the interference constraint are thinned out.

D. SIMULATION AND EMULATION

We summarize simulation and emulation platforms utilized for researches on the convergence of satellite and terrestrial networks in TABLE 4. Five simulation and emulation tools are widely employed for delicate deployments to achieve specified scenarios: MATLAB, OPNET, OMNET++, NS2/NS3, STK, Open SAND.

Usually, MATLAB is employed for performance evaluation, especially in algorithm comparisons and theoretical analysis. OPNET, OMNET++, NS2/NS3 are used for systemic level simulation and related performance evaluation. STK is usually employed for investigating the parameters simulation of the space network, while Open SAND, an emulator system which can communication mechanism and the behavior, comprises modules of entities in satellite-terrestrial networks. In our opinion, as satellite shall be a part of 5G network, open air interface (OAI) being used with field-programmable gate array (FPGA) is suitable to emulate the 5G satellite thus it can be easily integrated with 5G terrestrial networks.

VII. STANDARDIZATION AND RELATED PROJECTS

The realization of the next generation communication network is on the way. The convergence of satellite and terrestrial networks is destined to augment service offer and address problems encountered in verticals such as transport, navigation, multimedia, emergency relief. There is no doubt that ubiquitous network access and resilient high-speed connectivity across the globe will unleash the potential life experience and empower the change of living style. Innovations in satellite and novel applications are breaking the limitations of legacy terrestrial networks. It is essential to develop protocols and executive projects to enhance the industrialization of satellite-terrestrial networks.

A. STANDARDIZATION

The convergence of satellite and terrestrial network helps push 5G services to areas where there is lack of communication entities, increasing the reliability and availability of service. Because of the heterogeneous resources and continued growth of applications, ensuring a seamless communication experience has become a challenge. The circumstances triggered the development of standards to guide the implementation of the satellite-terrestrial network with high performance. Related standards for satellite and terrestrial network convergence are presented in Figure 6.

Lots of works for satellite-terrestrial network convergence have been done by 3GPP. These standards explore the requirements of the scenarios and identify key enablers for the new architecture [228]–[230]. New architectures including satellite networks for the next generation network are proposed in [231], new radio (NR) and access schemes are studied in [138], [232], [233], and some related usecases are illustrated in [234], [235].

In TR 38.913 [228] (Study on Scenarios and Requirements for Next Generation Access Technologies), 3GPP clarifies the scenario that satellite extension to terrestrial. The mMTC broadcast and delay tolerant services should be supported in the deployment of satellites. Specific requirements of multiple access technologies, resource efficiency, content delivery and connectivity, which satellites can take part in, are presented in TS 22.261 [229] (Service requirements for the 5G system).

TR 22.891 [230] (Feasibility Study on New Services and Markets Technology Enablers) aims to identify the market segments and verticals, also it includes related use cases and requirements for the future networks. The case of 5G connectivity using satellites is provided in clause 5.72. The enhancements of existing terrestrial specifications should consist of potential service requirements: (i) full geographic coverage, (ii) air-interface with latency of up to 275ms and (iii) seamless mobility between terrestrial and satellite-based networks.

To integrate satellites with the next generation communication network, in TR 23.799 [231] (Study on Architecture for Next Generation System) the 3rd Generation Partner(3GPP) listed 5G connectivity via satellite as a key issue in the

