5G Embraces Satellites for 6G Ubiquitous IoT: Basic Models for Integrated Satellite Terrestrial Networks

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Abstract—Terrestrial communication networks can provide high-speed and ultra-reliable services for users in urban areas but have poor coverage performance for the ubiquitous Internet of Things (IoT) in harsh environments, such as mountains, deserts, and oceans. Satellites can be exploited to extend the coverage of terrestrial fifth-generation (5G) and beyond networks. However, satellites are restricted by their high latency and relatively low data rate. Hence, the integration of terrestrial and satellite components, taking advantage of both networks, has been widely studied to enable seamless broadband coverage. Due to the significant difference between satellite communications (SatComs) and terrestrial communications (TerComs) in terms of channel fading, transmission delay, mobility, and coverage performance, the establishment of an efficient hybrid satellite-terrestrial network (HSTN) still faces many challenges. In general, it is difficult to decompose a HSTN into the sum of separated satellite and terrestrial links, due to complicated coupling relationships therein. To uncover the complete picture of HSTNs, we regard the HSTN as a combination of basic cooperative models, which contain the main traits of satellite-terrestrial integration, but are much simpler and thus more tractable than the whole network. Particularly, we present three basic cooperative models for HSTNs and provide a survey of the state-of-the-art technologies for each of them. We investigate some main problems and their solutions, including cooperative pattern, performance analysis and resource management issues. We also discuss open issues to envision an agile, smart, and secure HSTN for the sixth-generation (6G) ubiquitous IoT.

Index Terms—Basic cooperative model, hybrid satellite-terrestrial network, Internet of Things, resource management.

I. INTRODUCTION

With the development of 5G communication systems, the world has witnessed a huge shift in the daily lives of people. People are not merely content to use the network to deliver messages but use it to interact with everything. Undoubtedly, the era of the Internet of Things is around the corner. Numerous items, such as sensors, vehicles, tablets, and wearable devices, are joining the network, fostering a series of techniques and applications. For example, by leveraging the autonomous inspection of monitors, smart grids [1], [2], coastal monitoring [3] and intelligent agriculture [4] are under rapid evolution. In addition, the agile measurement of sensors enables autonomous driving [5], smart health care [6] and automatic disaster recovery [7]. To accelerate the development of these technologies, accompanying techniques such as fog computing [8], unmanned aerial vehicles (UAVs) [9], [10], and blockchain [11] have been introduced to tackle communication, computation and security challenges. However, the items to be connected are widely distributed. For remote areas such as seas, mountains, and depopulated zones, traditional cellular base stations (BSs) are still difficult to deploy [12]. In this sense, satellites could provide global coverage, and it is necessary to combine satellite and terrestrial communications to embrace the coming ubiquitous IoT world.

When talking about satellite communications (SatComs), there are several problems that need to be taken into account. First, the distance of a satellite link is much longer than the distance of a terrestrial link. Thus, the path loss of SatComs is very high, which requires ground terminals to be equipped with high-power transmitters and high-sensitivity receivers. As a result, it is difficult to keep the terminals small. Second, the beam spots from adjacent satellites may overlap, resulting in severe inter-satellite interference. Thus, the cost of providing broadband communication services via satellites is very high. It is of great interest to combine satellite and terrestrial networks to make use of the wide coverage of satellites and the high capacity of terrestrial networks [13] [14].

There have been a few key milestones in the conceptualization and development of hybrid satellite-terrestrial networks (HSTNs). The concept of HSTNs originated in 1964 [15] and 1965 [16], [17], where mutual interference between BSs and fixed terminals (FTs) was studied. In 1983, Lee et al. first introduced the symbiosis of mobile satellites and terrestrial systems and discussed key issues [18]. Later, in 1988, Rich-
Table I: Abbreviations.

| Abbreviation | Full name |
|--------------|-----------|
| 3GPP         | 3rd Generation Partnership Project |
| 5G           | fifth-generation |
| ADMM         | alternating direction method of multipliers |
| AF           | amplify-and-forward |
| ARQ          | auto repeat request |
| ASER         | average symbol error rate |
| AWGN         | additive white Gaussian noise |
| BS           | base station |
| CCI          | channel interference |
| CNR          | carrier-to-noise ratio |
| CSI          | channel state information |
| D2D          | device-to-device |
| DF           | decode-and-forward |
| Diffserv     | differentiated service |
| EC           | ergodic capacity |
| eMBB         | enhanced mobile broadband |
| FEC          | forward error control |
| GEO          | geostationary earth orbit |
| GMT          | ground mobile terminal |
| HAP          | high-altitude platform |
| HMT          | hybrid mobile terminal |
| HSTN         | hybrid satellite-terrestrial network |
| IntServ      | integrated service |
| IoT          | Internet of Things |
| IP           | Internet Protocol |
| ITU          | International Telecommunication Union |
| LEO          | low earth orbit |
| LOS          | line of sight |
| MEC          | mobile edge computing |
| MEO          | middle earth orbit |
| MGF          | moment generating function |
| MIMO         | multiple input multiple output |
| MISO         | multiple input single output |
| MMSE         | minimum mean squared error |
| mMTC         | massive machine type of communication |
| mmWave       | millimeter wave |
| MPSK         | multiple phase shift keying |
| MPTCP        | Multipath Transmission Control Protocol |
| MRC          | maximum ratio combination |
| NFV          | network function virtualization |
| NLOS         | non-line of sight |
| NOMA         | nonorthogonal multiple access |
| NTN          | non-terrestrial network |
| OP           | outage probability |
| PDF          | probability density function |
| PoA          | point of attachment |
| PU           | primary user |
| QoE          | quality of experience |
| QoS          | quality of service |
| QUIC         | Quick User Datagram Protocol Internet Connection |
| RTT          | round trip time |
| RSVP         | Resource Reservation Protocol |
| SaT5G        | satellite and terrestrial network for 5G |
| SatCom       | satellite communication |
| SC           | selective combination |
| SCTCP        | Stream Control Transmission Protocol |
| SDN          | software defined networking |
| SER          | symbol error rate |
| SFT          | satellite fixed terminal |
| SIMO         | single input multiple output |
| SINR         | signal-to-interference-plus-noise ratio |
| SISO         | single input single output |
| SMT          | satellite mobile terminal |
| SNIR         | signal-to-noise ratio |
| SU           | second user |
| TCP          | Transmission Control Protocol |
| TerCom       | terrestrial communication |
| UAV          | unmanned aerial vehicle |
| V2V          | vehicle-to-vehicle |

haria et al. introduced the synergy of mobile satellites and terrestrial systems [19]. In 1992, Caini et al. introduced a satellite-terrestrial system and proposed a co-channel interference (CCI) evaluation [20]. The interference from terrestrial sources to satellite receivers was investigated in 1992 [21] and 1993 [22]. In 1995, Ananasso et al. considered the integration of SatComs and terrestrial networks [23]. In 1996, Bond et al. proposed the same idea as in [23] from a business perspective [24].

