Integrated Satellite-Terrestrial Networks Toward 6G: Architectures, Applications, and Challenges

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***Abstract*—With the increasing global communication demands and the development of Internet of Things (IoT), extending the connectivity to rural and remote areas has become imperative for future networks. The sixth-generation (6G) network is expected to provide heterogeneous services and seamless network coverage for everyone and everything. Combining the advantages of both satellite and terrestrial networks, the integrated satellite-terrestrial network architecture is promising to provide global broadband access for all types of users, which has drawn much attention from both the academia and industry. In this article, we present a comprehensive survey of the state-of-the-art of integrated satellite-terrestrial networks toward 6G. First, an executive classification and summary of the integration architecture is presented from network design to performance optimization. Then, typical applications of the integrated satellite-terrestrial network are discussed based on the architecture. By considering the unique characteristics of the two networks, main challenges are pointed out when performing integration, such as the long propagation delay, complex link conditions, and high dynamics of the network topology. Finally, some promising future techniques are explored from the perspective of the integrated architecture. A detailed survey of the potential integration architectures is of great importance to enable more flexible network design and construction in future 6G networks. This article will provide a valuable guideline on future research and development of integrated satellite-terrestrial networks.**

***Index Terms*—Cooperative transmission, integrated satellite-terrestrial networks, Internet of Things (IoT), sixth-generation (6G).**

I. Introduction

FROM the first generation (1G) wireless network to the fourth generation (4G) wireless network, terrestrial wireless networks have proved a great success for the enhancement in communication speed and the Quality of Service (QoS) [1]. By means of mobile phones or other intelligent terminals, broadband services of low latency can be acquired within the coverage of terrestrial base stations (BSs). However, considering economic benefits, terrestrial networks are mainly deployed for developed areas, and areas of high-density populations [2], which is the same with the fifth-generation (5G) wireless network. Moreover, for geographic constraints, the vast airspace and sea area cannot be covered by terrestrial networks. As a matter of fact, when it comes to connecting everyone and everything in the 6G wireless network [3], a more urgent need is coverage, instead of only intensity. It has been witnessed that the 6G wireless network would penetrate into a wide range of applications, such as industry, transportation, and energy [4]. The connection would commonly happen among humans, machines, and things in a vast area. Especially, with the increasing development of Internet of Things (IoT), the number of IoT devices would reach more than 24 billion by 2030 [5], for which ubiquitous communication coverage is crucial to support the widely distributed devices. Extending the connectivity to the rest areas has become imperative to move forward for future communication networks.

Satellite communication networks provide a direct solution for the coverage issue with the wide coverage ability [6]. In the past decades, due to the high construction cost and limited communication capacity compared with traditional terrestrial networks, large-scale satellite communication networks have not been successfully deployed [7]. However, with the increasing communication demand and also the advances in communication technologies, achieving global coverage with satellite constellations has now become a hotspot for both the academia and industry. Various satellite constellation projects have been established to construct satellite communication networks for global coverage, such as Starlink, OneWeb, and Telesat [8]. On the other hand, conventional terrestrial networks cannot be replaced for providing low-cost and high-speed services when covering densely populated areas. Thus, combining the advantages of both satellite and terrestrial networks, the integrated satellite-terrestrial network architecture is promising to provide global broadband access, enabling ubiquitous network service [9]. In the 3rd generation partnership project (3GPP) Rel-15, Rel-16, and Rel-17, 3GPP has studied the integration of terrestrial networks and nonterrestrial networks [10]–[12]. With the wide coverage ability, nonterrestrial networks are expected to provide service for areas that cannot be covered by terrestrial networks, ensure service continuity, and also provide efficient multicast/broadcast transmission. In the White Paper of the 6G wireless network, it has been proposed that the future wireless network must be able to seamlessly interface with terrestrial and satellite networks [13]. The integrated satellite-terrestrial network is the

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new development trend for the next generation communication network [14].

In current communication systems, satellite networks, and terrestrial networks are developed and operated separately [15]. Although much attention has been paid to the integrated satellite-terrestrial network, how to integrate the two networks remains an open issue. Up to now, plenty of works have focused on the integrated architecture of the two networks from simple integration to deep cooperation. For example, terrestrial relays can be integrated to help forward satellite signals when the direct links of satellites are unavailable due to the masking effect [16]. In areas without connection of optical fiber, satellites are considered to provide backhaul transmission for terrestrial BSs or other access points [17]. Also, for improving spectrum efficiency, dynamic utilization of spectrum resources can be enabled in the two networks by using the technique of cognitive ratio (CR) [18]. By exploiting the cooperation of satellite and terrestrial networks, cooperative global coverage can be realized with the converged architecture [19]. Moreover, the two networks can be operated in a deep cooperation mode to provide enhanced transmission for ground users [20]. Combining the advantages of both the networks, the integrated satellite-terrestrial network architecture can help to increase network reliability, expand network coverage, improve resource efficiency, ensure service continuity, and provide enhanced transmission, which will be discussed in more detail in Sections III and IV. However, as a novel architecture, the integrated satellite-terrestrial network is challenging due to the unique characteristics of the two networks [21]. The long propagation delay, complex link conditions, and high dynamics of network topology need to be addressed when performing the integration. Also, different from a traditional single network, integrated mobility management, routing, offloading, and resource management of the two networks bring new problems that cannot be solved by existing methods. Therefore, elaborate network design and integration techniques are of great importance to optimize the performance of the integrated satellite-terrestrial network.

As an important direction of widespread concern, there have been some survey articles on satellite-terrestrial networks in recent years. Niephaus *et al.* [22] investigated the QoS provisioning problem in the integrated satellite-terrestrial network, where the satellite network was converged to provide supplementary connection in parallel to terrestrial links. In [23], the state-of-the-art of the space-air-ground integrated network was surveyed. Comprehensive reviews of physical layer characteristics, mobility management, system integration, and applicability issues were presented. Yao *et al.* [24] discussed the main challenges and techniques when integrating the extended space network with mobile wireless networks to provide seamless coverage. Di *et al.* [25] surveyed the backhaul issues in the integrated satellite-terrestrial network, in which the satellite was utilized to provide backhaul transmission for satellite-based small cells. In [26], from the two perspectives of unicast transmission and multicast transmission, the cooperative transmission architecture in integrated satellite-terrestrial networks was investigated. In [27], the major use cases for integrated satellite-terrestrial networks were presented. The satellite network was introduced into the 5G network to enhance the network reliability, to guarantee the service ubiquity, and to enable the service scalability. In [28], the hybrid satellite-terrestrial network for maritime communication was surveyed. Three types of enabling technologies were discussed in depth to provide broadband maritime communications, including enhancing transmission efficiency, extending network coverage, and provisioning maritime-specific services.

In the existing surveys discussed above, they all only focused on one certain architecture or one certain application scenario for integration of satellite and terrestrial networks. Since how to integrate the two networks remains an open issue, various integration architectures and application scenarios have been proposed from simple integration to deep cooperation. However, a comprehensive survey and analysis is still missing. Especially, considering different communication scenarios, different integration architectures may be applied for distinct purposes. Then, specialized techniques need to be developed according to the integration architecture. A detailed survey of all the potential integration architectures is of great importance to enable more flexible network design and construction in future communication systems. In this article, we are the first to present a comprehensive survey of the state-of-the-art of integrated satellite-terrestrial network architectures toward 6G, based on which we discuss the typical application cases, main challenges, and future techniques with respect to different architectures. The main contributions of this article are summarized as follows.

1) We present an executive classification and summary of the integrated satellite-terrestrial network architectures from network design to performance optimization. The integrated satellite-terrestrial network architecture is promising to provide global broadband access for all types of users. A detailed survey of all the potential integration architectures is of great importance to enable more flexible network design and construction in future 6G networks.
2) We provide a conclusion of the typical application cases for the integrated satellite-terrestrial network based on the integration architecture, including rural coverage, sea area communication, airborne communication, emergency communication, and multicast/broadcast transmission.
3) We analyze the main challenges for the integrated satellite-terrestrial network from the perspective of future network deployment. Due to the unique characteristics of the two networks, the integration brings new problems that cannot be solved by existing methods.
4) We give a presentation of the possible techniques and future directions in the integrated satellite-terrestrial network. Novel and revolutionized techniques that fit within the integration architecture are discussed, in which full cooperation of the two networks is exploited to improve the system performance.

The remainder of this article is organized as follows. In Section II, we introduce the existing network and development tendency as the background knowledge. In Section III, we give a comprehensive conclusion of the proposed satellite-terrestrial architectures in existing works, based on which the typical application cases for the integrated satellite-terrestrial network are discussed in Section IV. In Section V, we analyze the main challenges for the integrated satellite-terrestrial network from the perspective of future network deployment. Then, in Section VI, we give a presentation of the possible techniques and future directions in the integrated satellite-terrestrial network. Finally, Section VII concludes this article.

II. Background

A. Terrestrial Networks

Terrestrial cellular networks are now widely deployed for the great success in wireless communication, providing services for billions of people worldwide. During the past decades, terrestrial cellular networks have experienced rapid development from the 1G wireless network to the 4G wireless network. To meet the global increasing demand of mobile data traffic, terrestrial networks are now evolving toward the 5G wireless network, which is designed to support higher data rates, lower latency, larger connectivity, and improved QoS [29]. With the technologies of massive multiple-input multiple-output (MIMO), dense heterogeneous networks (HetNets), millimeter wave (mmWave) communication, etc. Luong *et al.* [30], the 5G wireless network is expected to increase the data rates by ten times, and reduce the latency by ten times. The following three cases are proposed as the main application scenarios of 5G [31].

1) *Enhanced mobile broadband (eMBB)*, which is designed for the human-centric application scenario with ultrahigh transmission data rates and mobility guarantees under wide coverage.
2) *Ultrareliable and low latency communications (URLLC)*, which is designed for high-reliability and low-latency communications, such as automatic drive, industrial control, telemedicine, and other special applications.
3) *Massive machine-type communications (mMTC),* which is designed to support large-scale access with low data rates and latency requirements, such as smart cities, environmental monitoring, and other special applications.

Then, with the deployment of the 5G wireless network, the beyond 5G (B5G) network is expected to further improve the data rate, expand the communication space, and improve the communication intelligence in the next decade [32].

B. Satellite Networks

Based on the top-down nature of the satellite, satellite networks are able to provide services for wide areas. With the development of satellite networks, the satellite services have evolved from conventional voice and broadcasting services into broadband Internet services [33]. Considering different service types, the users can be mobile users, buildings, airplanes, ships, emergency BSs and also other satellites [34]. According to the altitude of orbits, the satellite around the earth can be classified into geosynchronous earth orbit (GEO) satellites, medium earth orbit (MEO) satellites, and low earth orbit (LEO) satellites [6].

1) *GEO satellites* are operated on the fixed orbit of 36 000 km. GEO satellites can provide the most comprehensive coverage because of the high altitude. However, the high altitude also leads to large propagation delay and signal attenuation, which brings high requirements for antennas to communicate with GEO satellites. Also, since the altitude of GEO satellites is fixed, the orbit resources of GEO satellites are limited. With the development of satellite networks in the past decades, the GEO orbit resources are almost exhausted.
2) *MEO satellites* are generally operated on the orbit between 2000 and 36 000 km. MEO satellites have the advantages of both GEO and LEO satellites. The propagation delay and signal attenuation of MEO satellites are smaller than those of GEO satellites while the coverage is larger than LEO satellites. Also, since the altitude of MEO satellites is not fixed, the MEO orbit resources are relatively sufficient.
3) *LEO satellites* are generally operated on the orbit between 500 km and 2000 km. Thanks to the low altitude, the propagation delay and signal attenuation of LEO satellites are much smaller than those of GEO and MEO satellites. Thus, achieving global broadband access to the Internet by LEO satellite constellations is feasible and promising. Also, since the altitude of LEO satellites is not fixed, the LEO orbit resources are relatively sufficient.