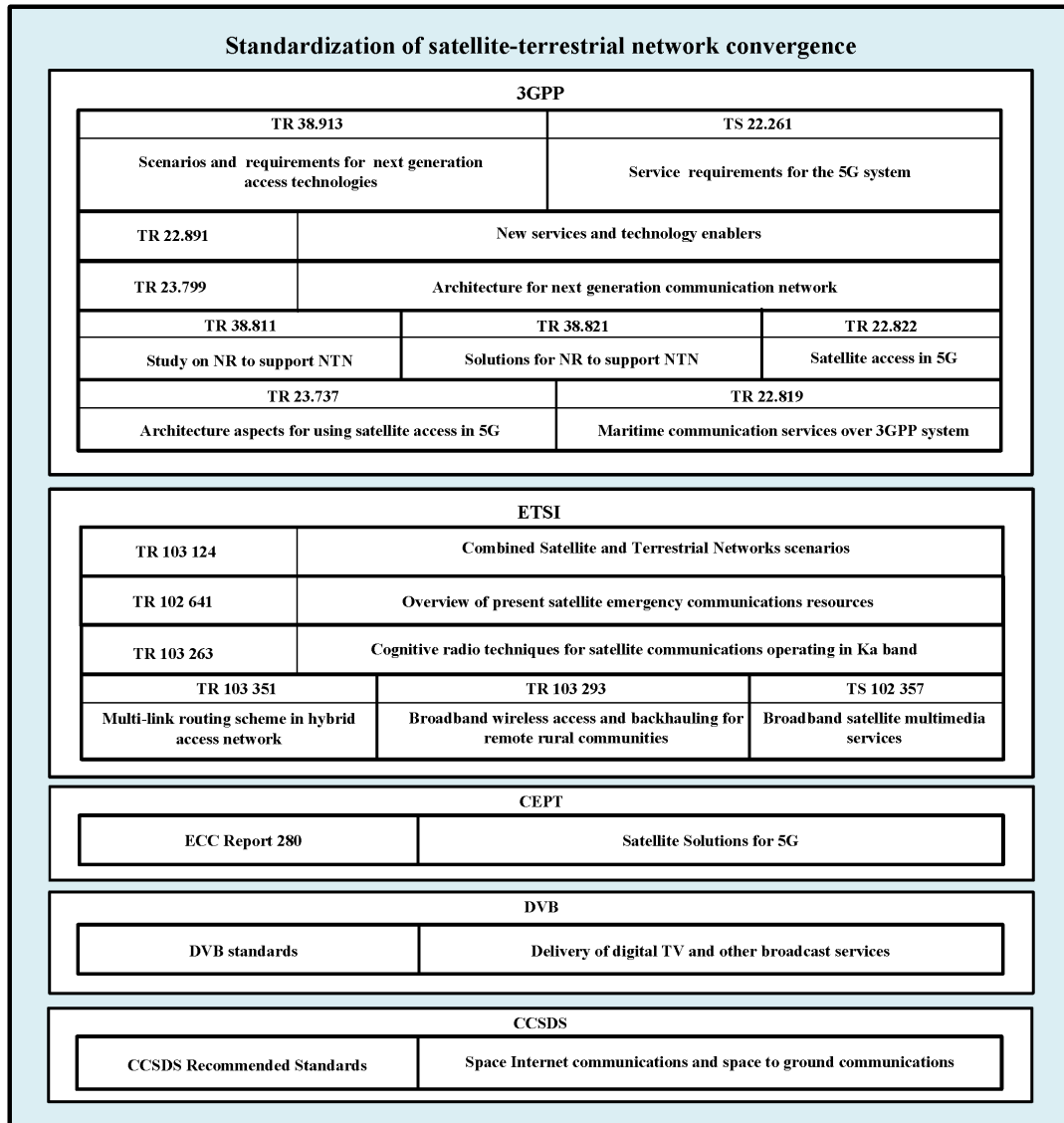


FIGURE 6. Related standards on satellite and terrestrial network convergence.

system architecture for the next generation mobile networks. Satellites provide a solution in the reselection of efficient user plane path with minimum service interruption to support service continuity.

TR 38.811 [138] (Study on New Radio (NR) to support non-terrestrial networks) provides study items of NR to support non-terrestrial networks (NTN). Satellite and aerial access network architecture principles are considered, differences between satellite/HAPS and cellular channel modeling are compared elaboratively. Based on the outcomes of the 3GPP TR 38.811, to study a set of necessary features as well as adaptations enabling the operation of the NR protocol in non-terrestrial networks for 3GPP Release 16 with a priority on satellite access, 3GPP TR 38.821 [232] (Solutions for NR to support NTN) studies consolidation of potential impacts on the physical layer and definition of related solutions if needed and performance assessment of

NR in selected deployment scenarios (LEO-based satellite access, GEO-based satellite access) through link-level (radio link) and system-level (cell) simulations. TR 22.822 [233] (Study on using Satellite Access in 5G; Stage 1) has worked on use cases for the provision of services when considering the integration of 5G satellite-based access components in the 5G system. In the technical report, it classified used cases into three classes: continuity, ubiquity and scalability. It is worth to point out that 5G satellite network-based architectures which refers to the combination of a radio access network and a core network are proposed in the study.

Two use cases: (i) Roaming between terrestrial and satellite networks and (ii) 5G fixed backhaul between satellite enabled NR-RAN and the 5G core are studied in 3GPP TR 23.737 [234] (Study on architecture aspects for using satellite access in 5G).

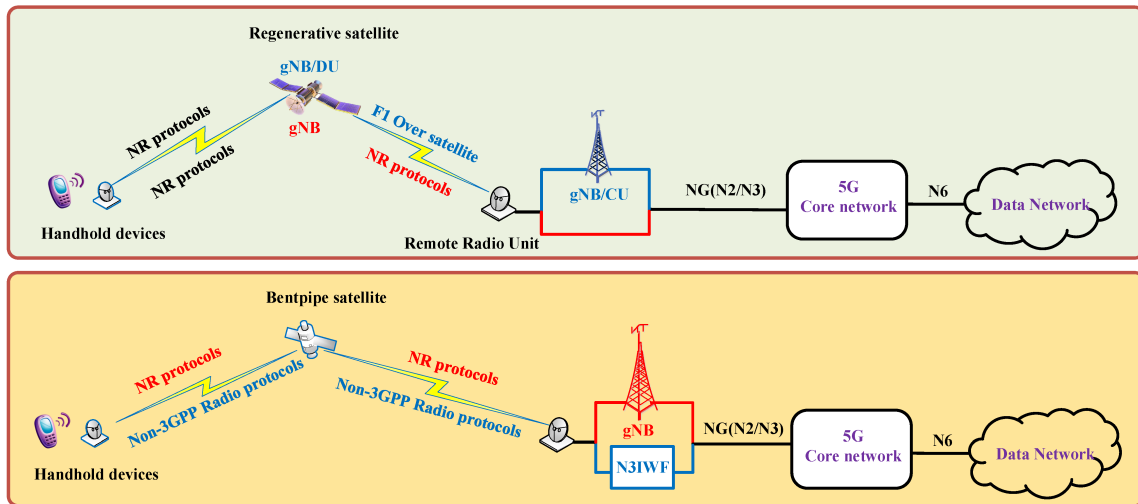


FIGURE 7. 3GPP 5G communication architectures evolved with satellites.