With the development of the 5G networks, the integration of satellites and 5G networks has attracted much attention from standardization organizations, companies and research institutes. Several organizations, such as the 3rd Generation Partnership Project (3GPP) and the International Telecommunication Union (ITU), have set up special working groups for the standardization of HSTNs. The ITU has proposed four application scenarios for satellite-5G integration and the key factors that must be considered to support these scenarios, such as intelligent routing and dynamic caching. The 3GPP has defined the deployment scenarios of non-terrestrial networks (NTNs) in 5G networks, including 8 enhanced mobile broadband (eMBB) scenarios and 2 massive machine-type communication (mMTC) scenarios [25]. Some enterprises have also conducted researches on satellite-terrestrial integration. In 2018, Satellite and Terrestrial Network for 5G (SaT5G) experimentally demonstrated the architecture of HSTNs, where a pre-5G test platform using software defined networking (SDN), network function virtualization (NFV) and mobile edge computing (MEC) technologies was integrated with geostationary earth orbit (GEO) satellites [26]. By February 2020, SaT5G finished the demonstration of 5G hybrid backhaul on the Zodiac Inflight Innovations testbed, which not only adopts network virtualization in both satellite and terrestrial components but also achieves integrated resource management and orchestration [27]. In September 2020, European Space Agency announced the completion of SatNex IV project and finished the early assessment of promising terrestrial telecommunication technology spinning into space applications [28].

Different from a separate terrestrial or satellite network, the establishment of an efficient HSTN still faces several challenges. First, the diverse cooperative patterns and models in the HSTN, such as cognitive cooperation, relaying, and multi-radio cooperation, make it difficult to analyze the overall performance. It is necessary to divide the HSTN into separate cooperation segments for performance analysis and resource allocation. Second, due to the unbalanced resources and different protocols between terrestrial and satellite networks, as well as among different cooperation segments, the heterogeneous HSTN requires innovative technologies in the network layer with respect to mobility management, route scheduling, etc., to better satisfy the constraints imposed by each network segment. Third, the development of 5G and beyond 5G networks has put forward higher quality of service (QoS) requirements. How to facilitate innovative services using the latest technologies, such as artificial intelligence and blockchain technologies, is still an open issue [29].

To date, several survey papers have reviewed HSTNs from different perspectives. In particular, the authors of [30] in-
investigated the channel models and terrestrial interference for satellite television broadcasts. Focusing on the network and transportation layers, the authors of [31] investigated the challenges, opportunities, and solutions of HSTNs. The authors of [32] conducted a survey on the QoS performance of the HSTN. In [33], a review of several important issues related to HSTNs was presented, such as network design and optimization. In [34], a comprehensive survey of the converged satellite and terrestrial network was presented. The authors provided a generic overview of the representative architectures, present researches and evaluation works of different satellite-terrestrial networks. The open issues and future challenges were also discussed.

The above surveys provided very useful discussions on the concept, challenges, and key technologies of HSTNs from different perspectives, such as channel models, the network framework, and cross-layer optimization. However, to the best of our knowledge, the basic cooperative models in HSTNs have not been investigated. Due to the significant difference between SatComs and terrestrial communications (TerComs) in terms of channel fading, transmission delay, mobility, and coverage performance, a large-scale HSTN can not be simply decomposed into a sum of separated satellite and terrestrial links. The gap between mature link analysis and network evaluation need to be filled, so as to uncover the complete picture of HSTNs. Towards this end, we may consider the HSTN as a combination of basic cooperative models, which contain the main traits of satellite-terrestrial integration, but are much simpler and thus more tractable than the whole network. In this paper, we present three basic cooperative models for HSTNs and provide a survey of the state-of-the-art technologies for each of them. We investigate some main problems and their solutions, including cooperative pattern, performance analysis and resource management issues. We also discuss open issues to envision an agile, smart, and secure HSTN for 6G ubiquitous IoT.

The remainder of the paper is organized as follows. In Section II, an overview of HSTNs, including the coordination patterns and satellite-land channel models, is presented. In Section III, we discuss three basic cooperative models used in HSTNs and present the corresponding challenges and solutions. Section IV reviews the works on the network layer of HSTNs, including mobility management, routing, caching, and security issues. Some open issues for the development of future 5G-HSTNs, such as the utilization of SDNs, cognitive radio, artificial intelligence, and blockchain technologies, are discussed in Section V. Finally, conclusions are given in Section VI. The contents and architecture of this paper are shown in Fig. 1. The abbreviations used in the paper are listed in Table I.

II. SYSTEM SCENARIO

As depicted of in the bottom of Fig. 2, the HSTN is an integration of satellite networks and terrestrial networks. The BSs, ground mobile terminals (GMTs) and backbone on the ground together make up the terrestrial networks. The BSs can access the cloud through wired backhaul. The GEO satellites, low/middle earth orbit (LEO/MEO) satellites, satellite terminals (STs) including satellite mobile/fixed terminals (SMT/SFT), hybrid mobile terminals (HMTs)\(^1\), gateways, and high-altitude platforms (HAPs)\(^2\) make up the satellite networks. In the HSTN, satellite networks and terrestrial networks are integrated together. Satellites can access the cloud from gateways [35]. In urban areas, the cellular BS and the GMT coexist with the satellite receiver, and CCI is an important problem. In suburban areas such as those near the sea, SatComs can be jointly used to provide seamless connections. HMTs can gain access to terrestrial BSs when they are within the coverage of BSs and could communicate via satellites when terrestrial BSs are not available. In remote regions such as desert, far sea, and rural areas, where cellular services are hardly available, satellites can

\(^1\)In this paper, we refer to dual-mode mobile terminals, which can be used for both SatComs and TerComs, as HMTs.

\(^2\)Planes or airplanes can serve as relays for SatComs and can be referred to as HAPs.
Fig. 2. Illustration of a HSTN, which is composed of satellite, aerial, and terrestrial domains. Focusing solely on wireless links, the HSTN can be considered as a combination of three basic cooperative models: Model $X$, Model $L$, and Model $V$.

provide communication services, and terrestrial BSs usually work as relays to forward signals between satellites and STs [36] [37]. In a word, the coverage for incomplete terrestrial networks can be much strengthened in HSTNs through careful satellite constellation design [38]. In addition, ultra-dense LEO networks can achieve efficient data offloading [39]. Airships and airplanes can serve as high-altitude relays [40], and UAVs can provide complementary coverage [41]. Thus, the HSTN is composed of satellite, aerial, and terrestrial domains [42] [43].

To analyze such a large-scale HSTN, it is impossible to treat the network as a whole due to the high complexity and the evaluation of a single transmission between a satellite and a ST or a BS and a GMT neglects difference patterns of satellite and terrestrial components. As an alternative, considering a package of links in the same cooperative model is more feasible. And thus the basic cooperation model abstracted from HSTNs, as shown in the second layer of Fig. 2 can fill the gap of link levels and network levels and give a more clear sight to uncover a complete picture of HSTNs.
A. Cooperative patterns

From the perspective of channel usage, satellite and terrestrial networks cooperate with each other mainly in two modes. In the first mode, satellite and terrestrial networks complementarily transmit a part of data, and both mutually construct a closed-loop network. In the other mode, there is no service distinction between satellite and terrestrial networks. In other words, satellite and terrestrial networks independently serve their own traffic at the same time.