Generally, services in satellite networks are divided into fixed satellite services (FSS) and mobile satellite services (MSS) [35]. In FSS, satellite users communicate with satellites by fixed devices on the ground. Since mobility is not considered for FSS, large antennas can be equipped in FSS systems. Thus, FSS is the type of service provided by most conventional communication satellites, especially for GEO satellites providing services, such as VSAT communication and television broadcast. In MSS, satellite users communicate with satellites by portable mobile devices, which can be deployed on cars, ships, airplanes, or individual users. Since the antenna size is limited in MSS systems to ensure mobility, LEO satellite networks are more suitable for MSS with relatively smaller signal attenuation.

C. Existing/Future Satellite System

Due to the top-down nature, satellite networks are able to provide global coverage with relatively low costs, which is infeasible in terrestrial networks for both economic and geographic constraints [36]. In the past decades, several satellite systems were constructed and applied for global communications. Following are the typical existing satellite networks.

1) *O3b* is an MEO satellite network operated by O3b Networks [37]. The name of O3b means “the other

3 billion," which represents the goal of the O3b satellite system, providing coverage for the other three billion users without Internet access. The first-generation system consists of 12 MEO satellites on the orbit of 8000 km, mainly covering the area between 45 north latitude and 45 south latitude. The coverage area of O3b is divided into seven regions, with ten user beams in each region, and the total number of user beams is 70 with 12 satellites.

2) *Iridium* is an LEO satellite network operated by Motorola [7]. The first-generation system consists of 66 LEO satellites in six orbit planes on the orbit of 780 km. Each Iridium satellite is equipped with multi-beam antennas, and can support on-board processing, switching, and routing. Also, each satellite is equipped with four intersatellite links (ISLs), which guarantees that the entire process of satellite communication can be achieved by one gateway. The Iridium network mainly provides global personal communication services for handheld mobile phone users.
3) *Globalstar* is an LEO satellite network operated by Loral Corporation and Qualcomm [38]. The system consists of 48 LEO satellites in eight orbit planes on the orbit of 1400 km. The system mainly covers the area between 70 north latitude and 70 south latitude. Each service area is always covered by two to four satellites, and users can access the system at any time.

The existing satellite networks in the past decades did not work well in the communication market. Most of these satellite networks eventually went bankrupt due to the high construction costs. Recently, driven by the development of Internet applications, micro-satellite manufacturing and low-cost launch technologies, satellite Internet is proposed to enable global access of the Internet via satellite networks. The typical proposed satellite projects include Starlink, OneWeb, and Telesat [8].

1) *Starlink* is an LEO satellite network proposed by SpaceX [39]. The Starlink network is designed to provide global high-speed Internet access by nearly 42 000 LEO satellites on different orbits from 340 km to 1150 km. Each satellite can support a transmission capacity of 20 Gb/s using the Ka-band, Ku-band, and V-band. By July 2021, SpaceX has launched more than 1700 satellites, providing communication service for ninety thousand users in dozens of countries.
2) *OneWeb* is an LEO satellite network proposed by OneWeb [40]. The OneWeb network consists of 648 LEO satellites in 18 orbit planes on the orbit of 1200 km. The transmission capacity of each satellite is up to 7.5 Gb/s using the Ka-band and Ku-band. The OneWeb network adopts the simple design of transparent forwarding to directly provide users with Internet access services through ground gateways. By September 2021, OneWeb has launched more than 300 satellites, and full global commercial coverage is expected by 2022.
3) *Telesat LEO* is an LEO satellite network proposed by Telesat [41]. The Telesat LEO network consists of 300 LEO satellites on the orbit of 1000 km, which includes both the polar and inclined orbits to balance global coverage and capacity density. The total capacity of the network will be more than 1 Tbps using the Ka-band. Currently, Telesat has launched the phase one LEO, and the global service is expected to begin by 2022.

D. 6G-Integrated Networks

Although the 5G network promises higher data rates, lower latency, larger connectivity, and improved IoE, there are still many challenges remaining unsolved. To date, including the 5G network, the development of wireless networks mainly focuses on increasing the communication rates based on the terrestrial cellular architecture. However, simply pursuing high communication rates cannot support the future demands for the Internet of Everything (IoE) system [42]. For massive IoT in future networks, the 5G network will gradually reach its limitations and be unable to provide satisfactory communication support [43]. Also, for both economic and geographic constraints, terrestrial networks are mainly deployed in developed areas such as urban areas. There are still large numbers of populations and devices remaining unconnected even after the construction of the 5G network [44]. Extending the connectivity to the rest areas is of great importance for the next generation communication network. With the deployment of the 5G network, research on the 6G wireless network comes into focus to overcome these unsolved challenges. The International Telecommunication Union (ITU) has built the group of Network 2030 for developing the next generation wireless network. China has established the project to study the 6G wireless network for 2030 and beyond [45]. In September 2019, the 6G White Paper was released based on the first 6G Wireless Summit in Finland [13], which clarifies the basic direction of 6G development.

The development targets of the 6G network are shown in Fig. 1(a) [13]. The peak data rate is expected to reach 100 Gb/s to 1 Tbps, which is 10 to 100 times larger than the 5G network. The ratio latency is expected to decrease to 0.1 ms, which is only a tenth of the 5G network. Also, other targets include higher positioning accuracy, higher energy efficiency, extreme ultra reliability, larger connectivity density, and longer battery life time. Beyond the three main scenarios of eMBB, URLLC, and mMTC in the 5G network, new application scenarios are proposed for the 6G network [46], [47]. In [46], three new scenarios were discussed: 1) ubiquitous mobile ultrabroadband (uMUB); 2) ultrahigh-speed-with-low-latency communications (uHSLLC); and 3) ultrahigh data density (uHDD). Especially, in the uMUB scenario, by integrating satellite networks with terrestrial networks, ubiquitous coverage is expected in the 6G network.

In the 6G White Paper, it has been proposed that the future wireless network must be able to seamlessly interface with terrestrial and satellite networks [13]. Furthermore, the 6G Flagship has published a new White Paper on the connectivity of remote areas recently [48]. It was proposed that 6G is expected to be the first generation to solve global connectivity challenges. Due to the high costs of terrestrial networks, satellite wireless backhaul transmission

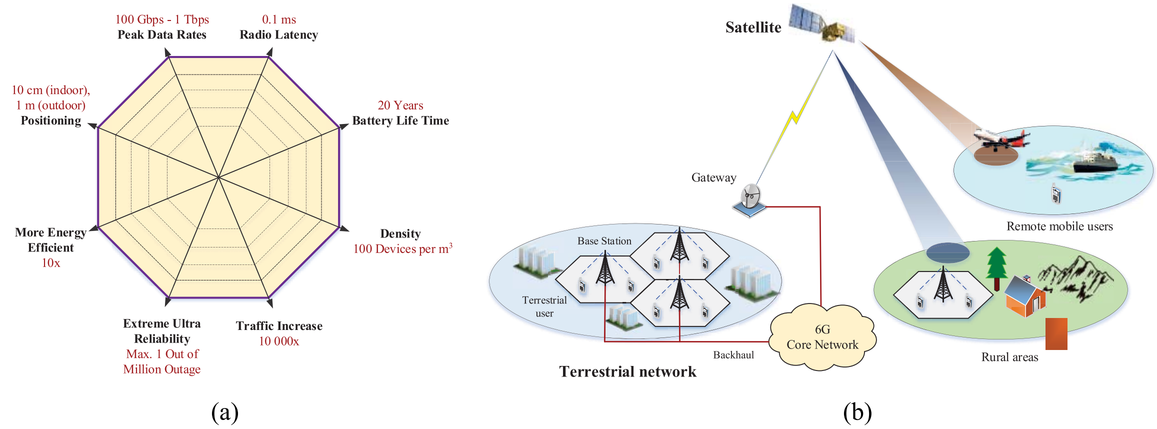

Fig. 1. 6G targets and integrated network architecture. (a) 6G targets. (b) Integrated network architecture.

is considered for rural and remote areas in 6G. Also, nonterrestrial networks, in particular satellite networks, are proposed to be integrated with terrestrial networks in early 2030s. The integration architecture is expected to overcome the limitations of conventional communication networks, and find the new development path toward ubiquitous 6G communication.

Combining the advantages of both the networks, the integrated satellite-terrestrial network architecture is promising for the 6G network to enable global coverage and Internet access [49], [50], and provide ubiquitous communication support for IoT systems [51]. As shown in Fig. 1(b), the integrated network consists of the conventional terrestrial networks and also the satellite for extension of the coverage. The terrestrial network provides broadband services for developed areas based on cellular networks, in which the BSs are linked to the core network by backhaul links. With the wide coverage, the satellite can extend the connectivity to everyone and everything in rural and remote areas. For users out of the coverage of terrestrial networks, they can access the satellite network by their own terminals, which may be capacity-limited based on the type of users and terminals. Also, satellite-based BSs and access points can be deployed to provide relative broadband service, while users can access the BSs and access points for communication based on 6G or Wi-Fi technologies.

The coverage of the integrated satellite-terrestrial network is mainly guaranteed by the wide coverage ability of the satellite. For GEO satellites on the orbit of 36 000 km, global coverage can be achieved by only three satellites. For MEO and LEO satellites on lower orbits, dozens of satellites are generally required to construct the global satellite communication network, such as the O3b network and the Iridium network. With the increasing communication demand and also the advances in communication technologies, a large number of satellite constellation projects have been established, such as Starlink, OneWeb, and Telesat. By 2030, there will be tens of thousands of satellites around the earth, based on which global broadband coverage can be guaranteed. Then, various types of users can access the integrated satellite-terrestrial network via different integration architectures.

III. Integration Architecture

The integrated satellite-terrestrial network architecture shows great potential in future wireless networks. By now, there have been a large number of works that studied the possible integration architectures of the two networks. In this section, we give a comprehensive conclusion of the proposed satellite-terrestrial architectures in existing works. Compared with the conventional single network architecture, the integrated satellite-terrestrial network architecture can first help to increase network reliability by introducing terrestrial relays into satellite networks, which is discussed in Section III-A. Second, the integrated satellite-terrestrial network architecture can help to expand network coverage based on satellite backhaul transmission, which is discussed in Section III-B. Third, the integrated satellite-terrestrial network architecture can help to improve resource efficiency with spectrum sharing, which is discussed in Section III-C. Fourth, the integrated satellite-terrestrial network architecture can help to ensure service continuity and provide enhanced transmission based on the cooperation of the two networks, which is discussed in Section III-D. Finally, the integration of the satellite network, the air network, and the terrestrial network is further discussed in Section III-E.

A. Hybrid Satellite-Terrestrial Relay Networks

In satellite networks, the communication links between the satellite and users are unstable due to rain/fog attenuation, poor elevation angles, and obstacles, which may lead to the masking effect between the satellite and users. In this case, the direct links from the satellite to users will be unavailable, resulting in a communication outage for the satellite users. To overcome the masking effect in satellite networks, the hybrid satellite-terrestrial relay network (HSTRN) is proposed by introducing terrestrial relays into satellite networks [16].