In the aspect of use cases for interworking and harmonization, except satellite access to support maritime communication services over 5G system in [138], 3GPP TR 22.819 [235] (Feasibility Study on Maritime Communication Services over 3GPP system; Stage 1) mentions the function used in the interworking with very high frequency data exchange system. As demonstrated in these 3GPP standards, satellite networks have already been taken for 5G communication networks consideration, which provides ubiquitous access function and flexible backhaul function for guaranteed services. Figure 7 shows the existing 3GPP communication architectures evolved with satellites [138], [229]. In the proposed architectures, regenerative satellites with on-board processing abilities and bentpipe satellites, which have no on-board processing capabilities, are depicted in the 5G satellite access networks respectively. It also considers possible ways to combine non-3GPP satellite access network entities, i.e. Non-3GPP InterWorking Function (N3IWF), with the 5G Core Network.

ETSI is another standards organization focus on ICT-enabled systems. It also proposed some standards on satellite and terrestrial network convergence. Here we list some important standards for the combination of the systems. ETSI TR 103 124 (Satellite Earth Stations and Systems (SES); Combined Satellite and Terrestrial Networks scenarios) [5] identifies the definitions and classification of scenarios combining satellite networks as well as terrestrial networks. And the role of space technology in disaster management is proposed in ETSI TR 102 641 (Satellite Earth Stations and Systems (SES); Overview of present satellite emergency communications resources) [236], also it lists the resources used in covering earth observation, satellite navigation and satellite communications. Specifically, in ETSI TR 103 263 (System Reference document (SRdoc); Cognitive radio techniques for Satellite Communications operating in Ka band) [237], the potential regulatory that impacts associated with the operation of

SatCom solutions implementing cognitive radio techniques are identified. Particularly it emphasizes different scenarios in Ka band (17.3 GHz - 20.2 GHz for space to earth and 27.5 GHz–30.0 GHz for earth to space) using CR technologies. At the same time, content in ETSI TR 103 351 (Satellite Earth Stations and Systems (SES); Multi-link routing scheme in hybrid access network with heterogeneous links) [238] deals with a traffic distribution problem from the view of access networks. As a typical scenario in the convergence of satellite and terrestrial networks, the rural area backhauling needs to be considered. ETSI TR 103 293 (Broadband Radio Access Networks (BRAN); Broadband Wireless Access and Backhauling for Remote Rural Communities) [239] provide details for implementation of cooperation with 3G femto base stations, and an amount of backhaul solutions using satellite-terrestrial networks is included. Besides, ETSI also concerns with typical services for convergence of satellite and terrestrial networks and the standard specification to address industrial technical problems. For instance, ETSI TS 102 357 (Satellite Earth Stations and Systems (SES); Broadband Satellite Multimedia (BSM); Common Air interface specification; Satellite Independent Service Access Point (SI-SAP) interface: Primitives) [240] explains the Satellite Independent Service Access Point (SI-SAP) and physical air interface specifications for broadband services in satellite-terrestrial networks.

Except for the 3GPP and ETSI, there exist some other organizations, which are pushing the standardization of satellite and terrestrial network convergence. In [241], CEPT (Conference of Postal and Telecommunications Administrations) the function that satellite networks playing in the 5G integration networks, the technical report describes related background context and several representative use cases of satellite-based solutions.

Taken satellite as a broadcaster to deliver digital TV and IP services to the ground, Digital Video Broadcasting (DVB), which is an industry consortium, proposed a series

TABLE 5. View of the related projects.

| Project | Scope | Reference | Start year |
|-----------|--|------------------|------------|
| Satis5 | A comprehensive testbed showcasing major technology progress and demonstrating the benefits of satellite technology for the main 5G use cases | [256] | 2018 |
| SaT5G | Developing solutions integrating satellite into the 5G telecommunication architecture | [244] | 2017 |
| SATNEX IV | Next generation satellite trunking, network architectures for flying ad-hoc networks nano-satellite swarms, access solutions assessment for satellite scenarios | [139][248]-[252] | 2017 |
| SANSA | Satellite-terrestrial networks to increase the backhaul network capacity and resilience | [245] | 2015 |
| VITAL | Federated resource management in hybrid satellite-terrestrial networks | [255] | 2015 |
| BATS | Hybrid architecture which combines the flexibility, large coverage and high capacity of future multi-spot beam satellites, fixed DSL lines, and the mobile or wireless access services | [246][247] | 2012 |
| CoRaSat | Efficient utilization of spectrum by combining CR techniques with SatCom systems | [253][254] | 2012 |

of technical standards include a large family of standards and specifications covering many categories and more than 100 specification documents [242].

Meanwhile, some space agencies seek the opportunity of interconnection between deep space communication and terrestrial networks. The Consultative Committee for Space Data Systems (CCSDS) aims at providing international standardization for space internet communications and space-to-ground communications. A series of protocols are proposed to allow interoperability between mission control centers and between the spacecraft and ground systems [243], these files guarantee the approach that more reliably integrates terrestrial and space-based networks.

B. RELATED PROJECTS

Except for the standards available and the ongoing process of standardization, some related projects also give insight in the convergence of satellite and terrestrial networks. All the related projects we surveyed are listed in Table 5.