1) With data separation: In the cooperation mode of data separation, satellite networks and terrestrial networks can take different responsibilities according to their own characteristics. According to the service division, three aspects have been considered: uplink and downlink, user plane and control plane, and fronthaul and backhaul.

   a) Uplink and downlink separation: In uplink and downlink separation, satellite and terrestrial networks provide uplink and downlink services separately. In 1997, Baras first proposed a scheme in [44], where satellite networks offer downlink broadcast services and terrestrial networks provide uplink services. Because satellites have wide coverage, using satellites to provide broadcast services and using terrestrial BSs for uplink services could enhance the spectrum efficiency. If the number of users for broadcasting is large enough, this scheme could also improve the energy efficiency.

   b) User plane and control plane separation: In this data separation, satellite and terrestrial networks provide user data and control data separately. On the one hand, the broadcast characteristics of the satellite network make it very suitable to transmit data for a large population at one time, such as distance learning, live broadcast, and television broadcast. However, the channel of SatComs is not ideal, and some users may endure more severe fading. As a result, bit errors and transmission failures are inevitable. For HSTNs, terrestrial networks can handle the control data and automatic repeat request (ARQ) data. For nonreal-time service, hybrid ARQ schemes could be used, where satellites provide high-speed data services and terrestrial networks transmit the control data of ARQ. For real-time scenarios, adaptive forward error correction (FEC) schemes can be used [45]–[47]. On the other hand, satellites could provide wide coverage and seamless connections. In this sense, satellites are suitable for taking charge of system signaling, public information, and some data for delay-tolerant users, while terrestrial networks serve users with high-capacity requirements and delay-sensitive users. In addition, the broadcast property of the satellite makes it suitable for global and local control when the SDN network is considered. The authors of [48]–[50] analyzed the performance of control and user separation in HSTNs. In [48], both centralized management and distributed management strategies were investigated. In [49] and [50], the tradeoff between energy efficiency and spectrum efficiency with control and user decoupling was studied for different user densities of the cell. Recently, a hierarchical architecture was proposed in [51], where the GEO satellite plays the role of master controller and the MEO satellites work as relays to connect terrestrial gateways, with LEO satellites acting as access points to provide services to users.

   c) Fronthaul and backhaul separation: For areas without wired backhaul, satellites could provide wireless backhaul for terrestrial BSs [52]–[54]. Satellite backhaul could extend the communication coverage to remote areas, improve the network stability, offer a more flexible networking architecture, help offload the traffic of terrestrial networks, and relieve the stress in the case of congestion [54]. The flow control, link scheduling [52], handover [53], and traffic management [54] strategies for the satellite-backhaul architecture are different from those of traditional networks, as the bandwidth of satellite backhaul is much smaller than fiber backhaul and the delay is much longer.

2) Without data separation: A large number of works have studied satellite-terrestrial coordination through the sharing of spectrum, time, power, and spatial resources. In these scenarios, both satellite and terrestrial stations deal with the same types of data.

B. Difference between SatComs and TerComs

In SatComs, the signal propagation environment is quite different from that of terrestrial channels [30], [55], such as the existence of rain attenuation [56]–[60]. In [56], the influence of the coupling between satellite and terrestrial radios due to rain attenuation was analyzed. In [61], a unified multiple input multiple output (MIMO) channel model for mobile satellite systems with ancillary terrestrial components was presented. In [62], [63], some approaches to predicting satellite channel statistics were proposed. The interference impact between two links was also discussed.

In addition to the channel models, there is also a significant difference between SatComs and TerComs in transmission delay, mobility, and coverage performance, as depicted in Table II. Moreover, HSTNs need to serve a large number of users with various QoS requirements under limited spectrum and power resources. Resource reuse presents complex and varied interference under the influence of dynamic services, which directly restricts system capacity and performance. Therefore, the cooperative model plays an important role in the performance of HSTNs.

III. Basic Cooperative Models

IV. System Scenario

In a basic HSTN, there exist one satellite

1. A cooperative pattern

2. A system scenario

In an SDN network, one satellite

Because the network is similar for satellites at different orbits, we draw only one satellite to represent a GEO/MEO/LEO satellite.
Table II: Comparison between SatComs and TerComs.

| Characteristics       | SatComs                                                                 | TerComs                                                                 |
|-----------------------|------------------------------------------------------------------------|------------------------------------------------------------------------|
| Wireless channel      | Higher propagation loss                                                | Lower propagation loss                                                |
|                       | Mainly affected by atmosphere and rain                                 | Mainly affected by blocks and scatters                                 |
|                       | Mostly Rician channels (with a direct path)                            | Mostly multipath channels (Rician channels in open areas)              |
|                       | High Doppler frequency offset for MEO/LEO satellites (e.g., approximately 35.4 kHz for Iridium) | Low Doppler frequency offset for low-speed GMTs                        |
| One-way transmission delay | High GEO satellites: approx. 270 ms                                    | Low 4G: less than 10 ms                                                |
|                       | MEO satellites: approx. 130 ms (e.g., for O3b)                          | 5G: less than 1 ms                                                    |
|                       | LEO satellites: less than 40 ms (e.g., 10–30 ms for Globalstar)        |                                                                       |
| Mobility              | GEO satellites: static to earth                                        | Cellular communications: static                                        |
|                       | MEO/LEO satellites: fast (e.g., period less than 130 min for Globalstar)| Device-to-device (D2D) and vehicle-to-vehicle (V2V) communications: up to hundreds of kilometers per second |
| Coverage              | Wide                                                                    | Limited                                                                |
|                       | Wide beam: over 100 km with a single beam for GEO satellites           | 4G: 500–2000 m for a single cell in urban areas                       |
|                       | Spot beam: depends on the beam width and altitude                      | 5G: 100–300 m for a single cell in urban areas                        |

Fig. 3. Illustration of the system structure for Model X, Model L, and Model V.

- Model V: a satellite cooperates with a terrestrial BS to serve the same terrestrial user (HMT) simultaneously. The two lines in V represent the satellite link and the terrestrial link, while the intersection denotes the HMT.

In this way, an arbitrary HSTN can be considered as a combination of these aforementioned cooperative models, and studies on each model will contribute to uncovering the complete picture of HSTNs.

A. Model X

As shown in the left of Fig. 3, when a satellite and a terrestrial BS share the same wireless resources to communicate with the ST/GMT, the satellite link and the terrestrial link will cause mutual interference [64] [65]. The interference from terrestrial users to satellites has been studied by infield measurements and simulations [66]. Different from the CCI between two links in a single satellite or terrestrial network, the interference patterns in Model X are diverse and complicated, depending on satellite-terrestrial differences such as the wireless channels and beam/cell coverage.

The main interference in urban and rural areas differs greatly due to the different coverages of a single beam/cell between SatComs and TerComs [67]. In urban areas, the satellite user and terrestrial user coexist, and each receiver can receive undesired co-channel signals. For the ST, the interference from adjacent BS is the main interference, having more of impacts than the interference from the GMT. For the satellite, the interference from the GMT is negligible compared to the interference from the BS. For the BS and the GMT, the interference from neighboring ST is much stronger than that from the satellite, as satellite signals endure more severe fading. The gateway may also experience interference from the BS when they are close to each other. The relative position of the BS and the gateway could be designed to mitigate this interference [68].