1) Basic Relay Architecture: The basic architecture of the HSTRN is shown in Fig. 2(a). In the HSTRN, there is no direct link from the satellite to the user due to the masking effect. The satellite transmits the signal to the user with the help of the terrestrial relay. The total transmission process will consist of two phases. In the first phase, the satellite transmits the desired

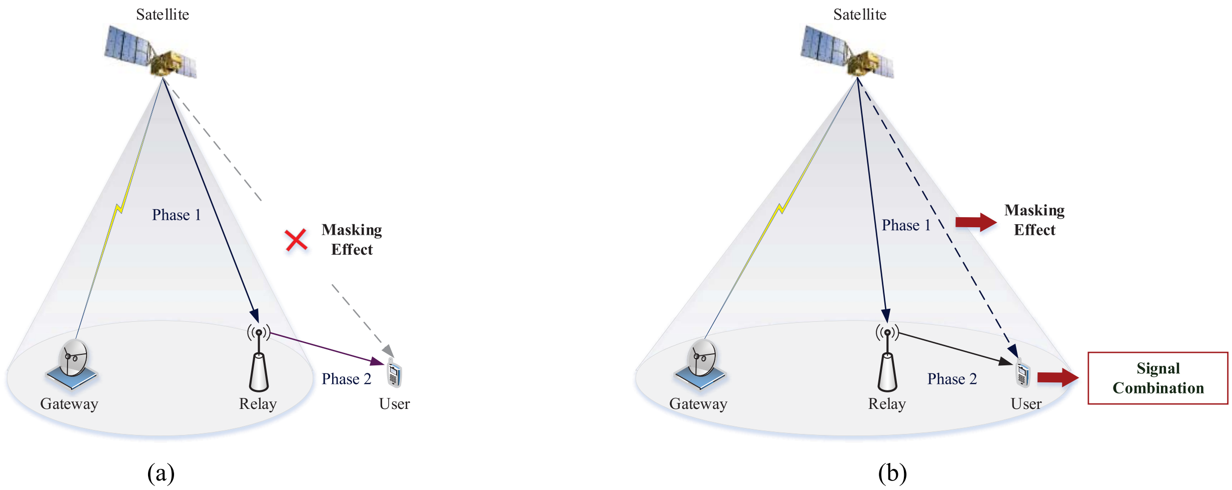

Fig. 2. Architecture of HSTRNs. (a) Basic relay architecture. (b) Cooperative relay architecture.

signal to the terrestrial relay. Then, in the second phase, the terrestrial relay forwards the received signal to the satellite user via the terrestrial link. With the help of the terrestrial relay, the satellite user can communicate with the satellite even when the direct link is masked, which increases the system stability. However, traditional terrestrial cellular networks are not integrated into the system, which limits the application and extension of this architecture.

Generally, two types of forwarding protocols are utilized for relay transmission, the amplify-and-forward (AF) protocol, and the decode-and-forward (DF) protocol. In the AF protocol, the relay simply amplifies and forwards the received signal to the user [52]. Thus, the noise in the first phase will also be amplified and transmitted to the user. In the DF protocol, the relay will decode the satellite signal in the first phase, and then transmits the desired signal to the user in the second phase [53]. Although the communication noise can be reduced in the DF protocol, it is of higher complexity and the relay process is limited by the satellite-relay channel. If the relay cannot decode the source signal, it will make no contribution in the network.

The basic architecture of the HSTRN was studied in [16] and [52], in which one relay and one user were considered. The average symbol error rate (SER) was analyzed for the HSTRN. Then, in [54] and [55], the case of multiusers was studied for the HSTRN. The ergodic capacity was analyzed with the selection of the best relay user. Especially, the technique of nonorthogonal multiple access (NOMA) was applied to the multiuser HSTRN in [56]–[59], in which the outage probability and the ergodic capacity were analyzed for users in the NOMA group. In [60] and [61], the HSTRN was extended to multirelays. The relay selection schemes were investigated for improving the outage and capacity performance of the system. Furthermore, the case of multiusers and multirelays was discussed in [62] and [63], in which the combined user-relay selection schemes were studied to improve the system outage performance. In [64], a distributed Q-learning scheme was proposed for joint relay selection and access control in IoT-oriented satellite-terrestrial networks. While the literature above only considered the transmission from the satellite to users via relays, the two-way transmission in the HSTRN was investigated in [65] and [66]. The satellite and the user can communicate with each other via the two-way relay, and the outage performance was analyzed for the two-way transmission.

2) *Cooperative Relay Architecture:* In the basic architecture of the HSTRN, the direct link from the satellite to the user is not considered for the masking effect. Taking both the masked direct link and the relay link into consideration, the HSTRN can be extended to the cooperative architecture as shown in Fig. 2(b) [67]. The total transmission process also consists of two phases. In the first phase, the satellite broadcasts the desired signal to the terrestrial relay and also the user. In the second phase, the terrestrial relay forwards the received signal to the satellite user via the terrestrial link. Similarly, both the AF protocol and the DF protocol can be applied. Then, the user can combine the signals received in the two phases by techniques such as maximum ratio combining (MRC), which is generally utilized to combine multiple received signals to maximize the received signal-to-noise ratio (SNR). With the help of the terrestrial relay, spatial diversity can be exploited at the satellite user, which improves the system performance when the direct link is masked.

The cooperative architecture of the HSTRN was studied in [67], in which the SER performance was analyzed for the case of one relay and one user. In [68] and [69], multirelays were considered for cooperative transmission, in which the user combines the signal from the satellite and the signals from multiple relays to achieve higher diversity orders. Bit error rate (BER) and SER performance were then analyzed by adopting the MRC technique for signal combination.

B. *Satellite-Terrestrial Backhaul Networks*

For both economic and geographic constraints, conventional terrestrial networks cannot achieve 100% coverage, especially for the populations and devices in rural and remote areas. The key obstacle that prevents these areas from being

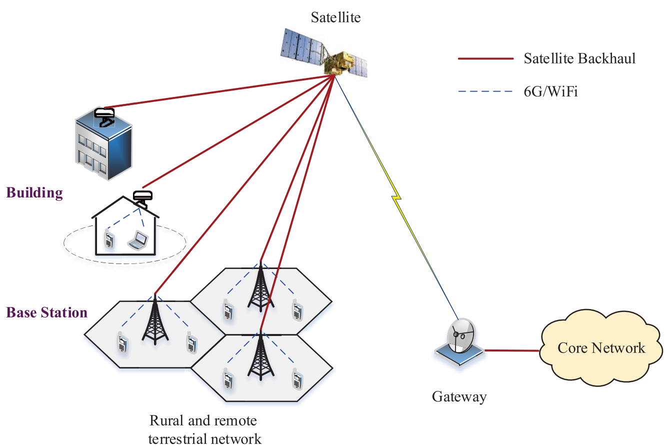

Fig. 3. Architecture of STBNs.

connected is the construction of backhaul links. Deploying optical fiber backhaul links in these areas is inefficient and uneconomic [70]. Fortunately, the wide coverage of satellites provides an alternative for establishing backhaul links in these areas. As shown in Fig. 3, the architecture of the satellite-terrestrial backhaul network (STBN) can be applied for rural and remote areas [17]. In the STBN, the terrestrial network is constructed with BSs and building-based access points. Then, the ground users access the BSs and access points for communication services based on 6G or Wi-Fi technologies. Differently, the BSs and access points in rural and remote areas are linked to the core network by satellite backhaul links. For the terrestrial network of small scale, each BS and access point may establish the backhaul link separately. For the terrestrial network of large scale, a terrestrial gateway with antenna farms may be deployed to establish satellite backhaul links. Then a WLAN can be constructed in this area, in which the BSs and access points are linked to the terrestrial gateway by optical fiber for backhaul transmission [71]. Also, by deploying BSs that support the communication protocol of the existing terrestrial networks, the coverage of the existing terrestrial networks can be extended based on the STBN architecture. With the help of terrestrial BSs, users can access the satellite network with traditional terrestrial communication devices. The large numbers of existing terrestrial communication devices can be integrated into the system. However, since additional BSs designed for satellite backhaul transmission need to be deployed for communication in rural and remote areas, the coverage area is still relatively limited due to economic and geographic constraints.

Generally, fixed antennas of large sizes can be deployed at the BSs and access points, by means of which broadband communication services can be accessed for mobile users with portable devices. However, different from the fixed backhaul transmission in conventional terrestrial networks, the fast-periodic motion of satellites results in a dynamic time-varying feature of the STBN, which further leads to frequent changes in the connectivity of satellite-terrestrial links. More efficient and reliable technologies need be applied to improve the backhaul capacity and enhance the link stability, such as spatial multiplexing, spectrum sharing, and robust beamforming. Also, since the wireless backhaul link of the satellite is shared by the large numbers of BSs within the coverage, dynamic traffic offloading, and load balancing technologies are of great importance, considering the uneven service distribution in the integrated satellite-terrestrial network.

In [72], the STBN architecture was studied by using satellite networks as the high-speed backbone network for terrestrial networks in less-developed areas. The connection between terrestrial networks and satellite backbones is enabled by the entity of interworking gateways. A comprehensive analysis of the STBN in the 5G network was given in [17] and [73]. By overcoming the constraints of conventional fixed backhaul, the STBN can extend the 5G network to rural and remote areas, achieving ubiquitous coverage for ground users. In [74], the STBN architecture was considered to collect data of IoT devices, while the completion time was optimized among satellite beams. In [75], the STBN architecture was discussed for disaster recovery in emergency scenarios. In disasters, such as earthquakes and hurricanes, the terrestrial infrastructure with optical fiber links may be destroyed. Then, the satellite backhaul links can be used to restore emergency communication. Considering limited satellite backhaul capacity, the backhaul allocation and data offloading problem was investigated in [76]. The system total data rate and the user capacity were maximized with LEO satellite backhauls. In [77], an adaptive coding transmission scheme was proposed for the STBN. The proposed scheme can significantly improve the system throughput when using GEO satellites for backhaul transmission.

C. Cognitive Satellite-Terrestrial Networks

Due to the increasing demand of broadband communication services, spectrum resources are always insufficient for both satellite and terrestrial networks. In addition to exploit higher frequency bands, such as mmWave and terahertz, improving the spectrum efficiency of existing spectrum resources by spectrum sharing is another promising method [78]. Thus, the technique of CR was proposed to enable dynamic utilization of spectrum resources among networks [79]. With the development of satellite-terrestrial networks, the CR technique is also applied to satellite-terrestrial networks. The cognitive satellite-terrestrial network (CogSTN) is investigated to make full use of the spectrum resources [80].

1) Basic Cognitive Architecture: The basic architecture of the CogSTN is shown in Fig. 4, which is composed of the primary satellite network and the secondary terrestrial network. The primary satellite network owns the license of the spectrum resource, and is free to transmit at any time. The secondary terrestrial network shares the licensed spectrum with the primary network, but it can only transmit when it does not affect the normal operation of the primary network. By sharing the spectrum resource between the two networks, higher spectrum efficiency can be achieved, alleviating the pressure of scarce spectrum resources. However, existing infrastructures need to

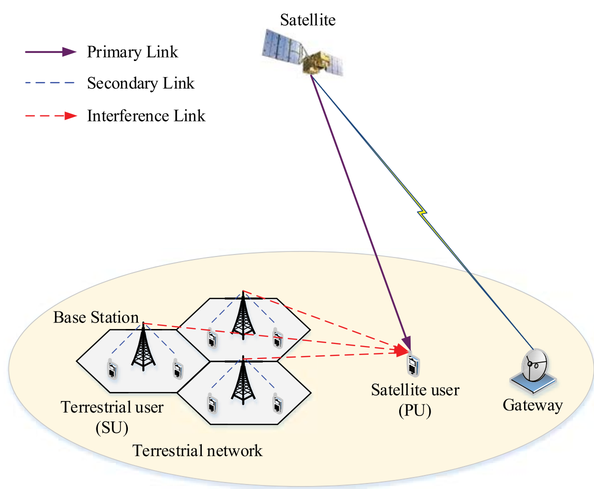

Fig. 4. Architecture of CogSTNs.

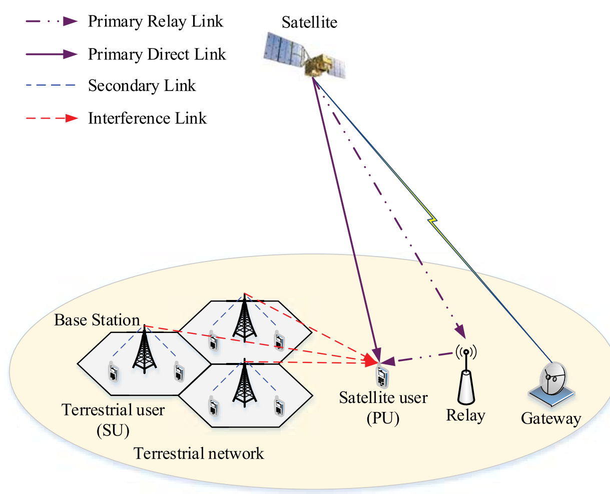

Fig. 5. Architecture of CogSTRNs.

be updated to support the different frequency bands in conventional satellite and terrestrial networks. Also, cooperation of satellite and terrestrial operators is required for interference mitigation and more efficient resource management.