Satellite and terrestrial network for 5G (SaT5G) is a project to develop solutions integrating satellite into the 5G telecommunication systems [244]. By defining optimal backhaul networks involving space and ground part and traffic offloading strategies, SaT5G tries to address the technical challenges in leveraging SDN, NFV, caching and multicast optimization for network management and orchestration.

Shared Access Terrestrial-Satellite Backhaul Network enabled by Smart Antennas (SANSA) is aiming at improving the performance of mobile wireless backhaul networks [245]. To eliminate the pressure of the backhaul network which is a result of data traffic explosion. SANSA proposed a terrestrial satellite network to increase the backhaul network capacity and resilience, at the same time it facilitates the networks in both low or highly populated areas.

Broadband access via integrated terrestrial and satellite system (BATS) is a closed project and its objective is to use a hybrid architecture to facilitate rural areas. The project utilized satellites, fixed DSL (Digital Subscriber Line) and wireless networks to forge a pervasiveness information system with high capacity and low latency [246]. It investigates and designs new techniques to improve the efficiency of communication. Also, a wireless Back-haul architecture, which

implements software-defined network concepts, is investigated in BATS [247].

SATellite Network of Experts IV (SATNEX IV) is a project that needs to accomplish. It makes a preliminary evaluation of novel technologies and evaluates the possibility of utilizing them into the space networks services [132], [248]. Until now, it mainly focusses on next generation satellite trunking [249]–[251], network architectures for flying ad-hoc networks (FANETs) and nano-satellite swarms, and access solutions assessment for satellite scenarios [252].

Cognitive Radio for Satellite Communications (CoRaSat) project aims at combining CR techniques with satellite networks to improve the utilization of limited frequency resource [253]. Spectrum exploitation plays a key role in the performance of the transmission. Aiming at providing high-speed broadband service access, it implements a flexible spectrum usage allocation on scenarios and use cases [254].

Virtualized hybrid satellite-Terrestrial systems for resilient and flexible future networks (VITAL) is sponsored by the European Commission under the H2020 Research and Innovation program [255]. The project aims to provide a federated resource management in hybrid satellite-terrestrial networks by bringing NFV and SDN into satellite networks. The project mainly demonstrates three scenarios: (i) Virtualization and sharing of satellite communications platforms, (ii) 4G/5G backhauling services and (iii) federated satellite-terrestrial access services.

Concerning the various technology enablers, the SATis5 testbed is built under the ESA ARTES (Advanced Research in Telecommunications Systems) activity “SATis5: Demonstrator for Satellite Terrestrial Integration in the 5G Context”, funded by the European Space Agency and it is expected to be ready for live demonstrations [256]. The project means to provide a testbed which showcases major technology progress and demonstrates the benefits of satellite technology for the main 5G use cases. And it highlights the advantages of satellite technology in a range of situations and thus feeds into a roadmap and vision, which creates a very substantial impact on the telecommunications industry going beyond the satellite industry and facilitate primarily through 3GPP standardization. Till now two usecases have already been demonstrated: (i) 5G connectivity “on the move” with a

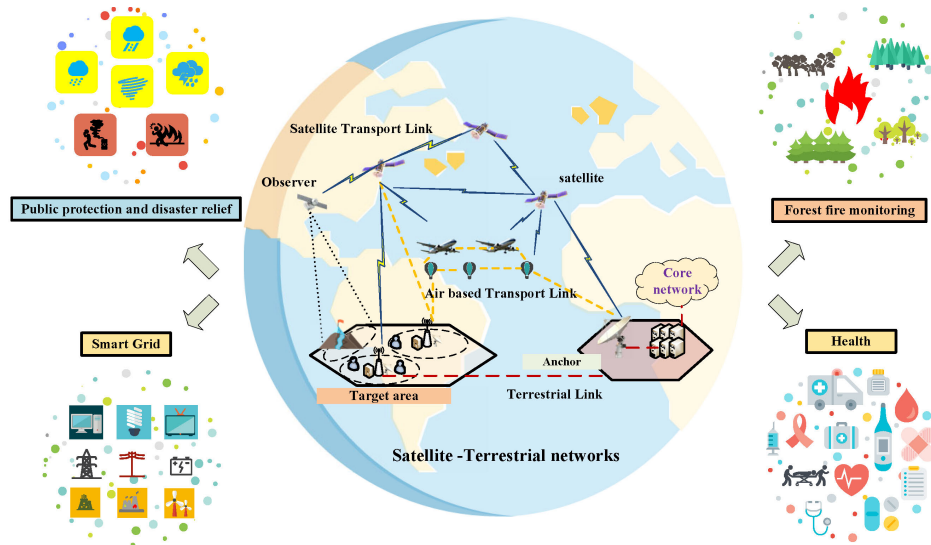


FIGURE 8. Main existing application areas of satellite-terrestrial networks.

Satcom-enabled van and addressing communication requirements including eHealth, rapid response and temporary deployments for public events and (ii) “edge delivery” through a stationary network extended by satellites.

VIII. KEY APPLICATION AREAS

Integrated satellite-terrestrial networks bridge diverse communication resources distributed in dimensions of time, frequency, and space to enhance or enable different services required by the market. It is expected to improve the quality of civil life by making breakthroughs in connectivity worldwide. For decades, innovations in onboard processing and amount explosion of nanosatellites and microsatellites, have rapidly become more advanced and have been featured in more missions [257]. Particularly, combining with M2M, satellites can play critical roles in many use cases such as environmental monitoring, information delivery services and so on [258]. The new architecture redefines the industry and meets critical reliability and performance requirements for services in the future. Figure 7 illustrates the main application domains of integrated satellite-terrestrial networks.