In rural areas, the interference between the ST and the BS and between the ST and the GMT can be ignored because they are far away from each other. For the BS, the interference from the satellite is much smaller than the desired signal from its ground user and can be neglected. For the GMT, the interference from the satellite is much smaller than the desired signal from its belonged BS and can also be neglected. For the satellite, the interference from the BS is the main interference, and the interference from the GMT can be ignored [69].
In the following, we discuss the core problem of Model X for the above two scenarios as well as various channel models from the perspectives of system performance and resource management and then suggest some future works for this model.

1) Performance: A large number of papers have analyzed the performance of HSTNs under Model X, including symbol error rate (SER), average symbol error rate (ASER), capacity, ergodic capacity (EC), and outage probability (OP) [70]–[74]. We summarize the works on the system performance under Model X in Table III. The OP is defined as the probability when the capacity $C$ is below the target capacity $R$, i.e.,

$$\text{OP}(R) = \Pr[C < R]. \quad (1)$$

For terrestrial links, the Nakagami model is typically used. With the channel gain denoted by $h$, the probability density function (PDF) of $h^2$ in this model follows [75]

$$f(x; m, \Omega) = \frac{2m^m}{\Gamma(m)\Omega^m} x^{2m-1} \exp\left(-\frac{m}{\Omega} x^2\right) \quad (2)$$

where $m = \frac{E[X^2]}{\text{var}[X^2]}$, which indicates the fading severity and the curve of the PDF, and $\Omega = E[X^2]$ is the average power of the received signal [76].

The Rayleigh model is also used for non-line of sight (NLOS) terrestrial links. The PDF of $h^2$ in this model follows [77]

$$f(x) = \frac{1}{2b} \exp\left(-\frac{x}{2b}\right) \quad (3)$$

where $2b$ is the average power of the multi-path components.

Assuming that $W$ is the system bandwidth, $N_0$ is the noise power, $P$ is the transmitting power of the designed signal, $H$ is the channel gain of the transmitting channel, $P_i$ is the transmitting power of the $i$th interference source, and $H_i$ is its channel gain, the capacity for Model X can be expressed as

$$C = W \log\left(1 + \frac{PH}{N_0 + \sum_i P_i H_i}\right). \quad (4)$$

For rural areas, the interference from the BS and the GMT to the satellite is the main interference [78] [79]. There may exist a direct signal path, and the Rician fading channel could be used. The PDF of $h^2$ can be calculated as [80]

$$f(x) = \frac{x}{\sigma^2} \exp\left(-\frac{x^2 + \nu^2}{2\sigma^2}\right) I_0\left(\frac{vx}{\sigma^2}\right) \quad (5)$$

where $\nu^2$ is the power of the line of sight (LOS) component, $\sigma^2$ is the sum of the power of NLOS components, and $I_0(\cdot)$ is the first kind modified Bessel function with zero order. In general, $K$ is defined as the ratio of the power of the LOS signal to the power of the multipath components, and $K = \frac{\nu^2}{\sigma^2}$. When $K = 0$, there is no LOS component, which degenerates to Rayleigh fading. The authors of [78] and [79] studied the capacity for satellite links with Rician fading. An upper bound capacity of single input multiple output (SIMO) uplinks from SFTs to the satellite was given in [78]. The decoding capacity and the minimum mean square error (MMSE) capacity under terrestrial interference were derived in [79].

For urban areas, the interference between the BS, the GMT and the ST is the main interference, which has been widely investigated. The performance of the ST with interference from the BS was studied in [81]–[83]. In [81] and [82], the satellite transmits to a ST as the primary user (PU) in the millimeter wave (mmWave) band, the BS with multi-antennas transmits to a GMT as the second user (SU), and the interference from the BS to the ST is considered. The EC of terrestrial users was derived in [81]. The authors of [82] considered a single input and single output (SISO) downlink and gave a closed-form expression of the OP of the SU with PU’s interference under a given threshold. In [83], the interference from the satellite and adjacent BSs to cellular users was considered, and a closed-form expression of the OP was derived. The performance of the ST with interference from the BS was studied in [74] and [84]. In [74], the interference from the satellite to the GMT and the interference from the BS to the ST were considered, and a closed-form expression of effective capacity based on the moment generating function (MGF) for the satellite link was derived. The authors of [84] analyzed the interference between fixed-satellites and terrestrial radio relay services with measuring data. The performance of both the ST and the GMT with interference from the BS was studied in [85], and the relationship among the diversity gain, fading parameter, and shadowing parameter was presented.

In the above studies, the Shadowed-Rician fading channel was the most widely used channel model between the satellite and the ground station [74], [83], [85]. The PDF of $h^2$ in this model can be calculated as [80]

$$f(x) = \frac{1}{2b} \left(\frac{2mb}{2bm + \Omega}\right)^m \exp\left(-\frac{x}{2b}\right) I_1(m; 1; \frac{\Omega}{4b^2m + 2\Omega}) \quad (6)$$

where $m$ is the Nakagami parameter, $\Omega$ is the power of the LOS component, $2b$ is the sum of the power of the NLOS components, and $I_1(\cdot; \cdot; \cdot)$ is the confluent hypergeometric function [75]. It can be seen that the Shadowed-Rician fading degenerates to Rayleigh fading when $m = 0$, and degenerates to Rician fading when $m = 1$.

In [86], the authors analyzed the interference of the HSTN with dual satellite/terrestrial terminals. In [87], the authors investigated the OP and EC of satellite uplinks under the consideration of imperfect channel state information (CSI). In [88], the author analyzed the interference level of the terrestrial fixed service and the capacity of cognitive fixed satellite service in light of standard recommendations of the ITU, which offer a useful guideline for the coexistence scenario.

2) Resource management: To enhance the spectrum efficiency, the spectrum is usually shared. How to manage radio resources, including the spectrum, power and beams, remains to be investigated. The main literature on resource management for HSTNs is summarized in Table IV.

a) Power allocation: Power allocation has been extensively studied to enhance the system performance of HSTNs under Model X. In [89], the authors proposed a power control algorithm under the QoS requirement. In terms of capacity optimization, the authors of [90] studied the power control scheme when the satellite uplink and the terrestrial downlink coexist in the Ka band. In [91], the authors proposed a power allocation scheme to mitigate the intercomponent interference between satellite beams and terrestrial cells with spectrum
Table III: Performance analysis for Model X and the major satellite-terrestrial differences considered.