The CR techniques can be mainly divided into three modes: 1) underlay; 2) overlay; and 3) interweave [81]. Due to the high spectrum efficiency and easy implementation, the underlay mode is more attractive and widely studied for the CogSTN in existing works [82]–[84]. In the underlay mode, the secondary network is allowed to share the licensed spectrum with the primary network simultaneously, as long as the interference caused to the primary network does not affect the normal operation of the primary network. In the overlay mode, the secondary network helps to improve the transmission of the primary network while also transmits its own data with the spectrum. The interweave mode was discussed for the CogSTN in [85], in which the secondary network is allowed to transmit when the licensed spectrum of the primary network is idle.

In Fig. 4, the satellite network is considered as the primary network while the terrestrial network is considered as the secondary network [86], [87]. However, both the satellite network and the terrestrial network can be the primary network and also the secondary network. When the terrestrial network is considered as the primary network, the satellite secondary network shares the licensed spectrum of the terrestrial network [88], [89]. The satellite network can transmit when it does not affect the normal operation of the terrestrial network.

To mitigate the interference caused to the primary network, efficient resource allocation strategies are important in the CogSTN. In [90], the joint power and subchannel allocation strategy was investigated considering both the efficiency and fairness. The interference caused by the satellite secondary network was constrained by the maximum tolerable outage probability of primary terrestrial network. In [91], the beamforming design, as well as the allocation of carrier, power, and bandwidth in the CogSTN were investigated. To reduce the signal overhead from global information collection, a noncooperative game with limited information exchange was proposed for optimal power allocation in the CogSTN [92]. The system throughput was maximized while guaranteeing the minimum received signal-to-interference-plus-noise-ratio (SINR) of the primary satellite network.

Also, the concept of exclusion zones was introduced into the CogSTN to mitigate the interference caused by spectrum sharing [93], [94]. The exclusion zone is a circular area centered in the satellite user. The terrestrial network is not allowed to be deployed within the exclusion zone. In this case, the interference caused by spectrum sharing in the CogSTN can be reduced due to the signal attenuation.

2) Cognitive Relay Architecture: As shown in Fig. 5, the CogSTN can be extended to the HSTRN, forming the architecture of the cognitive satellite-terrestrial relay network (CogSTRN) [95]. In the CogSTRN, the primary satellite network transmits to the satellite user with the help of terrestrial relays using the licensed spectrum. The secondary terrestrial network shares the licensed spectrum with the primary network, which will cause interference to the primary satellite user and also terrestrial relays. Similarly, the CogSTRN can be divided into the basic relay architecture [95], [96], and the cooperative relay architecture [97]–[99], while both the AF protocol and the DF protocol can be applied, which are the same as in Section III-A. The SER performance, BER performance, and outage performance were analyzed for the CogSTRN with the co-channel interference (CCI). Also, the role of the terrestrial relay in the satellite network and the role of the terrestrial BS in the terrestrial network are similar in the CogSTRN. Thus, the terrestrial relay and the terrestrial BS can be merged in a cooperative way in the CogSTRN. Considering the satellite network as the primary network, the secondary terrestrial network is allowed to share the licensed spectrum with the primary satellite network, if the secondary terrestrial BS acts as the relay to assist the transmission of the primary satellite network. The total transmission process will consist of two phases. In the first phase, the satellite transmits the desired signal to the terrestrial BS. Then, in the second phase, the terrestrial BS forwards the received signal to the satellite user and also transmits its own signal to the terrestrial user with the same spectrum.

In Fig. 5, the satellite network is considered as the primary network. In [100]–[102], the terrestrial network is also considered as the primary network in the CogSTRN, while the satellite network shares the licensed spectrum for relay transmission. In this case, both the satellite and the terrestrial relay will cause interference to primary terrestrial users. The outage performance of the CogSTRN was then analyzed, and efficient power control schemes were discussed to protect the transmission of the primary terrestrial network. In [103], the outage performance for the merged CogSTRN was analyzed, in which the NOMA technique was applied for simultaneous transmission of the forwarded primary signal and also the secondary signal. In [104], multiusers were considered for the primary satellite network, and the user scheduling strategy was explored to optimize the outage performance. In [105], multiple secondary networks were considered for assisting the transmission of the primary network. The outage probability was minimized by optimizing the secondary network selection and also the power allocation. In [106], it was proposed that the primary satellite network can recruit the cluster heads in IoT networks as relays. The secondary IoT network is allowed to access the licensed spectrum by sharing the infrastructure with the primary satellite network. Moreover, in [107], the secondary IoT devices were utilized as the relays for transmission of the primary satellite network. The outage probability was derived for both satellite and IoT networks.

D. Cooperative Satellite-Terrestrial Networks

The satellite-terrestrial network architectures discussed above are mainly designed to assist the transmission in only one of the networks (HSTRN, STBN), or designed for spectrum sharing (CogSTN), in which the two networks are operated separately. The cooperation of the two networks in satellite-terrestrial networks is not fully exploited. While the terrestrial network has been well deployed in developed areas, enabling broadband access to the Internet at low cost, the satellite network is able to provide ubiquitous coverage with the top-down nature. Taking advantages of both the two networks, the cooperative satellite-terrestrial network (CooSTN) is a promising architecture to further promote the development of wireless networks [24].

1) Complementary Architecture: By directly integrating the satellite network with the terrestrial network, the complementary architecture of the CooSTN is shown in Fig. 6(a), in which the satellite network and the terrestrial network act as the complement of each other. Instead of being operated separately in conventional networks, cooperation of the two networks is realized in the CooSTN. In the CooSTN, dual-mode terminals are required to access both the terrestrial network and the satellite network. When a user is located in the coverage of terrestrial networks, generally in urban areas, the user will access the terrestrial cellular network for broadband services. However, when the user moves to areas without terrestrial networks, such as rural areas, sea areas, and airspace, the user will be transferred to the satellite network for continuation of the service. Then, there will be a handover from the terrestrial network to the satellite network, which requires integrated mobility and resource management of the two networks. Also, by utilizing satellites that support the communication protocol of the existing terrestrial networks, the CooSTN architecture can be applied to the existing terrestrial networks. Based on the cooperation of the two networks, ubiquitous coverage and continuous service are achieved in the CooSTN [19]. Unified terminal devices can seamlessly access either the satellite network or the terrestrial cellular network using the same physical-layer protocols. When the integration moves from the top level to the bottom level, higher network efficiency, and quality of user experience can be acquired, but also with higher implementation complexity and deployment costs.

In [24], the complementary architecture of the CooSTN was discussed to enable comprehensive coverage of mobile wireless networks, in which the extended satellite network and the terrestrial cellular network were integrated with the Internet backbone. Similarly, in [108], the CooSTN architecture was proposed consisting of the satellite backbone network, the satellite access network, the terrestrial backbone network, and the cellular network. The interconnection between the satellite network and the cellular network was enabled by the terrestrial backbone network. To integrate various satellite networks with terrestrial networks, unified network protocols, or efficient network protocol conversion schemes are important in the CooSTN. A specific testbed for network protocol validation in the CooSTN was proposed in [109]. For better management of the spectrum resource in the integrated network, the CooSTN architecture with virtual resource pool was proposed [110], in which virtual cells were applied to guarantee the QoS of users.

2) Enhanced Architecture: In addition to achieving ubiquitous coverage with the complementary architecture, the CooSTN can also be exploited in the enhanced architecture for areas where the terrestrial link is weak or insufficient [26]. As shown in Fig. 6(b), users in the CooSTN are not strictly differentiated into terrestrial users or satellite users. Instead, with dual-mode terminals, users can access both the terrestrial network and the satellite network. The satellite network and the terrestrial network cooperate to provide enhanced communication services for ground users. Different from the complementary architecture, the satellite link or the terrestrial link is not the only connection to the Internet for users [20]. On the one hand, users can choose to access the satellite network or to access the terrestrial network according to the user preference. On the other hand, users may be passively transferred between the two networks according to the signal intensity or the service type. Also, simultaneous transmission of the two parallel links can be utilized with full cooperation in the enhanced CooSTN architecture, which can improve the communication capacity and reliability by exploiting the spatial diversity.

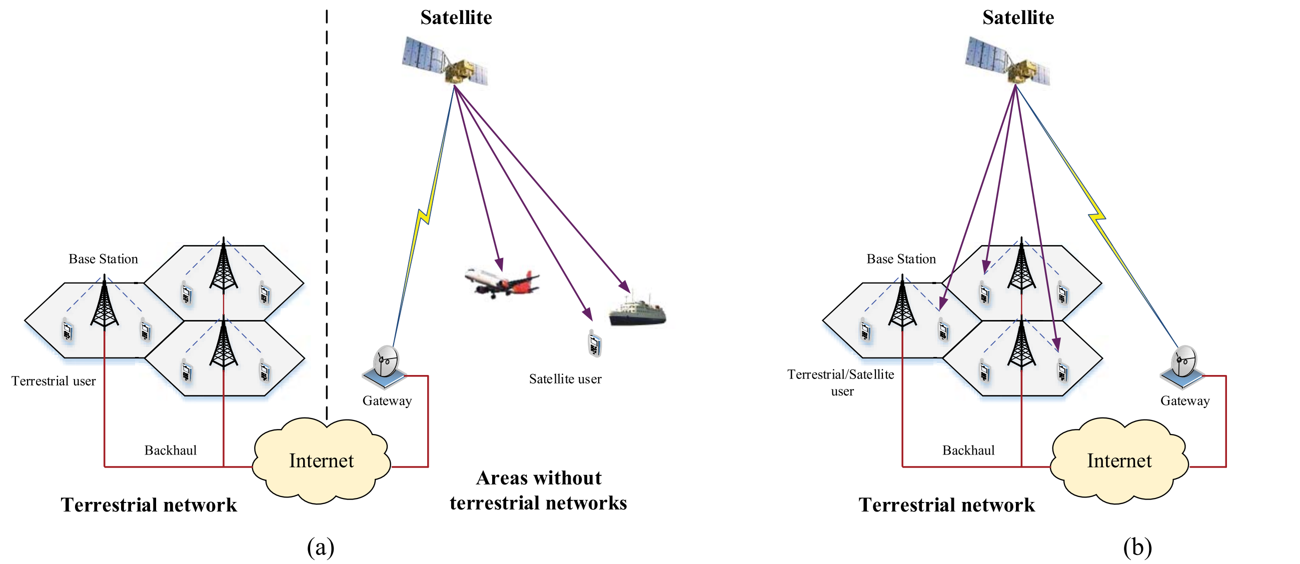

Fig. 6. Architecture of CooSTNs. (a) Complementary architecture. (b) Enhanced architecture.

In many less-developed areas, the communication capacity of the terrestrial network is limited due to the infrastructure deployment costs, which cannot support broadband access to the Internet. Also, for well-developed terrestrial networks in urban areas, the terrestrial network may be overloaded in peak time due to the high traffic demands and limited spectrum resources. In these cases, with the enhanced CooSTN architecture, some traffics can be offloaded to the satellite network, which reduces the pressure of the terrestrial network and also improves the QoS of users [111]–[113]. In [111], the enhanced CooSTN architecture was discussed, in which a channel-based algorithm was proposed to control the network access of users. In [112], by offloading some traffics to the satellite network, part of the terrestrial BSs can go into the sleep mode, which improves the spectrum efficiency and energy efficiency of the network. In [113], an auction-based spectrum sharing scheme was proposed for the enhanced CooSTN architecture. The satellite network is allowed to use part of the spectrum if it helps to offload the traffic of the terrestrial network.

In addition to traffic offloading, the satellite network can also be utilized to provide diversity gain with the extra satellite links in the enhanced CooSTN [114]. In [115], users in trains, ships, or vehicles were assumed to simultaneously use the satellite and the cellular BS for content services. Joint multipath communication and network coding were exploited to maximize the system throughput. In [116], cooperative multigroup multicast transmission in the enhanced CooSTN was investigated to overcome the affect of large fluctuation of terrestrial channels. The ground users are simultaneously served by the terrestrial network and the satellite network for multicast transmission. By combining the signals from the two networks using the MRC technique, the multicast capacity can be significantly improved.

Due to the wide coverage ability, the satellite network is inherently suitable for broadcast/multicast services. A combined unicast and multicast transmission scheme for content delivery in the enhanced CooSTN was proposed in [117]. The common contents, which are required by multiple users, are transmitted by the satellite with multicast. Then, the unique contents required by individual users are transmitted by the terrestrial BSs with unicast. By means of cooperative content delivery with the two networks, the QoS of users as well as the resource efficiency are improved.