A. PUBLIC PROTECTION AND DISASTER RELIEF

Public protection and disaster relief provide the support of guaranteed communication under the circumstance that the terrestrial network fail to function normally when unexpected man-made emergency or disaster happens. Lacking terrestrial infrastructures that help backhaul the information, people in the emergency area are deprived of the ability to contact outside. The cooperation of satellite and terrestrial networks can play a critical role in transforming the traditional network into a robust and quick response one. For example, a stable of multi-hop space backhaul can be established by satellite networks in an earthquake scenario where most eNodeBs are destroyed. Identifying reference scenarios, the approach

to build up a satellite-terrestrial architecture and relevant simulations is provided in [203], [259].

B. FOREST FIRE MONITORING

Monitoring the forest fire is essential for ecosystem management planning, appropriate planting geographical scheme and extinguishment deployment. Forest fire usually happens in remote or rural areas where barely can deploy terrestrial links and cause great economic losses and threat of lives. A predictable warning and quick extinction are effective to reduce the damage to the minimum, in the convention way, satellite networks are used to detect the hot spot by remote sensing or image analysis. But the granularity of these methods is still coarse and inaccurate location information would bring disadvantages to the quick response. Combining sensors networks with satellite networks, it provides a methodology for effective provision of accurate fire detection. For example, sensors for combustion detection, optical cameras and weather monitoring stations exploit low-cost Satcom is implemented in SFEDONA [260], [261]. Hence, the convenience brought by satellite-terrestrial networks is suitable for fire monitoring and other environmental protection activities.

C. SMART GRID

The integration of information technologies and the distributed power grid has already reduced energy consumption in different energy hungry sectors for years. Machine to machine communication monitoring energy distribution improves the efficiency of electrical grids. Characterized as intelligence, sensing the unfit distribution and adjust the power scheduling in time is essential in smart grid (SG).

Real-time power control management from generation station to customers is quite pivotal in energy transmission. Similar to fire monitoring, long-range wide area network facilitates the low power wide area networks easier access

to space network for better transmission and distribution monitoring [262], [263]. As the transmission and distribution monitoring in the network should always take large area into consideration [264], satellites at the high altitude can help balance the uneven power distribution. It is expected that satellite networks together with sensors on the ground, can serve a relevant role for varied SG applications.

D. HEALTH

The adoption of satellite networks and ground stations for telemedicine or remote health consulting is a hot topic to improve the quality of people's life across the world. LEO satellites can provide rich connectivity to medical centers with places where people need aid. Specifically, the fields of application for health in the network of satellite-terrestrial network are the emergency scenario and the far remote scenario. Architectures for remote health were proposed during past years. Audio and video interactions should be guaranteed as some procedures need careful queries and observations [265]. To achieve this goal, satellite-terrestrial systems guaranteed QoS for effectiveness and reliability is proposed in [266] and [267]. In the future, more attention should be paid on the security of satellite-terrestrial networks, since remote community network devices may be infected by malware [268].

IX. CHALLENGES AND OPEN ISSUES

So far, we have performed a survey on different aspects of converged satellite-terrestrial networks. Based on the literature we reviewed, open issues and challenges of the network are crucial in future elaborations. Management and orchestration, transmission scheme, security issue, resource allocation scheduling incurred in the implementation procedure of the converged network are challenging the multi-layer multi-domain communication architecture. However, there exists no such a unified system model that is adaptive to all scenarios emerged in next generation communication networks. In this section, we identified the challenges and open issues from the perspective of future development.

A. ARCHITECTURE

The scalability of the converged satellite-terrestrial network is a major concern. Although the architecture is evolving to adapt new scenarios and demands on availability and high efficiency. Current architecture may not be compatible with what required from 5G. The challenges can be elaborated from three dimensions:

- **Integration of customized architectures**

In section VI, combined with new technologies separately, satellite-terrestrial networks are structured differently to improve the performance on different aspects. However there still need coordination between different layers and entities to increase the overall efficiency, even though SDN efforts are deployed and thoroughly tested. More validations, in conjunction with new emerging technologies, may concrete a

more flexible architecture. For example, an SDN based ICN architecture for the satellite-terrestrial integration network is proposed in [269], which not only provide seamless communication and QoS, but also allow flexible resource utilization. It is believed that a general system model that is compatible with novel technologies can achieve the benefit most.

- **Integration of networks supported different protocols**

With regard to that services in the future will be heterogeneous, networks for communication, navigation, and remote sensing should cooperate to solve the problem of limited functioning ability in existing isolated information systems. For now, services mentioned above are solely supported by independent systems. To develop a communication network with the ability to fit numerous purposes, integration of protocols for different services should be ensured as it is the foundation for industrialization. For example, UAV is characterized as heterogeneous one in communication networks, as recently UAV is added to global capabilities, there are many aspects of software defined networking that will continue to unfold. UAV can be deployed with flexibility and take up lower cost for setting up. SDN can help provide a global view and allocate the UAV to the appropriate area. The combination of UAV and SDN is promising but more technical specifications should be considered when operator want to merge them into satellite-terrestrial networks. Indeed, SDN based UAV networks has better controllability and visibility for network components, especially in on-demand forwarding switches [270]. And in some disaster areas and battle filed, the quasi-stationary merit is suitable to provide a relatively stable network topology. Moreover, efficient resource utilization in such a scenario is extremely important because traffic demands are extremely high [271], [272]. When SDN-based UAV networks and satellites or terrestrial networks forge together, a scalable and compatible architecture of is needed to fit the complex environment in satellite-terrestrial networks for flexible, adaptable, and intelligent in the aspects of topology, bandwidth, and payloads.