| Scenario | Channel difference (satellite/terrestrial) | Delay difference | Interference model (due to the coverage difference) | Performance parameters | Achievements and analytic tools |
|----------|--------------------------------------------|------------------|-----------------------------------------------------|------------------------|--------------------------------|
| Satellite to SFT, SISO, downlink | Yes (log-normal / cluster based scattering) | No (both space propagation loss) | BS interferes SFT | OP of GMT | Closed-form expression with constraints for PU, approximation of Gamma distribution [82] |
| | No (both Rician / Nakagami-m) | Yes (synchronal receiving assumed) | Satellite interferes cellular users, BS interferes SFT | Effective capacity of SFT | Closed-form expression [83] |
| | Yes (Shadowed-Rician / Suzuki) | No (both Rician fading channels) | BS interferes SFT, satellite interferes GMT | OP and EC of SFT and GMT, diversity/coding gain | Unified closed-form analysis, the diversity/coding gain relationship, the fading parameter, the shadowing parameter [85] |
| SFT to satellite, SIMO, uplink | No (both rain-fading with log-normal distribution) | SFT interferes the terrestrial receiver | Capacity of the satellite | Capacity of the satellite | Approximation of optimal joint decoding capacity and MMSE capacity with Haar measuring [79] |

reuse. In [92], the authors proposed an alternating direction method of multipliers (ADMM) based power control scheme to optimize the uplink throughput for cognitive HSTNs. The authors of [93] investigated the power control scheme to optimize the delay-limited capacity and the OP for real-time applications. In [94], the authors proposed a centralized power control scheme in cognitive radio networks using modulation and coding classification feedback. In addition to the central processing, the author of [95] proposed a distributed power allocation scheme based on game theory to reduce the overhead of central control. By taking the mobility of LEO satellites, the authors of [96] investigated the power control scheme to maximize the capacity and minimize the OP. The authors of [97] investigated a joint power allocation and channel access scheme to maximize the terrestrial user rate. Moreover, the authors of [98] considered a cognitive HSTN where the BS and the UAV serve a GMT cooperatively using the licensed spectrum of the satellite, and optimized BS/UAV transmit power to maximize the achievable rate of the GMT.

Energy efficiency is also very important for HSTNs because the load of satellites is always limited. In [99], the authors proposed a power allocation scheme in cognitive satellite-vehicular networks to provide a tradeoff between energy efficiency and spectral efficiency. In [100], an energy efficient power allocation strategy was proposed for cognitive HSTNs under delay and interference constraints. More recently, the authors of [101] investigated an energy efficient power allocation scheme with the outdated CSI. The interference constraint of terrestrial components and the minimal rate requirements of satellite networks were also considered.

b) Spectrum sharing and frequency allocation: To tackle the spectrum scarcity problem, reasonable planning of spectrum resource usage has aroused wide concerns in the literature. The authors of [102] studied the spectrum sharing strategy and the mutual interference between the satellite link and the terrestrial link was considered. The authors of [103] used a database approach for spectrum sharing in the Ka band. In [104], a large-scale CSI based spectrum sharing strategy for HSTNs was proposed. By applying the exclusive zone for interference mitigation, the authors of [105] proposed a cognitive spectrum sharing and frequency reuse scheme for HSTNs, to improve the energy efficiency and intercell fairness. In [106], the authors provided a distributed resource allocation algorithm for cognitive HSTNs under non-ideal spectrum sensing. In [107], joint beamforming and carrier allocation for the satellite downlink and joint power allocation, carrier allocation, and bandwidth allocation for the satellite uplink were studied. In [108], the authors proposed a carrier allocation scheme between satellite and terrestrial wireless backhaul. In [109], the resource allocation algorithm was designed to reduce the interference with imperfect CSI with consideration of the uplink interference from the BS to the GEO satellite. Recently, the tradeoff between user fairness and efficiency was discussed in [110].

c) Beamforming: The beamforming scheme could mitigate complicated interference and combat high path loss. Combined with the technique of mmWave communications, beamforming could greatly improve the spectrum efficiency as well [111]. For uplink transmission [69], [112]–[114], Khan et al. proposed an iterative turbo beamforming algorithm
Table IV: Resource management for different models and the major satellite-terrestrial differences considered.

| Model  | Goal  | Schemes                                | Achievements and analytic tools                                                                 | Channel difference | Delay difference |
|--------|-------|----------------------------------------|--------------------------------------------------------------------------------------------------|---------------------|------------------|
|        |       | Capacity                               | Effective capacity under QoS requirements, with both perfect and imperfect CSI considered [89]    | Yes                 | Yes              |
|        |       |                                        | Power control of STs to reduce the interference affecting terrestrial links [90]                  | Yes                 | No               |
|        |       |                                        | Spectrum reuse between satellite beams and terrestrial cells, power allocation to mitigate interference according to the traffic demand [91] | Yes                 | No               |
|        |       |                                        | Delay-limited capacity under average and peak power constraints [93]                            | Yes                 | Yes              |
|        |       |                                        | Power allocation of both the satellite and terrestrial BSs in a distributed way based on game theory [95] | Yes                 | No               |
|        |       |                                        | Power control schemes from long-term and short-term perspectives to tackle spectrum sharing problems [96] | Yes                 | No               |
| Model X|       | Energy                                 | Improving the spectrum efficiency in the S band by beamforming and spectrum coordination between satellite and terrestrial components [102] | Yes                 | No               |
|        |       |                                        | Database approach [103]                                                                           | Yes                 | No               |
|        |       |                                        | Spectrum sharing using large-scale CSI [104]                                                      | Yes                 | No               |
|        |       | Spectrum sharing and carrier allocation | Joint beamforming and carrier allocation for the satellite to the SFT [107]                     | Yes                 | No               |
|        |       |                                        | Sequential carrier allocation between satellite and terrestrial systems [108]                    | Yes                 | No               |
|        |       |                                        | Carrier and power allocation with imperfect CSI for interference reduction, using dual decomposition [109] | Yes                 | No               |
|        |       | Delay                                  | Joint power and subchannel allocation of the satellite uplink with the OP constraint required by terrestrial users [110] | Yes                 | No               |
|        |       |                                        | Power and bandwidth allocation based on nonideal sensing in a distributed manner [106]           | Yes                 | No               |
| Model V| Capacity| Access selection                       | Improving the mean service time [176]                                                          | Yes                 | Yes              |
|        |       |                                        | Power allocation, route path selection and beamforming                                            |                     |                  |
|        |       |                                        | Satellite and gateway selection, cross-layer optimization to improve the throughput [177]       | Yes                 | Yes              |
| Model L| Energy| Power allocation and relay selection   | Multi-relays, mixed binary and fractional optimization problem, binary relaxation and dual decomposition [167] | Yes                 | No               |
|        |       | Power and subchannel allocation        | Power allocation for satellite and satellite-terrestrial terminal and subchannel allocation of ground downlink offloading, a binary search aided algorithm [171] | Yes                 | No               |
|        |       |                                        | Maximize the sum throughput under delay constraints of delay-sensitive services [172]          | Yes                 | Yes              |

Moreover, some novel techniques and practical assumptions were investigated by combining with the beamforming scheme. In [120] and [121], the authors proposed beamforming schemes to maximize the minimal achievable secrecy rate of the information receivers and minimize the total transmit power with eavesdroppers, respectively. In [122], the scenario where a UAV was regarded as a malicious eavesdropper was studied. The authors of [123] investigated the joint beamforming of satellite and terrestrial components where ground users were grouped into clusters based on the non-orthogonal multiple access (NOMA) technique. To explore the mmWave band in HSTNs, the authors of [124] optimized the downlink beamforming of terrestrial BSs with the interference probability constraint of satellite users. More recently, the authors of [125] investigated downlink beamforming with imperfect CSI and a nonlinear power amplifier. By making the most of the environmental and location information, the authors of [126] optimized the precoding matrix of maritime mobile users to maximize the ergodic sum capacity. To date, many studies have investigated the applications of MIMO for HSTNs. We summarize these studies in Table V.