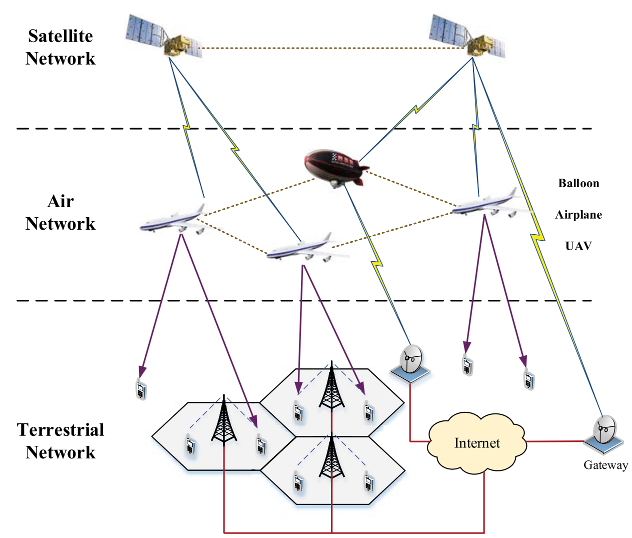

Fig. 7. Architecture of SATNs.

E. Satellite-Air-Terrestrial Networks

In the discussion above, the integrated satellite-terrestrial network architecture is composed of two network layers, the satellite network and the terrestrial network. The terrestrial network can support broadband services at relatively low cost. However, the coverage of each BS is rather limited, which restricts the deployment of terrestrial networks due to economic and geographic constraints. On the other hand, the satellite network is able to provide wide coverage with the top-down nature. However, the satellite network generally experiences large signal attenuation and latency. Then, the air network, which is located between the terrestrial network and the satellite network, is considered to be further integrated into the network, forming the satellite-air-terrestrial network (SATN) architecture [23]. As shown in Fig. 7, the SATN consists of three network layers, the satellite network, the air network, and the terrestrial network. Due to the large channel attenuation of the satellite-ground link and also the difference in communication protocols, some terrestrial users may not be able to access the satellite network. Then, the air network can provide connectivity to users out of the coverage of terrestrial networks based on 6G or Wi-Fi, in which the backhaul transmission is enabled by either satellites or by terrestrial macro BSs. Note that the SATN is still one of the integration architectures for the integrated satellite-terrestrial network. While the satellite network and the terrestrial network can be utilized as in the architectures discussed above, the air network is further deployed to provide coverage and capacity enhancement for various types of users and devices with mobility support [118], [119]. On the other hand, due to the inherent characteristics of heterogeneity, self-organization, and time-variability, it will bring much more challenges for network design and protocol optimization in the SATN [23].

The air network generally consists of balloons, airplanes, and unmanned aerial vehicles (UAVs) [120], which are deployed at the altitude less than 30 km. High altitude platforms like balloons can be utilized in the quasi-stationary way to provide rural coverage of tens of kilometers. By using the solar energy, the balloons can provide continuous service for a certain area for several years [121], while the deployment costs are much lower than terrestrial networks due to the mobility and the flexibility. Low altitude platforms like UAVs are deployed at the lower altitude, and the operation time is relatively short due to the battery limitation. However, UAVs enjoy much higher mobility and ease of deployment with the small size [122]. UAVs can be utilized flexibly to enhance the transmission in hotspot areas [123], [124], where the terrestrial network may be congested by large traffic demands. Also, with the increasing development of IoT, UAVs can act as aerial BSs or relays to provide temporal wireless access services for IoT devices in rural and remote areas.

A comprehensive survey of the SATN was given in [23], in which the architecture, physical layer characteristics, mobility management, and system integration were discussed. The three segments of the SATN and the integration issues were analyzed in depth. In [125], a UAV-aided space-air-ground network was proposed for uplink data transmission in IoT networks. In [126], an airplane-based SATN architecture was proposed. The civil airliner network was utilized to provide both inflight communication and air-to-ground coverage. To make full use of the spectrum resource, the cognitive architecture was also investigated for the SATN in [127]. The satellite network was considered as the primary network, while the air network and the terrestrial network were considered as the secondary network. The BS and UAV cooperatively provide service for the secondary terrestrial user under the interference constraint. Then, a comprehensive simulation methodology for the SATN was proposed in [128], which can be utilized for simulations of various mobility traces and protocols in the three-layer network.

IV. Application Case

In the previous section, we discussed five different satellite-terrestrial architectures for future wireless networks, in which some possible applications have been mentioned with the architectures. In this section, we now give a conclusion of the typical application cases for the integrated satellite-terrestrial network, which are specialized for the integrated satellite-terrestrial network, while conventional networks may be inapplicable or cannot work well due to the limitations of conventional networks. Compared with conventional terrestrial networks, the benefit of the integrated satellite-terrestrial network is mainly brought by the wide coverage of the satellite and the cooperation of the two networks, based on which the application cases of the integrated satellite-terrestrial network are discussed as follows. First, considering the capability of expanding network coverage and ensuring service continuity, the integrated architecture can be applied for rural coverage, sea area communication, and airborne communication, which are discussed in Sections IV-A–IV-C separately. Second, considering the capability of increasing network reliability and expanding network coverage, the integrated architecture can be applied for emergency communication, which is discussed in Section IV-D. Third, considering the capability of ensuring service continuity and providing enhanced transmission, the integrated architecture can be applied for broadcast/multicast communication, which is discussed in Section IV-E.

A. Rural Coverage

Among all the possible application cases, the most important and promising application of the integrated satellite-terrestrial network is to provide rural coverage. The concept of rural areas is defined as the opposite of urban areas, which can be less-developed areas and areas far away from large towns or cities. As discussed above, although terrestrial networks have experienced rapid development in the past decades, terrestrial networks are only appropriate for deployment in developed areas due to the high cost. In rural areas, there are large numbers of populations and devices remaining unconnected even after the construction of the 5G network. According to the statistics of ITU, nearly half of the populations in the world have no access to the Internet by 2019 [129]. Also, numerous IoT devices in rural areas cannot be uncovered by terrestrial networks [130]. Then, based on the wide coverage of the satellite, the integrated satellite-terrestrial network can extend the communication service to these unserved areas, connecting the remaining populations and devices.

For areas of sparse users, mobile users can access the satellite-terrestrial network by their own terminals, which may be capacity-limited based on the type of users and terminals. Also, for residences or buildings in rural areas, fixed satellite antennas can be deployed to provide relative broadband service for users inside based on 6G or Wi-Fi technologies [131]. Then, for areas of dense users, as discussed in the STBN architecture, a terrestrial gateway with antenna farms may be deployed to establish satellite backhaul links. Users can access the satellite-terrestrial network by BSs or other access points with satellite backhauls [132]. Furthermore, the satellite-terrestrial network can also provide additional links to enhance the transmission in rural areas without broadband terrestrial networks, as discussed in the CooSTN architecture.

B. Sea Area Communication

In addition to providing rural coverage, the integrated satellite-terrestrial network can further extend the connectivity to remote areas on the earth, which are generally far away from places where people live. Although humans mainly live on land, the sea area is also of great importance for transportation, marine resource exploitation, and tourism, for which the support of communication is indispensable [133]. Compared with land, the sea area is much larger, which accounts for 71% of the entire surface of the earth. However, traditional terrestrial networks can only be deployed on land. Based on BSs on the shore, communication services can be supported within 30 km from the shore. Then, by using ship-to-ship relays, the communication range may be extended to 100 km [134], which is unstable and inefficient compared with fixed links.

While traditional terrestrial networks can only support offshore communication, the satellite system is able to cover the whole sea area with the wide coverage ability. The integrated satellite-terrestrial network can connect the isolated sea area with land, extending conventional terrestrial-based services to the sea area for various users. For a cruise liner on the sea, the users inside can obtain the same terrestrial services as on land based on the integrated satellite-terrestrial network. Also, maritime information collection and maritime monitoring play an important role in guaranteeing the safety and security of the sea area. The concept of maritime IoT is introduced for data collection and integration [28], [135], for which reliable communication means are the basis. The integrated satellite-terrestrial network can provide efficient storage, transmission, and calculation for the collected maritime information [136]–[138], improving the ability of continuous situational awareness of the sea area.

C. Airborne Communication

Similarly, the integrated satellite-terrestrial network can also extend the connectivity to airborne networks. The airborne network generally consists of balloons, airplanes, and UAVs, among which airplanes are in great need of broadband access to satisfy the urgent communication demands of passengers. In 2019, the global airline passenger traffic exceeds 4 billion [139]. However, the current in-flight communication, such as the Wi-Fi service, is rather capacity limited, failing to satisfy the broadband communication demands of passengers. Although ground BSs can be utilized to establish air-to-ground communication in specific areas along the route [140], the construction cost is relatively high and BSs are undeployable in sea areas.

With the wide coverage ability, the integrated satellite-terrestrial network can provide continuous broadband service for passengers during the flight [141], connecting the air with ground. Since airplanes move at high speed, GEO, or MEO satellites can be utilized to avoid frequent handover between satellites, while LEO satellites can be utilized to reduce the communication latency. Besides, the integrated satellite-terrestrial network is also applicable for communication of balloons and UAVs, which can be deployed for regional coverage, environmental monitoring and border surveillance.

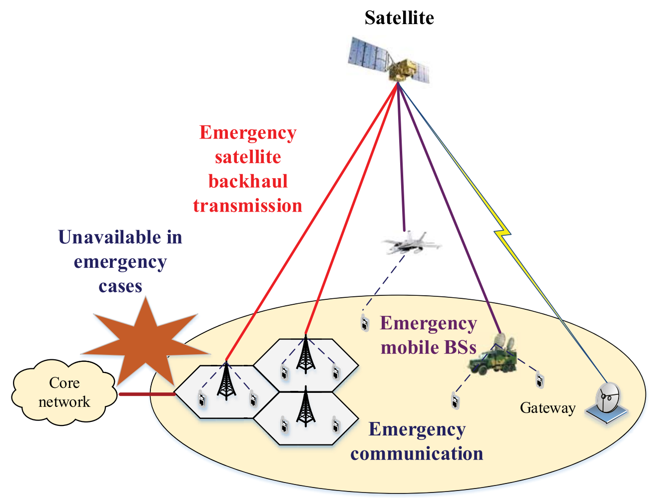

Fig. 8. Emergency communication in the integrated satellite-terrestrial network.

D. Emergency Communication

In addition to providing ubiquitous network coverage, the integrated satellite-terrestrial network can also provide reliable communication support for emergency cases. Communication support is critical for public protection and disaster relief in emergency cases. In the discussion above, we assume the normal operation of communication networks. However, conventional communication networks may not work all the time, especially in disasters or wars. Since terrestrial networks are deployed based on ground BSs and underground optical fiber, which are unreliable and vulnerable, terrestrial communication may be paralyzed or destroyed in emergency cases [142]. Although some efforts can be made to improve the reliability and restorability of terrestrial networks, it requires huge input and the effect is not satisfactory.

Since satellites are deployed on orbits of 500 to 36 000 km, they are immune to most of the disasters and wars on the ground. Thus, satellite-based communication can still be maintained in most emergency cases. As shown in Fig. 8, the integrated satellite-terrestrial network comes to be a promising solution to provide communication guarantee for emergency cases [75], in which the existing terrestrial networks and future 6G networks may be out of service due to damage of infrastructures. In the enhanced CooSTN architecture, users are equipped with dual-mode terminals, and can access the Internet by both satellite and terrestrial links. In normal conditions, terrestrial networks are preferred for broadband services, while satellite networks act as the complementary for enhanced transmission. Then, when terrestrial networks are unavailable in emergency cases, such as earthquakes and hurricanes, satellite networks turn to be the dominant network for emergency communication. Also, for areas with only terrestrial links in normal conditions, the STBN architecture can be utilized to establish emergency communication links and construct a temporary WLAN. The single-mode terrestrial users can access the Internet by satellite-based temporary BSs or emergency vehicles [143]. In the worst cases, the terrestrial network is completely destroyed, and thus the satellite network is the only choice. In better cases, part of the terrestrial infrastructures may remain working if undamaged. Then, cooperation between the survival terrestrial network and the satellite network can be implemented to improve the communication capacity and avoid network overload [75], [143].