It is necessary to unify the specifications of new technologies and novel data transmission schemes. For instance, how to apply the terahertz antenna or millimeter wave technology to the new satellite-terrestrial network? How to guarantee the transmission of remote sensing network data or navigation network data in communication networks? We believe that the action of integrating networks supported different protocols are full of importance and it is a trend for next generation communication networks.

- **Integration of service providing the ability for large scale geographical area**

Users in space, ground and sea should provide a guaranteed experience of services with their demands. The network in the future can support for all kinds of information systems. It should break through the barrier among space, aviation, terrestrial and maritime service domains by software-defined

collaborative network technology, transmission and forwarding technology.

A fundamental challenge here is that links in the air have very specific characteristics that may hinder the convergence of the networks. Different from terrestrial links, the long-distance satellite link is delicate to the atmosphere like rain and cloud, resulting in a loss or attenuation [273]–[275]. Besides, sometimes terminals in trees without LoS links can also receive the degraded signals [276]. One possible way to alleviate the situation is to use dynamic adaptive coding and modulation (ACM) according to the CSI feedback [277]. Techniques that vary the modulation and forward error correction (i.e. ACM) are regularly used to maximize both total throughput and individual link availability, which is implemented in the modems at each end of the link.

Site diversity techniques are developed to mitigate rain attenuation effects [278], [279]. However, in some extreme circumstances that the SINR is too weak for receiving, it is necessary to relay the information to regions where circumstances are suitable for transmission via other satellite or terrestrial nodes. Thus, the novel architecture with the controller entitled global view should be necessary.

When GEO satellites are utilized in the satellite-terrestrial networks, the relatively long latency (about 250ms) will bring drawbacks [277]. One typical problem is the long latency will hinder the TCP/IP protocol-based transmission. Many schemes had been proposed based on performance enhanced proxy servers which could provide data compression, pipeline requirement. Some schemes introduce LEO constellations into the architecture, since it can reduce the latency as 10ms [280]. However, mobility problems and Doppler frequency shifts should be considered as LEO satellites move fast. The other problem is that the long round-trip time will degrade the QoE of services like video streaming. One possible solution is to precache the popular content at the edge networks by GEO satellites' broadcasting or multicasting ability. Mobile edge computing, consisting of sending the "popular" content before the user requests it, can also conceal the delay issues.

Besides, in the next generation of satellite and terrestrial networks, especially in aerial-terrestrial networks [281], the lack of technical specifications restricts the practical implementation. Although innovations embed in the architecture can provide customized services which are required from devices, many legacy entities implement the protocols that don't support IPv6 and OpenFlow. A set of new technical specifications is urgently required to bring opportunities to the convergence of satellite-terrestrial networks.

B. TECHNOLOGIES

Innovations are always the trigger to boost the development of the communication network. Some technologies may take part in and play roles in enhancing the performance of networks.

1) MOBILE EDGE COMPUTING

New service models such as mobile edge computing (MEC) and fog computing architectures break the obsolete and limited framework of the cloud computing system. They bring computing and storage resources closer to the devices so that and high computing agility and low latency can be achieved [282], [283]. On-board processing technology enables satellite networks with more powerful communication abilities, equipped with the MEC server, we believe that the multi-level edge computing network can optimize the efficiency of network resource utilization, task distribution realizes intelligent scheduling of cross-domain network resources. More attention should be paid on the cooperation of mobile edge computing or fog computing task offloading and caching schemes.

(i) Task offloading and computing: MEC servers usually have limited computing resources compared with remote cloud servers. Therefore, an optimal cooperative offloading and computing scheme leveraging MEC servers distributed at the edge network should be carefully designed. MEC servers deployed in space network should have smaller amounts of computing resources than that on the ground according to the merits of the satellite. In this regard, the computing system that consists satellite-based edge computing network, terrestrial edge network, and remote cloud servers should be defined. We envision the schemes able to provide flexible computing structures and enhance service experiences.

(ii) Cooperative caching strategy: Another point should be taken into accounts is the impact on storage. Caching placement and content delivery are two themes included in the caching problem. Most works focus on ways to improve the hit rate of caching content and updating schemes that can improve efficiency. As satellite has large area coverage, these problems should be considered in the satellite and terrestrial networks with a cooperative view. Schemes combined with ICN and CDN give some insight to implement it. Besides, user behavior and social relationship [284] are also pivotal factors for effective caching. We strongly believe that the caching scheme in converged satellite-terrestrial networks should be more extensively investigated in the future.

2) MACHINE LEARNING

In satellite-terrestrial networks, the hybrid and heterogeneous network structure, sharply increasing communication traffic and dynamic social behaviors have undoubtedly made the related scientific issues complicated. It is difficult for conventional methods to make the computational decision on thousands of uncertain model parameters hidden in the massive service data sets.