3) Summary: In this subsection, we have reviewed the performance and resource allocation schemes for Model X in HSTNs. Most existing works focused on the satellite-terrestrial
differences in wireless channels and coverage performance, while the delay difference was ignored. In addition, performance analysis and resource allocation based on a general statistical model (such as [127]) instead of a practical channel for certain scenarios are still lacking.

In the future, the interference mechanism suitable for different scenarios will need to be clarified. On that basis, the signal waveform can be optimized in terms of time, space and frequency to match the characteristics of interference. In particular, the delay and coverage differences need to be addressed in the time domain and the spatial domain.

B. Model L

As shown in the middle of Fig. 3, there exist one satellite, one satellite relay and one destination user in Model L, where the terrestrial transceiver serves as a relay between the satellite and the terrestrial user. For urban areas, the relay can enhance the transmission of satellite-STs and for remote areas like suburban, rural, desert and sea, it can provide wide and reliable connections. In addition to the satellite-terrestrial differences in wireless channels and beam/cell coverage, which impact the performance of Model X, the delay difference is also a critical factor concerning the user QoS in Model L. In the following, we discuss the core problem of Model L from the perspectives of system performance and resource management and then suggest some future works for this model.

1) Performance: For Model L, the channel model from sources to relays is different from that of traditional terrestrial relays, and the performance of relay systems depends on the relay mode. We summarize the literature on the performance of Model L in Table VI.

a) Amplify-and-forward (AF) relaying: In AF mode, the relay amplifies the received signal from the satellite and then forwards it to the destination. Assuming $h_{sr}$ is the channel gain from the satellite to the relay, $h_{sd}$ is the channel gain from the satellite to the destination, $h_{rd}$ is the channel gain from the relay to the destination, and $x$ is the transmitting symbol of the satellite, the signal received at the receiver $y_{sr}$ can be expressed as

$$y_{sr} = h_{sr}x + e_{sr}$$

where $e_{sr}$ is the channel noise with variance $\sigma_{sr}^2$. The signal from the satellite to the destination $y_{sd}$ can be expressed as

$$y_{sd} = h_{sd}x + e_{sd}$$

where $e_{sd}$ is the channel noise with variance $\sigma_{sd}^2$. When the signal from the satellite to the destination is too weak, $h_{sd}$ and $y_{sd}$ can be assumed to be zero. Assuming the relay amplifies $y_{sr}$ by a factor of $G$, the signal from the relay to the destination $y_{rd}$ can be expressed as

$$y_{rd} = G h_{rd} y_{sr} + e_{rd}$$

where $e_{rd}$ is the channel noise with variance $\sigma_{rd}^2$. When the maximum ratio combination (MRC) is used, the signal-to-noise ratio (SNR) at the destination $\gamma_d$ can be expressed as

$$\gamma_d = \frac{G^2 |h_{sr}|^2 |h_{rd}|^2 E_s}{G^2 |h_{rd}|^2 \sigma_{sr}^2 + \sigma_{rd}^2}$$

(10)

where $\gamma_{rd}$ is the SNR from the relay to the destination, $\gamma_{sd}$ is the SNR from the satellite to the destination, and $E_s$ is the power of symbol $x$.

Most of the existing literature on the performance of Model L in the HSTN focuses on the performance achieved using one-way relay, including the SER, ASER, OP and EC. For the one-way relay, the source transmits to the relay in the first phase, and the relay forwards the received signal to the destination in the second phase. In [128], the OP is derived with AF relays over non-identical fading channels. In [129], the authors analyzed the OP and the SER of the Alamouti HSTN. The ASER of multiple phase shift keying (MPSK) was derived for different terrestrial channels in [80] and [130]. In addition, with the introduction of a multi-antenna relay, the ASER was derived under a proposed beamforming scheme in [131]. In [132], the distributions of the SNR and the ASER were provided for the HSTN where the relay node and the destination node could receive CCI from terrestrial networks. In [133], an approximate closed-expression of the EC was derived with a single-antenna relay, a multi-antenna satellite, and a multi-antenna mobile station. In [134], the system capacity and the OP were analyzed. In [135], the authors analyzed the OP of NOMA-based HSTNs with multiple terrestrial users. In addition, the authors of [136] investigated the NOMA technique with an AF relay that not only forwards the signal of the satellite user but also transmits its own signal to the terrestrial user. The OP expressions of two users were presented, showing great superiority of the NOMA scheme. Furthermore, the authors of [137] investigated a similar scenario where multiple satellite PUs employ the NOMA scheme while sharing the same spectrum with a SU, and the OP performance was analyzed.

In addition to a single relay, the HSTN with multiple relays has been widely investigated [138]. In [76], spectrum sharing between the satellite PU and terrestrial SUs was considered, and the OP of the PU was minimized by selecting the best BSs as relays. In [139], the OP with multi-hop AF relays was analyzed, where the destination node uses the MRC strategy. In [140], the problem of relay selection with multi-antenna satellites was investigated. In [141], the OP of a multi-relay multi-user HSTN was analyzed, and the authors presented a relay selection scheme based on the rain attenuation value to improve the OP performance. In [142], the authors analyzed the OP of AF-HSTNs and derived a closed-form expression of the MGF. Recently, the authors of [143] focused on a MIMO-enabled HSTN where the satellite, relay and user are all equipped multiple antennas.

In addition to the above works, some special scenarios have also been discussed. The authors of [144] derived the ASER and the average capacity for AF-HSTNs with imperfect CSI. In [145], the OP was derived with multiple users and an AF relay to illustrate the impact of outdated CSI and CCI.
The performance of the two-way relay was investigated in [146], [147]. In this scheme, there are two sources (satellite and GMT) and one relay. The two sources transmit to the relay in the first slot, and the relay transmits to the sources in the second slot. In [148], the authors proposed an energy harvesting based spectrum sharing scheme for the HSTN, and analyzed the OP of both the satellite network and the terrestrial network. In [149], the OP performance of cache-enabled relays was investigated. Recently, the authors of [150] investigated an overlay HSTN where multiple IoT receivers work as relays to transmit data from the satellite to users and transmit their own signals to terrestrial IoT devices. Furthermore, the performance of this network was analyzed in terms of the OP under interference originating from extra satellite and terrestrial equipment.

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b) Decode-and-forward (DF) relaying: For HSTNs with multiple DF relays, the satellite broadcasts to multiple relays and the destination node in the first time slot, while in the second time slot, the relay decodes the received signal and forwards the decoded information to the destination.