E. Multicast/Broadcast Transmission

Last but not least, we introduce the multicast/broadcast transmission case in the integrated satellite-terrestrial network. With the increasing demand of broadband multimedia services, especially the mobile video demand, wireless networks are facing much more pressure to satisfy the huge data traffic. Different from conventional communication services of messages and phone calls, same multimedia contents may be required by multiple users, such as popular videos or live streaming. In this case, multicast/broadcast transmission can be utilized for simultaneous transmission to multiple users that require the same contents [144]. Although terrestrial multicast transmission has been studied and applied to improve the network performance, the decreasing cell size limits the application of multicast transmission in terrestrial cellular networks.

With the top-down nature, satellites are inherently suitable for multicast/broadcast transmission [145]. Taking advantages of both satellite networks and terrestrial networks, the integrated satellite-terrestrial network is promising to further enhance the network performance with integrated multicast/broadcast transmission. The integrated multicast/broadcast transmission can be implemented in several modes. First, the combined unicast and multicast transmission mode can be implemented for content delivery with the enhanced CooSTN architecture [117]. The common and popular contents are transmitted by the satellite with multicast transmission, while the unique contents required by individual users are transmitted by the terrestrial BSs with the unicast transmission. Second, the cooperative multicast transmission mode can be implemented to overcome the large fluctuation of terrestrial channels with the enhanced CooSTN architecture [116]. The ground users are simultaneously served by the terrestrial network and the satellite network for multicast transmission. By combining the signals from the two networks using the MRC technique, the multicast capacity can be significantly improved. In addition, the multicast backhaul and caching mode can be implemented for more efficient content fetch from the service provider with the STBN architecture [25]. By means of multicast transmission, the common and popular contents that are not cached can be transmitted to a number of BSs simultaneously with satellite backhaul links.

V. Challenges for Integration

As discussed above, the integrated satellite-terrestrial network is promising to enable ubiquitous coverage and Internet access for all types of users, connecting every corner of the world. Although various architectures and applications have been proposed and studied, achieving full integration of satellite and terrestrial networks still faces plenty of challenges due to the unique characteristics of the two networks. In this section, we analyze the main challenges for the integrated satellite-terrestrial network from the perspective of future network deployment.

A. Long Propagation Delay of Satellites

Communication latency is the important and basic performance metric for wireless communication to guarantee the QoS of users. From 1G to 6G, the development of communication networks is always pursuing the reduction of communication latency. Generally, the communication latency of users is composed of the transmission delay, the propagation delay, the processing delay, and the queuing delay. While the other three types of delay may be comparable for both satellite and terrestrial networks, the propagation delay of satellite networks is much longer than terrestrial networks due to the high orbit of satellites.

In all the integration architectures discussed in Section III, a complete communication process will include at least two satellite-ground links. As listed in Table I, for GEO satellites on the fixed orbit of 36 000 km, the one-way propagation delay will be as long as 240 ms, which is much longer than the 5G end-to-end latency requirement of 1 ms. Although in MEO/LEO satellite networks the propagation delay can be reduced to tens of milliseconds, multihop transmission in MEO/LEO satellite networks will lead to longer propagation delay for additional ISLs or satellite-ground links [146]. Also, the high dynamic of MEO/LEO satellite networks will lead to unstable link topologies [147], which will add to the propagation delay in satellite networks.

For the above reasons, although the integrated satellite-terrestrial network extends the connectivity greatly compared with traditional terrestrial networks, the communication latency is much longer due to the propagation delay of satellite links. To improve the QoS of users, efforts are needed to reduce the communication latency in the integrated satellite-terrestrial network. For multihop transmission of MEO/LEO satellites, the propagation delay is significantly influenced

TABLE I
PROPAGATION DELAY OF SATELLITES

Satellite type	Altitude	One-way propagation delay
GEO	36,000 km	240 ms
MEO	20,000 km	133.33 ms
MEO	10,000 km	66.67 ms
MEO	3,000 km	20 ms
LEO	1,000 km	6.67 ms
LEO	600 km	4 ms

by the path length from the source satellite to the nearest satellite with connection to gateways. Thus, reasonable placement of gateways is important for the efficient establishment of satellite-ground links. The joint placement problem of controllers and satellite gateways was investigated to minimize the average latency in the integrated satellite-terrestrial network [148]. Also, for less interactions with the distant cloud, which are of long latency, the technique of mobile edge computing (MEC) can be applied in the integrated satellite-terrestrial network to reduce the latency [149], [150]. Different from the terrestrial network, where the MEC server is generally deployed at the BS, the MEC can be deployed at the BS, the satellite, and the gateway in the integrated satellite-terrestrial network [71]. When designing offloading strategies, it is challenging to exploit the cooperation of different serving locations, which are of different latency and computation capacity. Also, considering the wide coverage of the network, a large number of users need to be scheduled with limited computing and energy resources. Thus, specialized MEC schemes need to be further investigated for the integrated satellite-terrestrial network.

B. Complex Characteristics of Link Conditions

In addition to the long propagation delay, satellite links also suffer from the complex characteristics of link conditions. Since satellites are operated on the orbits of hundreds to thousands of kilometers, the satellite communication link needs to penetrate the atmosphere before reaching the ground. As a consequence, satellite communication links are vulnerable to weather conditions, such as rain, cloud, water vapor, and fog, among which rain attenuation is the most critical influence for spectrum over 10 GHz [151]. Different from terrestrial links, significant channel fading may be caused to satellite links by unfavorable weather conditions, leading to communication outage in the integrated satellite-terrestrial network. To guarantee communication stability, reliable modulation and coding schemes can be designed and utilized for quickly adaptation to the weather conditions. In [77], an adaptive coding transmission scheme was proposed to overcome the rain attenuation in the integrated satellite-terrestrial network, which can significantly improve the system throughput.

In terrestrial communication, we generally assume the quasi-static channel model for most transmission scenarios [152]. However, different from the fixed BSs on the ground, MEO/LEO satellites move at high speed relative to the ground. Then, the satellite-ground links will experience more rapid time variation, larger doppler shift, and larger phase shift. Nonstationary channel models are needed to characterize the high dynamics of satellite link conditions in the integrated satellite-terrestrial network [153], which is of much more complexity. Also, considering the long propagation delay of satellite links, obtaining timely and accurate channel state information (CSI) is more difficult compared with terrestrial networks. The effect of imperfect channel estimation needs to be investigated for the integrated satellite-terrestrial network [89].

Due to the complex characteristics of satellite link conditions, the HSTRN architecture can be utilized to improve the transmission when the communication links between the satellite and users are unstable caused by unfavorable weather conditions or high dynamics of channels. As discussed in Section III, the terrestrial relay helps to forward the desired signal to the satellite user via terrestrial links. With the help of the terrestrial relay, the satellite user can communicate with the satellite even when the direct link is unavailable, which increases the system stability.

C. Mobility and Handover Management

In communication networks, the technique of handover is utilized to transfer the connection between cells when users move out of the coverage of the original connection. Due to the orbital motion of MEO/LEO satellites and also the mobility of mobile users, handovers occur more frequently in the integrated satellite-terrestrial network. Thus, efficient mobility and handover management is important to guarantee the service continuity and satisfy the QoS requirements of users. Considering the integrated architecture, there are two types of handovers in the integrated satellite-terrestrial network: 1) the horizontal (intranetwork) handover and 2) the vertical (internetwork) handover [154]. The horizontal handover occurs when the connection is transferred between terrestrial cells, between satellite spot-beams, or between satellites. In contrast, the vertical handover occurs when the connection is transferred between the terrestrial network and the satellite network. For the horizontal handover, since the handover occurs solely in the terrestrial network or the satellite network, it can be performed by the conventional handover techniques in each network [155], [156]. On the other hand, there are more challenges for the vertical handover in the integrated satellite-terrestrial network, in which the connection is transferred between two different networks.

In the complementary CooSTN architecture, when the user moves to areas without terrestrial networks, the user will be transferred to the satellite network for continuation of the service, and vice versa. Also, for all the application cases discussed in Section III, satellite networks and terrestrial networks may exist simultaneously sometimes, while only one of the two networks exists at other times. Efficient handover schemes are in great need to make full use of the integrated network architecture. In [157], a new handover mechanism was proposed for the integrated satellite-terrestrial network to enable handovers between satellite and terrestrial components. The handover decision and preparation processes are separated to reduce the probability of failure for long handover preparation cases. In [158], a handover scheme was proposed based on the SNR and user locations. The dual-mode terminal will perform the vertical handover to transfer the connection between satellite and terrestrial networks when the predefined thresholds are crossed.

While the discussion above only considers the handover of a single connection, more complex handovers may occur in the enhanced CooSTN architecture, where the satellite network and the terrestrial network cooperate to provide enhanced communication services for ground users. In the enhanced CooSTN architecture, since users are served by two cooperative connections, when performing a handover for one of the connections, the cooperation also needs to be transferred to the new connection. In more special cases, simultaneous handovers of the two connections may occur, which adds to the complexity for handovers in the integrated satellite-terrestrial network.

D. Traffic Offloading in the Integrated Network

In the HetNet architecture, part of the data traffic can be offloaded from one network to other networks to reduce the network congestion, which has been widely investigated in heterogeneous cellular networks and vehicular networks [159], [160]. In the integrated satellite-terrestrial network, especially in the enhanced CooSTN architecture, the satellite can also be utilized to offload part of the terrestrial data traffic when the terrestrial network is insufficient or congested. Considering the unique characteristics of satellite networks, satellite-based traffic offloading is more complex compared with conventional traffic offloading schemes in terrestrial networks [161].

With the high mobility of MEO/LEO satellites, the satellite-ground links are unstable and the connection time is short. A complete data traffic may be offloaded consecutively by different links at different times. Thus, dynamic offloading schemes are needed to adapt to the varying offloading links. Different from terrestrial offloading, in which the link capacity is the main consideration to reduce congestion, the link latency should also be considered in the integrated satellite-terrestrial network due to the long propagation delay of satellites [162]. Since satellites on different orbits are of different propagation delays, the offloading scheme needs to be designed based on the various offloading links to maximize the network throughput while satisfying the QoS of users. Moreover, in the integrated satellite-terrestrial network, the satellite is not the only choice for traffic offloading. Combined satellite and terrestrial traffic offloading can be further exploited to improve the network overall performance.

In [163], an offloading scheme for backhaul transmission was proposed in the integrated satellite-terrestrial network. With the help of satellite offloading, the scheduling time for delivering the data traffic was minimized. As discussed in Section IV, satellites are inherently suitable for multicast/broadcast transmission. In [117] and [164], multimedia traffic offloading schemes were discussed for the integrated satellite-terrestrial network with multicast/broadcast transmission. With the wide coverage, the common and popular contents are offloaded to the satellite for multicast/broadcast transmission, which significantly increases the transmission efficiency and reduces congestion. Also, the reverse offloading from the satellite network to the terrestrial network was investigated in [123]. Due to the limited computation and energy resources of the satellite, computation-intensive tasks of the satellite can be offloaded to terrestrial components for efficiency promotion and energy saving.

E. Routing and Path Selection

Considering the heterogeneous architecture of the integrated satellite-terrestrial network, efficient routing algorithms are important to determine the routing path from the source node to the destination node. While terrestrial routing is generally performed based on IP protocols, most satellite routing algorithms were designed based on the asynchronous transfer mode (ATM) [165]. For continuity and also efficiency, unified routing protocols are required in the integrated satellite-terrestrial network to support integrated routing across different network components. However, conventional IP protocols designed for static terrestrial networks cannot be simply applied to the integrated satellite-terrestrial network. Due to the high dynamics of ISLs and satellite-ground links, the routing strategy needs to be updated timely according to the time-varying topology of the network, or frequent link interruptions may be caused by routing oscillation [166]. Also, the different propagation delays of terrestrial and satellite links need to be taken into account when determining the routing paths of different types of traffic. To satisfy the QoS requirement of users, low-latency paths are preferred for delay-sensitive traffic, for which ISLs and satellite-ground links of long propagation delays should be avoided. In addition, with the wide coverage of the satellite, the routing table in the integrated satellite-terrestrial network may be of large size, which adds to the complexity for calculating the routing strategies.