To solve the problem, recently artificial intelligence (AI) which learns patterns from data is introduced to simplify the modeling procedure and identify parameters. Using machine learning (ML) approaches, which is typically divided as training phase and decision-making phase, a systematic problem

model with networking merits can be formulated cost-effectively. AI networking is useful in analysis of resource allocation and traffic control supporting heterogeneous distributed systems [68], [285]. Similarly, it should also be introduced into satellite-terrestrial networks as the resources distributed in the networks needs to be utilized efficiently.

One of the typical areas in satellite-terrestrial networks that can benefit from ML is wireless sensor networks. Processing massive data generated from different devices and IoT nodes in satellite-terrestrial communication networks is a challenge for conventional computational systems. To reduce the effort for annotating and analyzing these data, more intelligent schemes should be proposed with the help of machine learning or deep learning. Another area is CR in satellite-terrestrial network applications. The rapid dynamic environment for transmission brings challenges for predicting the accurate link statement. AI networking learning schemes need to be formed to implement performance monitoring and resource allocation prediction [286]. The application of ML needs to be considered in flow prediction, mobile prediction, data classification and intrusion detection in satellite-terrestrial networks.

C. OPEN ISSUES

1) NETWORK INTEROPERABILITY IN THE UNIFIED ARCHITECTURE

Network interoperability in a unified communication architecture composed of space-based networks, air-based networks, terrestrial networks even sea-based networks will greatly improve the efficiency and enhance the performance. Moreover, the requirements of the next generation communication network ask for novel solutions with flexibility.

Although existing works offer interoperability in the references of this section, they only account for networks which have satellite and terrestrial infrastructures. Also, the consideration of the mobility of users and entities in space networks is much needed since it may affect the adaptive dynamic data exchange scheme, for this reason, the hand over scheme is pivotal for fluent transmission.

For those information transmission tasks that happened in far remote areas in the mountainous regions or the ocean, DTN protocol is a proper way for interoperability in unified networks [287]. Besides, multicast encapsulation protocols in 5G-Xcast give the vision to deliver content cost-effectively at the scale across fixed and mobile networks [288].

Apart from these, traffic load balancing which relief the overload is also crucial in the new networks. Many new technologies have already emerged to solve the problem in terrestrial networks, for example, cache-enabled networks can improve power utilization and decrease the traffic delivery latency in backhaul [289]. More considerations should be required when MEC [290], which integrated computing, storage and communication abilities, is utilized in satellite-terrestrial networks.

Thus, we list some possible fields for improvements.

SDN Based Architecture With CR Technologies: A unified management and consideration is critical for the satellite-terrestrial network orchestration. However, the frequency band is limited and is valued for new communication devices. SDN based architecture with CR technologies are promising to solve the problem. There are many aspects of software defined networking that will continue to unfold as broadband LEO systems and UAV capabilities are also added to global capabilities and also 5G cellular systems deployed globally [57], [270]. At the same time, dynamic spectrum access and reduced energy consumption brought by CR would enhance the spectrum efficiency with the globe view of SDN. More attentions should be paid on this aspect and from the article we surveyed, how to implement the security method into the SDN based architecture with CR is a hurdle.

Marine IoT Application: Marine IoT is a vital application scenario in satellite-terrestrial networks. Marine IoT need to monitor the sea surface and underwater seabed, in the future, we strongly believe that these node may interconnect underwater communication networks and satellite-terrestrial networks. The shifting and floating characteristic of the nodes is a challenge for information collection, thus ships or satellite networks with DTN networks are thought to be an effective way for information collection [287].

2) MULTISCALE INFORMATION AWARENESS AND COMPUTING IN COMPLEX ENVIRONMENT

There exist many types of network entities in the satellite-terrestrial communication architecture, such as satellites, airships, UAVs, macro base stations, micro base stations and even aggregate nodes for IoT sensors in the sea. The scales related to information awareness of entities in different networks are varied from each other. It means that different nodes may percept different amounts of data. In addition, the information obtained by different network nodes is heterogeneous, so it is necessary to consider three questions in the complex environment: How to integrate the data in a unified way to facilitate the massive data processing? How to deploy computational computing hierarchy and how to match massive data processing with timeliness requirements? Considerations like data fusion technology [291], computing hierarchy, and data mining [292] should be required to deal with these problems.

Here we list some possible fields for improvements.

Artificial Intelligence (AI) With MEC Technology: Delineating the characteristic figures of users in satellite-terrestrial networks with accuracy is expected to affect the context-aware resource allocation method. Unfortunately, the social relationship of the user and complex environment is difficult to model [199]. AI with MEC technology are promising to solve the problem. What's more, as UAV is utilized in satellite-terrestrial networks, autonomous flying operation can be enhanced by computing ability from edge network with rather low latency. Deploying the MEC servers on satellites, base stations, and even air-based networks,

the satellite-terrestrial networks can be entitled with a multi-level edge computing structure. In the multi-level satellite-terrestrial edge computing network, MEC servers with intelligence distributed in different of networks can form different edge computing groups cooperatively, according to the customized services. Quite few work is found in the aspect and we believe it is a promising trend of satellite-terrestrial networks.

Unmanned Vehicle Applications: The latency and the ability of trajectory planning is critical for unmanned vehicle applications. As the service area of base station is limited, satellites with MEC server can help predict the traffic congestion of the road. At the same time, MEC servers on the base station help reduce the computing process and meet the requirement of URLLC. We believe that the cooperation of satellite-terrestrial networks with MEC servers will be a promising way to enhance unmanned vehicle applications.