For HSTNs with multiple DF relays, the satellite broadcasts to multiple relays and the destination node in the first time slot, while in the second time slot, the relays that can decode the received signal successfully forward it to the destination. Assuming that the transmission from the $i$th relay is $x_{r,d}$ and the channel gain from the relay to the destination is $h_{r,d}$, the signal from the relay to the destination $y_{r,d}$ can be expressed as

$$y_{r,d} = h_{r,d}x_{r,d} + e_{r,d}$$ (11)

where $e_{r,d}$ is the channel noise with variance $\sigma^2_{e_{r,d}}$. The SNR at the destination can be expressed as

$$\gamma_d = \frac{y_{r,d}^2}{\sum_{i \in C} \gamma_{r,d}}$$ (12)
Table VI: System performance for Model L and the major satellite-terrestrial differences considered.

| Relay mode | Relay number | Performance | Satellite link | Terrestrial link | Direct link from S to D | Achievements and analytic tools |
|------------|--------------|-------------|----------------|------------------|------------------------|--------------------------------|
| Single     | Single       | ASER        | Shadowed-Rician| Nakagami-m      | No                     | Performance analysis of single and multiple relays under two relay selection schemes [147] |
|            |              | ASER        | Shadowed-Rician| Nakagami-m      | Yes/No                 | Two underlying selection policies to minimize the OP [76] |
|            |              | OP          | Rician         | Rayleigh         | No                     | OP of satellite-relay-destination with beamforming performed in the relay [160] |
|            |              | ASER        | Shadowed-Rician| Nakagami-m      | No                     | OP analysis under imperfect CSI, power allocation to ensure user fairness [166] |
|            |              | OP          | Rician         | Rayleigh         | Yes                    | Selective decode-and-forward transmission, closed-form expression of symbol error probability using MGF [152] |
| Multiple   |              | OP          | Rician         | Rayleigh         | Yes                    | Best relay selection and analytical expression of OP using MRC and MGF [151], closed-form expression of OP [153] |
| Single     |              | OP          | Rician         | Rayleigh         | Yes                    | Selected decode-and-forward transmission, closed-form expression of symbol error probability using MGF [152] |
| DF         | Multiple     | OP          | Land mobile satellite fading | Rayleigh         | Yes                    | Best relay selection and analytical expression of OP using MRC and MGF [151], closed-form expression of OP [153] |

where $C$ is the set of relays that are selected to decode and forward the message. For the selective DF strategy, $C_{SDF} = \{ i | \gamma_{ri,d} > \gamma_{th} \}$, and for the best selection strategy, $C = \{ \arg \max_i \gamma_{ri,d} \} \cap C_{SDF}$.

In [155], the authors considered the mobility of nodes and derived the closed-form expression of SER under time-selective fading. In [156], the authors analyzed the EC with AF and DF protocols and proposed a relay selection strategy to lower the overhead. The capacity performance was also analyzed in [157] under two adaptive transmission schemes. In [158] and [159], the authors considered the impact of the carrier frequency offset and phase noise on the SINR with an adaptive-DF strategy. In [160], the OP of the satellite-relay-destination was derived for a cognitive HSTN with multi-antenna relays. By taking the hardware impairment into account, the OP performance was analyzed in [161]–[164]. The authors of [161], [165] focused on a NOMA-enabled single relay scenario, and in [162]–[164], multi-relay selection schemes were studied to improve the system performance. In addition, the NOMA scheme was discussed in [166], and both the AF and DF protocols were considered.
2) **Resource management:** Due to the asymmetric round-trip time (RTT), relay strategies that include power allocation, spectrum sharing and relay selection in HSTNs are quite different from terrestrial relays. In [167], a multiple relay selection and power allocation scheme was presented for the HSTN with multiple users and relays. The authors of [52] studied flow control and link scheduling in HSTNs with wireless backhauling. In [168], the beamforming vector of the relay node was optimized to maximize the secure rate. More recently, the authors of [169] investigated the potential of the UAV relay and designed a beamforming and user scheduling scheme to ensure fairness among ground users. Similarly, the UAV was applied as an aerial relay to assist satellite signal transmissions in [170]. A beamforming scheme was proposed for the UAV relay to achieve maximal energy efficiency.

In addition to the traditional relay model, the authors of [171] used a satellite-terrestrial terminal to forward satellite signals to remote users. A joint allocation strategy involving power allocation of the satellite backhaul and resource allocation of the satellite-terrestrial terminal was investigated to improve the satellite energy efficiency. Similarly, the authors of [172] applied a satellite-terrestrial station and proposed a power allocation and downlink resource allocation scheme to satisfy the delay requirement.

3) **Summary:** In this subsection, we reviewed the performance and resource allocation schemes for Model \( V \) in HSTNs. Most existing works focused on the satellite-terrestrial differences in wireless channels. Some also paid attention to the transmission delay under different relay schemes [173]. However, the processing delay and mobility of MEO/LEO satellites within the total delay have not been widely discussed. It should be noted that the dynamic topology of MEO/LEO satellites brings with non-ignorable handover time and how match the delay difference between SatComs and TerComs are still unsolved. What is more, the dynamic tracking capabilities of beam schemes and adaptive processing for the relay can be further investigated to flexibly adapt to the changing network while the how to reduce the high processing complexity is challenging.

C. **Model \( V \)**

For Model \( V \), as shown in the right of Fig. 3, there exist one satellite and one user, and the user can obtain access from both the satellite and the terrestrial BS which is common in sea areas and emergency situations. In the following, we discuss the main problem of Model \( V \) from the perspectives of the system performance and resource management and then suggest some future works for this model.

1) **Performance:** In Model \( V \), multi-diversity reception is used to compensate for the large channel fading in SatComs. At the HMT, the MRC and selective combining (SC) are usually used to combine the signals from the satellite and the terrestrial BS. In the MRC scheme, the HMT forms a new signal with the carrier-to-noise ratio (CNR) equal to the sum of the CNRs of the incoming signals, while in the SC scheme, the HMT selects the signal with the best diversity. The OP of MRC scheme and SC scheme was analyzed in [174] and [175], where the performance gain of MRC compared with that of SC and of a single satellite or single terrestrial link was demonstrated.

2) **Resource management:** In the scenario where both the satellite and the terrestrial BSs are available, how to choose the access point and how to allocate radio resources need to be solved. In [176], the authors proposed a multi-radio access algorithm for the HSTN. In [177], the authors investigated the scheduling strategy regarding whether to transmit to the mobile user directly or relay the signal by a ground gateway, where beamforming, user scheduling, and routing were jointly optimized. In [13], the authors introduced an integrated satellite-terrestrial system to Japan to provide a reliable solution for post-disaster communications. The cooperation technique, interference avoidance and frequency allocation scheme were discussed.

Furthermore, the space-time coding was studied in [179] and [180]. The Alamouti space-time code and prefilter were analyzed to mitigate the echoes for single-frequency HSTNs in [181]. A time division cooperative multigroup multicast scheme was proposed to improve the max-min fair capacity in [182]. A SDN network architecture was proposed to offer low rate multicast services for delay-tolerant users in [183].

3) **Summary:** In this subsection, we reviewed the performance and resource allocation schemes for Model \( V \) in the HSTN. It should be noted that the cooperative processing for Model \( V \) may result in higher inter-system communication complexity and additional overhead. In addition, protocol transformation and matching are required because the communication schemes and rates between satellite and terrestrial systems do not match. Based on this, it is necessary to further study low overhead multi-system cooperative interactions, including inter-system information transfer optimization and inter-system rate matching.

V. NETWORKING ISSUES AND SECURITY

In HSTNs, the RTT of satellite links is much longer than that of terrestrial links. The asymmetric RTT makes it quite difficult to deal with the handoff between satellite links and terrestrial links. In addition, the topology of the HSTN changes rapidly with the movements of mobile users and MEO/LEO satellites. Therefore, networking issues such as mobility management, routing, caching, and security problems should be considered for HSTNs.