In [167], a revised IP routing mechanism was proposed for the integrated satellite-terrestrial network. By utilizing the global geographical IP subnet division and address aggregation, the size of the routing table can be reduced. The number of abnormal users are controlled to avoid large partial routing cost. As discussed above, handovers occur more frequently for users in the integrated satellite-terrestrial network, which will lead to frequent updating of the IP address in IP-based systems. By applying the software-defined network (SDN) architecture [168], a unified virtual address can be maintained for users when moving across different network components. Also, the time-varying link connections can be modeled by the virtual topology, enabling unified, and efficient routing mechanism in the integrated satellite-terrestrial network. Since satellites are generally of limited computation and energy resources, computing the routing strategy of a large scale may be overburdened for onboard processing. The routing strategies for ISLs and satellite-ground links can be calculated on the ground [24], and then distributed to satellite components.

F. Resource Management

For both satellite and terrestrial networks, resource allocation and management problems have been extensively studied within each network [169]. In the integrated satellite-terrestrial network, efficient resource management is critical for improving the network performance with limited resources [2]. However, integrated resource management in the converged network architecture brings more challenges compared with conventional resource management problems in a single network. If we implement resource allocation for each network separately, or simply apply conventional resource management strategies to the integrated network, the network performance will suffer greatly due to the low resource efficiency. Considering the different characteristics of resources in satellite and terrestrial networks, novel resource management mechanisms need to be developed to enable integrated resource allocation and cooperation for the entire network [170].

As discussed in Section II, the basic communication architecture of the terrestrial network and the satellite network is distinct, which leads to different resource configurations of the two networks. While the spectrum resource and power resource are common in the two networks, the orbit resource and gateway resource are unique in the satellite network for the top-down nature. In the integrated satellite-terrestrial network, all the distinct resources need to be managed jointly to satisfy the QoS requirements of various users and traffic. In [24], the space network operating system was proposed for efficient resource management in the integrated satellite-terrestrial network. By applying resource abstraction and resource mapping to the diverse resources in the network, integrated resource management of all types of resources can be achieved for the network controller. Also, in terrestrial networks, resource allocation algorithms are generally performed for one or several BSs within a small range. However, the coverage radius of satellites ranges from tens to thousands of kilometers. Joint resource management for the thousands of BSs and the satellite will be of significantly high complexity. Instead of centralized resource management of the entire network, distributed resource management strategies may be more practical and efficient in the integrated satellite-terrestrial network of large scales [92], [171].

Different from terrestrial networks, in which the energy resource is relatively sufficient with connection to the power grid, satellites on the orbit are powered by solar energy. Also, as discussed in Section IV, for coverage extension or information collection, infrastructures and sensors may be deployed in remote areas without a power grid, for which solar energy or batteries are the main energy sources. Thus, improving energy efficiency is more important for resource management in the integrated satellite-terrestrial network [94], [172], [173], considering the energy imbalance between energy-sufficient components and energy-limited components. Similarly, satellites or remote sensors are generally of limited computation resources. For efficiency promotion and energy saving, computation-intensive tasks can be offloaded to cloud or edge servers. Since the computation resources in cloud or edge servers are shared by both satellite and terrestrial tasks, effective sharing and allocation strategies for the computation resource need to be studied in the integrated satellite-terrestrial network [174].

G. Security Guarantee

In the integrated satellite-terrestrial network, various types of users in wide areas are included for communication, in which large quantities of data may be private or sensitive [175], [176]. Due to the open environment, high dynamics of nodes and HetNet components, security guarantee of users becomes more difficult and challenging. Especially, the large number of IoT devices and machines are susceptible to security threats [177]. With the top-down nature of the satellite, satellite-ground links are vulnerable to eavesdropping and jamming. Encryption techniques can be used to protect the information security of users for satellite-ground transmission. However, data encryption will lead to additional latency of the communication [178], while the long propagation delay has already been one of the main challenges in the satellite-ground transmission. Thus, novel encryption techniques of low latency and high reliability need to be developed for security guarantee in the integrated satellite-terrestrial network [179]. The wide coverage and long propagation delay of the satellite also lead to more complex key management in the integrated satellite-terrestrial network, which is used for secure communication to ensure that only the authorized user can access the protected data. In order to avoid information blockage, distributed key computation, and management mechanisms may be preferred compared with centralized mechanisms [24], which are of high complexity and low efficiency in the case of wide coverage. In [108], the method of group block-design-based key agreement was proposed for secure group communication in the integrated satellite-terrestrial network. By using the structure characteristics, more efficient generation of the group member key can be achieved. In [180], an innovative infrastructure of secure scenario was proposed for 6G wireless network, which can provide a safe and efficient environment for sharing and managing large-scale data.

As discussed above, the mobility of MEO/LEO satellites and users causes frequent handovers and high dynamics of the network topology, which makes secure handover and routing more difficult in the integrated satellite-terrestrial network. Due to the open environment of satellite-ground links, the handover signals may be falsified of tampered during the handover process, leading to illegal access or privacy leaks. Efficient and reliable handover authentication mechanisms need to be developed to guarantee the security when users move across different network components [181]. Also, due to the diversity of satellite and terrestrial networks, revised IP protocols or other specially designed network protocols are required in the integrated satellite-terrestrial network, which may lead to new security problems with respect to protocols. Especially, routing in the integrated satellite-terrestrial network covers all the different components of the network, including conventional terrestrial links, open satellite-ground links, and dynamic ISLs. More attention needs to be paid to secure routing in the network protocol design.

VI. Techniques and Future Direction

Due to the large difference of the two networks, the techniques designed for conventional networks are not applicable in the integrated satellite-terrestrial network. Novel and revolutionized techniques need to be developed to adapt to the integration architecture. While the integration of satellite and terrestrial networks brings plenty of challenges, the integrated architecture also enables new techniques with full cooperation to improve the system performance. In this section, we give a presentation of the possible techniques and future directions in the integrated satellite-terrestrial network.

A. Spectrum Sharing

With the explosive increasing of global communication demand and the huge volume of IoT devices, the problem of spectrum scarcity tends to be more prominent, leading to spectrum competition between terrestrial and satellite networks. In addition to developing higher frequency band, such as mmWave or terahertz, exploring spectrum sharing techniques in the integrated satellite-terrestrial network is another promising solution. Instead of exclusive spectrum allocation and utilization within each network, reusing the same spectrum resource in the two networks can enhance the spectrum efficiency [182], [183], alleviating the pressure of scarce spectrum resources.

In current communication networks, the terrestrial network and the satellite network generally belong to different operators. The CogSTN architecture can be applied to enable dynamic utilization of spectrum resources among the two networks. Different cognitive architectures, cognitive modes, and network roles for the CogSTN were discussed in Section III. To enable spectrum sharing for existing systems, a spatial spectrum sharing method was proposed by introducing the protection area [184]. The cognitive users are only allowed to transmit with the shared spectrum out of the protection area. In addition to spatial separation, opportunistic spectrum sharing in time can be applied with the help of spectrum utilization information among systems. In [131], a real-time spectrum sharing scheme was proposed considering different timescales and periodicity of spectrum utilization. Moreover, in order to encourage spectrum sharing for existing systems with licensed spectrum resources, the sharing-and-offloading mechanism was proposed in integrated satellite-terrestrial networks [113]. The satellite will help to offload part of the terrestrial traffic if allowed to share the spectrum with terrestrial networks.

With the development of satellite Internet and the integrated satellite-terrestrial network, the terrestrial network, and the satellite network may be operated by the same operator in the future. Then, the operator can make full use of the spectrum resource by sharing the authorized spectrum among its own terrestrial and satellite networks. In [111], considering that the terrestrial network and the satellite network are operated by the same operator, an NOMA-based cooperative transmission scheme was proposed with full-spectrum sharing. Compared with the conventional exclusive mode, more users can be served and larger transmission capacity can be achieved for the operator with the same spectrum resource. For more efficient management of the integrated network resource of the operator, the cloud-based integrated satellite-terrestrial network architecture was proposed in [174]. By centralized baseband processing at the cloud, terrestrial users and the satellite can share the same spectrum for transmission, extending the network coverage with limited spectrum resources.

B. Beamforming

Although spectrum sharing can enhance the spectrum efficiency in the integrated satellite-terrestrial network, it will lead to interference for both of the networks due to the overlapped frequency. With the development of multiantenna transmission, beamforming techniques can be utilized to improve the capacity performance and also mitigate the interference in the integrated satellite-terrestrial network [17], [185]. By adjusting beamforming weights, the transmit signal can be focused to one or multiple desired directions, achieving higher transmission gains. Also, less or even zero power will be transmitted to undesired directions, by which the interference from spectrum sharing can be mitigated.

In [186], a joint beamforming and power allocation algorithm was proposed for the integrated satellite-terrestrial network while sharing the same mmWave frequency band. By designing the beamforming vectors of the two networks cooperatively, the interference for both the networks can be mitigated, and then the overall capacity performance was improved. Considering the limited computation and energy resources on the satellite, complex beamforming design algorithms tend to be performed on the ground. In [187], a cloud-based beamforming architecture was proposed for the integrated satellite-terrestrial network. The joint user scheduling and beamforming design problem was centralized at the cloud, enabling cooperative beamforming design of the entire network. However, due to the wide coverage and long propagation delay of the satellite, ground-based beamforming design adds to the burden of the feeder link and also the system latency. In [188], a semi-adaptive beamforming algorithm was proposed for the integrated satellite-terrestrial network to enable onboard satellite beamforming. By applying a robust switching mechanism, the beamforming complexity and energy consumption can be reduced while guaranteeing the system performance.

With the wide coverage, there are generally large numbers of users in the integrated network, and satellites are inherently suitable for multicast/broadcast transmission. The multicast multigroup beamforming design problem was investigated in [189]. Considering the unique and common content demands of users, efficient grouping, and multicast beamforming algorithms were proposed to optimize the system throughput. In [190], a robust multigroup multicast beamforming scheme was proposed for satellite-terrestrial IoT networks, in which the framing recommendation of the standard DVB-S2X was considered. Also, the large number of users and capacity demand lead to the increasing number of antennas, in which case applying digital beamforming will be of too high cost and complexity, especially for resource-limited satellites. In [191], a pure analog beamforming scheme was proposed for interference mitigation in the integrated satellite-terrestrial network. Compared with digital beamforming techniques, the proposed scheme can achieve similar performance with much lower cost and complexity. Combining the advantages of both digital and analog beamforming techniques, the hybrid analog-digital beamforming architecture was proposed as a tradeoff between performance and cost [192]. In [17], the analog-digital transmit beamforming scheme was applied in the integrated satellite-terrestrial network. Simulation results in two different scenarios showed that the proposed scheme can significantly improve the spectrum efficiency with low complexity.

C. Diversity Technique

Due to the channel fluctuation and shadowing effect in wireless transmission, the received signal of users may experience deep fading, leading to a high error rate or even communication outage. In conventional terrestrial networks, diversity techniques are utilized to overcome this problem by combining the multipath signals from multiple antennas or cooperative BSs. In the integrated satellite-terrestrial network, integrated diversity transmission can be exploited by combining the signals from both the satellite network and the terrestrial network [193]. As discussed in the enhance CooSTN architecture, the satellite link or the terrestrial link is not the only connection to the Internet for users. Deep cooperation of the two parallel links can be utilized for diversity transmission.