Content Delivery With MEC Technology: Satellites' altitude could provide a global view for network operators, HTS satellites have already been used in content delivery. Thus, an optimal cache strategy can be developed with the help of satellite-terrestrial networks. With the computing ability of MEC server, the result of the appropriate content can be achieved. For example, video files can be cached in the MEC server, when the video is required, code transcoding can be completed by the server according to users' context.

X. CONCLUSION

Satellite-terrestrial networks are growing importance as next generation communication systems envision a ubiquitous reliable network architecture for various civil applications. To cater the demand of 5G architecture along with future network technological directions, the orchestration of satellite and terrestrial networks will be an inevitable trend. Satellite networks operating at high altitude can provide a large service area and LoS links to user equipment and ground stations, the broadcasting and multicasting ability can help reduce additional cost for that satellites can deliver required content simultaneously. However, the convergence of satellite networks and current terrestrial networks is a complicated problem. Features like high latency, rapid mobility, intermittent links, and resource constraints make satellite networks apart from other networks on the ground. Thus, more technical specification should be considered to integrate satellite and terrestrial networks.

This survey offers a comprehensive view of the current state and emerging trends of satellite-terrestrial networks. We aim to provide a broad view of the satellite-terrestrial networks convergence across dimensions from academia to industry, which is different from related existing surveys.

To this end, we first introduce the background of the satellite-terrestrial network convergence and give an overview of the subject. Motivations and the requirements of satellite-terrestrial networks are explored for better understanding the ideology of the cooperative network. In motivation part, we identify the advantages brought

by satellite-terrestrial network convergence. As satellite-terrestrial networks bring benefits to communication systems, to implement the convergence, requirements of service supporting ability, seamless coverage, orchestration management, and security are proposed. In order to effectively provide available knowledge of the convergence, key enablers in satellite networks are summarized to provide a general development view in space. These years space networks developed independently, fortunately some key enablers like SDN/NFV, CR, IoT and new satellites pave the way for the integration with terrestrial networks.

There have some typical satellite-terrestrial network architectures proposed these years, it is necessary to categorize existing architectures to provide a guidance for the next generation communication networks. Through the different architectures like SDN-based satellite-terrestrial networks, ICN-based satellite-terrestrial networks and CDN-based satellite-terrestrial networks, we provide a generic satellite-terrestrial architecture including space-based networks, air-based networks and terrestrial networks. SDN-based satellite-terrestrial networks decouple the control plane and data plane. With the help of NFV, the communication infrastructure distributed in heterogeneous networks can be managed in a unified orchestrator. It provides an efficient and flexible way for satellite and terrestrial network convergence. ICN based satellite-terrestrial networks and CDN based satellite-terrestrial networks are aim to avoid the frequency transmission of the same content and improve the content delivery efficiency. The fundamental difference of the two architectures is that ICN based architectures decouple the data and service from the actual devices storing, while CDN based architectures only utilize satellites to receive the content and "push" them to base station cache by broadcasting or multicasting.

After the classification of system architectures has been done, we concentrate on the technical issues of transmission, control and management, resource allocation and security in satellite-terrestrial networks. We discuss the main problems and make insights on challenges of related issues as communication networks evolves. Specifically, performance indicators are vital to evaluate a satellite-terrestrial networks. Thus, performance evaluation of three typical networks, i.e. (i) Satellite-terrestrial backhaul networks, (ii) Hybrid satellite-terrestrial cooperative systems (HSTCS) and (iii) Cognitive hybrid satellite-terrestrial networks (CHSTN) are provided. In satellite-terrestrial backhaul networks, the goal is to transmit information efficiently, then traffic load, round trip time, and download time are taken as key performance indicators. For HSTCS, it is essential to evaluate the performance of cooperative system that the terrestrial relay nodes help to enhance the satellite transmission with diversity technology. With this regard, indicators like outage probability, symbol error probability, ergodic capacity are often utilized. As to CHSTN, the scheme for users to enhance the frequency efficiency is a vital part, thus outage probability usually gets the researchers' interest.

In industrialization and application aspect, first we explore related technical reports and technical specifications proposed by 3GPP and ETSI. Then some research and development projects are listed because of the significant guidance for utilization. These pioneer projects redefine the industry. The emulations of these projects provide significant importance in meeting critical reliability and performance requirements for services in the future. We pick out four application areas, which are public protection and disaster relief, forest fire monitoring, smart grid and health, to illustrate that satellite-terrestrial networks may affect deeply. As satellite-terrestrial networks evolve, we believe more services and application can be served by satellite-terrestrial networks.

Finally, future directions are identified from the perspective of architecture and technology. The importance of software defined networking is critical to the future of digital communications over satellite and terrestrial networks. Besides, MEC and ML are two promising technologies to enhance the satellite-terrestrial networks. MEC technology helps send resources to the edge and reduce the workload of the communication system. And ML can be utilized to solve problem model formulation in complex environment. Open issues, including network interoperability and multi-scale information awareness and computing, are analyzed and illustrated. We hope that the comprehensive review of satellite-terrestrial can give insights into the future development of satellite-terrestrial networks. More works in satellite-terrestrial networks with open research issues will be done and We believe that satellite-terrestrial networks will be a vital pillar of the new era of communication networks.

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