In [25], the cooperation of macrocell BSs, microcell BSs and satellites was utilized to achieve diversity gain in the integrated satellite-terrestrial network. Users were free to select one or multiple links from all the available networks according to the channel conditions, by means of which the system capacity can be enhanced. Considering the wide coverage of the satellite, diversity transmission can also be applied to multicast transmission in the integrated satellite-terrestrial network. In [116], a cooperative multigroup multicast transmission scheme was proposed to overcome the affect of large fluctuation of terrestrial channels. By combining the signals from the two networks, the received SINR of bottleneck users can be significantly improved. Due to the limitation of the satellite payload and also the Line-of-Sight (LoS) channel characteristic, exploiting diversity transmission with multiple antennas may not work well in satellite networks. In this case, virtual multiple antenna transmission can be applied based on the cooperation of satellite constellations [194], in which diversity gain can be obtained with the distinct channel of different satellites. Furthermore, in the integrated satellite-terrestrial network, both terrestrial BSs and the satellite can be utilized to form the virtual transmission architecture, achieving more reliable and flexible diversity transmission.

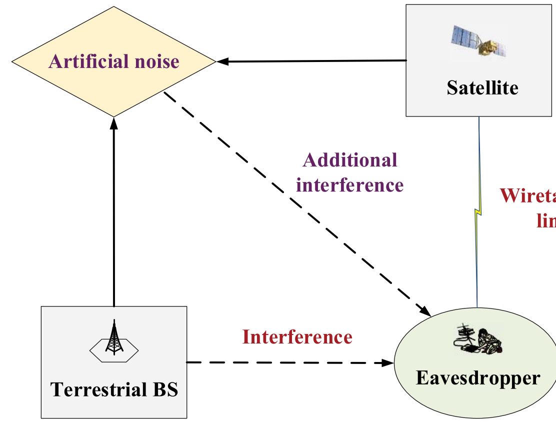

Fig. 9. Cooperative secure transmission in the integrated satellite-terrestrial network.

D. Cooperative Secure Transmission

Due to the open environment, satellite-ground links are vulnerable to eavesdropping and jamming. Security guarantee of users becomes more difficult and challenging in the integrated satellite-terrestrial network. Based on the integrated architecture, cooperative secure transmission can be achieved with the help of terrestrial networks, preventing the satellite signal from being wiretapped. As shown in Fig. 9, by transmitting on the same channel cooperatively with the satellite, the received SINR of eavesdroppers will be deteriorated, while the interference to satellite users can be controlled with information exchange and beamforming design. Also, since the terrestrial network reuses the same spectrum for transmission, the spectrum efficiency can be improved with spectrum sharing techniques. By building the physical layer security with the cooperative secure transmission, the information security of users can be enhanced without complex encryption techniques. The communication latency can then be reduced.

In existing works, the CogSTN architecture is generally considered for cooperative secure transmission, in which the satellite network acts as the primary network while the terrestrial network acts as the secondary network. In [195] and [196], the problem of secure beamforming design was investigated to protect satellite links based on the CogSTN architecture. The transmit power was minimized while satisfying the constraints for both the secrecy rate requirement of satellite primary users and the QoS requirement of terrestrial secondary users. In order to further enhance security in the integrated satellite-terrestrial network, the artificial noise technique can be utilized to improve the secrecy rate. Artificial noise is the additional noise added by the transmitter to deteriorate the received SINR of eavesdroppers, while the interference to legitimate users can be controlled. In [197], the artificial noise from the satellite was assumed to be known by legitimate users in the system. Therefore, the artificial noise will not cause harmful interference to legitimate users. In [198], the artificial noise from the satellite was constrained to be orthogonal to the channel of legitimate users, by means of which the interference for legitimate users can be canceled. A joint secure beamforming and artificial noise design algorithm was then proposed. Also, in [199], the artificial noise was considered to be generated by terrestrial BSs. Both perfect and imperfect CSI of users were investigated for optimal beamforming design. In [200], the CSI of eavesdroppers was considered to be unknown, which is the more realistic case since eavesdroppers are noncooperative and malicious. The secrecy outage probability was then analyzed with a secure beamforming design. In [201], the cooperative secure transmission was extended to broadcast transmission scenario. The satellite broadcasts a common signal to a group of legitimate users in the presence of multiple eavesdroppers. The secrecy broadcast rate was guaranteed with the cooperation of terrestrial BSs.

Cooperative secure transmission can also be applied in the HSTRN architecture, in which the terrestrial relay helps to forward the satellite signal to overcome the masking effect. Due to the masking effect, eavesdroppers cannot wiretap the satellite directly. While the relay-user link provides extra transmission for legitimate users, it may also be wiretapped by eavesdroppers. In [202] and [203], the opportunistic user-relay selection method was utilized to find the optimal relay-user pair that maximizes the secrecy rate. The secrecy outage probability was analyzed in the case of opportunistic communication. Similarly, the terrestrial network can be introduced to provide cooperative secure transmission, deteriorating the received SINR of eavesdroppers with extraterrestrial interference. Then, the secrecy rate for relay transmission can be improved.

E. SDN

As discussed in Section V, integrated network management and control is of great importance for handover, offloading, routing, and resource allocation in the integrated satellite-terrestrial network. However, due to the unique characteristics of the two networks, achieving full integration of satellite and terrestrial networks still faces plenty of challenges. The SDN architecture, in which the control plane is separated from the data plane, can be applied to the integrated satellite-terrestrial to enable efficient and intelligent network management [204]. An SDN-based satellite-terrestrial network architecture is shown in Fig. 10, which consists of the data plane, the control plane, and the application plane. The data plane includes the actual infrastructure and devices, such as satellites, gateways, BSs, and switches, which perform data processing and transmission under the management of the control plane. The satellite and terrestrial BSs can cooperatively provide service for various types of users in the network. With the characteristic of lower latency, LEO satellites are preferred for data service access, service aggregation, and data flow transmission. Switches are deployed on the ground and also on the satellite, forwarding the received packets following the instructions contained in the flow table. The control plane includes the terrestrial controller, the satellite controller, and the controller for the entire network. As the orchestrator of the whole network, the control plane determines the rules for integrated network management, achieving unified control of the two networks. Also, considering the long propagation delay of satellite links, both terrestrial and satellite controllers are placed to reduce the network latency [118]. In this way, the decision processes of handover, offloading, routing, and resource allocation are separated from the entities in the data plane, enabling more flexible network management and control. Then, the application plane can further provide various programmable services and functions based on the information from the control plane, such as remote sensing, navigation, communicating, and monitoring.

In [205], the SDN framework for integrated satellite-terrestrial networks was investigated, and the agility of the SDN architecture was analyzed based on a three-layer satellite constellation. In [206], an SDN-based architecture, named SI-STIN, was proposed to coordinate the various users and systems in the integrated satellite-terrestrial network. In addition to the basic three-layer vertical architecture of SDN, the network was also horizontally divided into the entity domain and behavior domain, which define all the entities and behaviors in the three vertical layers. In [207], the HetNet architecture was proposed to enable flexible network convergence in the satellite-terrestrial network. By dividing the original network into two core networks and multiple edge networks, the HetNet components can be managed with a general network architecture.

The SDN-based integrated satellite-terrestrial network was applied to vehicular networks in [121]. By performing network slicing for different segments, service continuality and also QoS requirements for vehicles of high mobility were guaranteed. In [162], the traffic offloading problem for the integrated satellite-terrestrial network was investigated relying on the SDN architecture. A detailed offloading scheme was proposed with extra offloading functions added to the control plane, which were specialized for offloading decision, execution, and monitoring. Then, with the SDN control architecture, an end-to-end routing scheme was proposed for unified routing in the integrated satellite-terrestrial network [168], which can significantly reduce the network congestion. In addition, due to the long propagation delay of satellite links, determining the location of controllers is more important and complex in the integrated satellite-terrestrial network. In [148], a joint controller and gateway placing scheme was proposed to enhance the reliability and also reduce the latency, which was validated with real topologies.

F. Artificial Intelligence

Recently, with the rapid development of AI techniques, AI-based communication has been widely investigated to improve

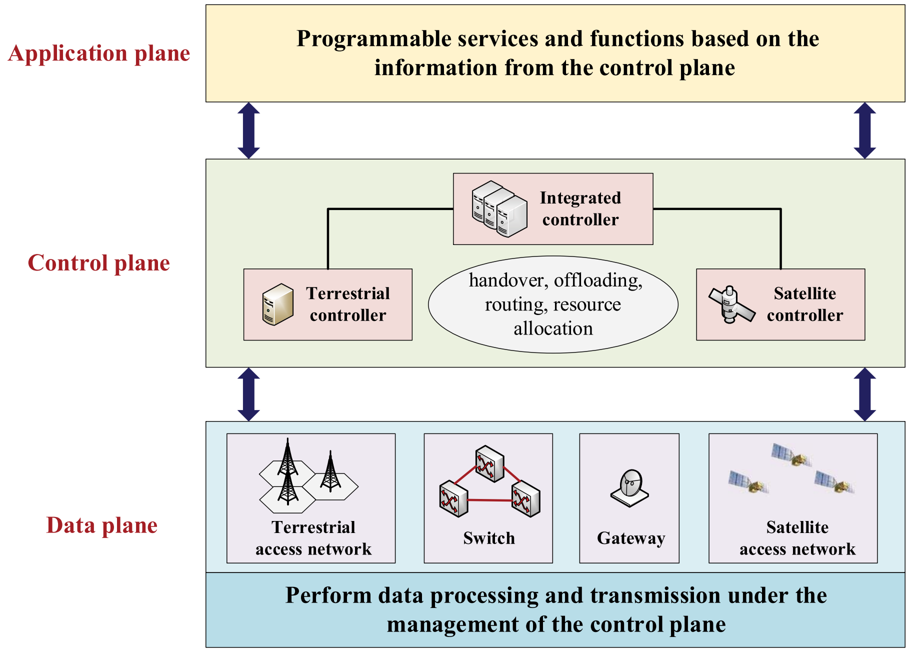

Fig. 10. SDN-based satellite-terrestrial network architecture.

the network performance in an intelligent way [208]–[210]. Especially, the advances in hardware make it possible to implement deep learning methods on communication devices, which are effective for solving complex optimization problems. Compared with conventional communication networks, network control and resource management in the integrated satellite-terrestrial network will be more complex considering the heterogeneous architecture and wide network coverage. AI techniques then provide a promising solution for the emerging challenges in the integrated satellite-terrestrial network.

As discussed in Section V, due to the high dynamics and delay of satellite links, the routing strategy needs to be updated timely according to the time-varying topology. In [211], a deep learning-based routing strategy was proposed to reduce the routing delay in the integrated satellite-terrestrial network. The convolutional neural network (CNN) was utilized to learn the traffic patterns in the integrated network, by means of which the routing paths obtained can achieve traffic balance for the network. For more efficient management of the various resources in the integrated satellite-terrestrial network, a deep Q-learning-based method was proposed to jointly allocate the networking, caching and computing resources among both satellite and terrestrial users [212]. Due to the great potential of spectrum sharing in the integrated satellite-terrestrial network, two spectrum sharing schemes were proposed based on the support vector machine (SVM) and CNN separately in [213]. Compared with traditional schemes, less interference and higher spectrum efficiency can be achieved with intelligent spectrum sharing. Considering the wide coverage of the satellite, accurate positioning for mobile terminals is important to ensure service continuality in the integrated satellite-terrestrial network. In [214], an AI-based self-learning method was proposed for antenna pointing and mobile tracking. By means of unsupervised learning, high-precision position information can be acquired when users move across different environments. Also, AI techniques can be used to enhance the security in future 6G networks. In [215] and [216], the secure machine learning scenarios in the IoT network were discussed, and two encryption algorithms were presented for the integration of IoT and cloud computing.

VII. Conclusion

In this article, we provided a comprehensive survey of integrated satellite-terrestrial networks toward 6G. We first gave the background knowledge of terrestrial networks, satellite networks, and the integration trend of 6G. Then, we presented an exclusive classification and summary of the five integration architectures from network design to performance optimization. Furthermore, we discussed five typical application cases of the integrated network based on the architecture. By considering the unique characteristics of the two networks, we also pointed out the main challenges when performing integration, ranging from the long propagation delay to security guarantee. Finally, we explored some promising techniques from the perspective of the integrated architecture. A detailed survey of the potential integration architectures is of great importance to enable more flexible network design and construction in future 6G networks. We believe that this survey will provide a valuable guideline on future research and development of integrated satellite-terrestrial networks. In future works, each integration architecture can be further investigated for different application cases, while the key techniques discussed in the article can be applied with full cooperation to improve the system performance.

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