A. **Mobility management and handover**

As shown in Fig. 4, when the mobile users and MEO/LEO satellites move, the network topology will change and handover is needed between satellites and BSs. Generally, handovers are divided into two types, namely, horizontal and vertical handovers. When a user moves to the edge of the serving satellite or terrestrial BS, it is passed on to the other satellite or terrestrial BS, which is called horizontal handover. If handover occurs between the satellite and the terrestrial BS, it is regarded as vertical handover [32]. In [31], the authors pointed out the challenges of mobility management for HSTNs, including handover in the Internet Protocol (IP) layer.
and in the physical layer. In [184], the authors discussed a suite of signaling protocols, including registration, call setup and intersegment handover for HMTs to enable IP-based HSTNs. In [185], the authors studied the bandwidth allocation and handover management in LEO HSTNs. To achieve global roaming, comprehensive mobility management was designed in [186], where an interworking agent was introduced for both horizontal and vertical handovers. The handover procedures of HSTNs were investigated in [187]–[189]. The author of [53] studied the handover problem with the satellite as the backhaul. In [190], the authors investigated the handover decision between the GEO satellite and the BS. The authors of [191] studied the handover problem by combining MIMO techniques. In [192], the authors proposed the named data networking scheme for fast handover and efficient forwarding in the HSTN. In [193], the authors provided a geographical subnet division protocol for HSTN addressing, which contributes to the mobility management.

B. Networking

Networking is a critical issue in the integration of satellite and terrestrial networks. Considering the different traits and limitations of space and ground components, many studies focused on the routing and transportation scheduling problems, which we discuss in the following.

1) Routing: In [194]–[197], the concept of different services was proposed. In satellite networks, the integrated service (IntServ)/resource reservation protocol (RSVP), which ensures the QoS of end-to-end services, is adopted. In core networks, differentiated service (DiffServ) is adopted, which is suitable for different QoS requirements. In [198], a routing algorithm was proposed for satellite-HAP-terrestrial networks. In [199], the authors addressed the issue of effective routing in HSTNs. The dynamic routing protocol, resource allocation and mobility management were analyzed in a suggested network where the satellite itself works as an internal router. In [200], [201], the authors studied a content size based routing scheme to ensure the quality of experience (QoE) in the HSTN. The authors of [202] proposed a collaborative theory based network modeling scheme for HSTNs and presented a smart load balancing and routing mechanism. In [203], the authors proposed a topology discovery sub-layer to predict satellite movement. And the proposed routing schemes could avoid unnecessary routing messages by using satellite movement prediction methods. In [204], the authors proposed a SDN-based routing algorithm for elastic data flows in HSTNs to reduce the blocking rate and bandwidth consumption. In [205], the authors presented a novel architecture for an integrated nano-satellite-5G system, giving a theoretical analysis from the physical layer to the network layer, and proposed a buffer-aware routing algorithm to reduce the end-to-end delay. In [206], the authors investigated a packet-based strategy of a SDN-aware architecture with a tag method, a path selection scheme and reordering rules to achieve efficient video delivery. More recently, the authors of [207] designed a greedy forwarding scheme based on the hyperbolic geometry that maps the network entities into a coordinate system to measure the distance among nodes. This routing method was proved to be cost-friendly, especially for large-scale networks. In [208], the placement of satellite gateways and a routing scheme were studied to minimize the total cost subject to the latency requirement.

2) Transportation control and flow assignment: In [209], the authors investigated the performance of on-board queueing strategies in HSTNs. The authors of [210] evaluated the performance of the Quick User Datagram Protocol Internet Connection (QUIC) for the HSTN in comparison with that of the Transmission Control Protocol (TCP). In [211], the authors adopted the Multipath TCP (MPTCP) with network coding to combine three different networks, i.e., WiFi, WiMax and the Iridium satellite, to achieve communication improvement. Moreover, a SDN-based HSTN using the MPTCP was proposed in [212]. Similar to the MPTCP, the Stream Control Transmission Protocol (SCTCP) also enables the data distribution in heterogeneous links [213]. Recently, the authors of [214] pointed out that neither the MPTCP nor SCTCP can resist channel fading, which needs to be considered for mobile scenarios, and designed a path-based network coding scheme between network layers and transport layers to tackle this challenge.

In [31], [215], [216], the authors investigated the flow control problem for HSTNs, where the RTT is asymmetric. The authors of [217] pointed out that flow assignment is related to link capacities which in turn are determined by radio resource allocation. A joint power and flow assignment scheme was then proposed to improve the network throughput. The authors of [52] minimized the traffic delivery time by backhaul activation for multi-hop HSTNs with a link scheduling and flow control scheme. In [218], the authors proposed a carrier allocation and flow control scheme for wireless backhauling in the HSTN.
C. Security

Security has become a critical problem in recent years. Different from traditional cellular networks, satellite transmissions are always large-scale and experience long-term delay, which inevitably provides chances for illegal hackers and leads to secure problems [219]. An increasing number of studies are intended to provide useful solutions to reduce the ubiquitous threats of insecurity. In [220], the achievable secrecy capacity was derived for HSTNs with eavesdroppers and AF relays. From the perspective of physical layer enhancement, terrestrial interference could be used to interfere eavesdroppers and enhance secrecy capacity [221]. The security performance with multiple colluding eavesdroppers was analyzed in [222], [223], and the case of non-colluding eavesdroppers was discussed in [224].

The beamforming scheme was discussed in [168], [225] to maximize the secrecy rate in HSTNs with terrestrial relays. The authors of [222] [226], [227] investigated a joint beamforming scheme for the satellite and terrestrial networks to improve the user secrecy rate. The precoding scheme was analyzed in [228] to minimize the transmit power. With the same goal of power minimization, the authors of [229], [230] considered a multiple eavesdropper scenario, and proposed an artificial noise aided beamforming scheme under the secrecy rate constraint. In [231]–[234], the authors addressed the issue of relay selection to improve the secrecy performance of the network. Specifically, the authors of [234] applied 3D mobile UAVs as relays and analyzed the system performance under three relaying strategies. In [235], a novel wireless power cognitive HSTN was investigated, where the power receivers were considered as potential eavesdroppers of mobile users. A joint beamforming scheme was further proposed to maximize the sum rate of GMTs and SFTs with the SINR, energy harvest requirements and security constraints.

Despite these fruitful schemes in the physical layer, upper-layer methods have also been discussed to defend against potential attacks. In [236], the authors designed a smart identifier HSTN with many identifiers and behavior descriptions in different layers to enhance network security. In [237], the authors proposed a set of emergent data protection schemes to enhance security, including data transmission, key agreement, and satellite information acquisition. Moreover, by introducing the SDN technique, the controller has the ability to dynamically analyze traffic data, which facilitates the dynamic management of potential attacks. A trust routing model and a hybrid routing model were investigated in [238]. In this paper, the authors introduced a trusted resource matrix derived from the controller dynamic monitor. Based on the matrix, a routing algorithm was proposed to protect legal transmissions and achieve high QoS in terms of delay, bandwidth efficiency and packet loss rate.

D. Caching

Due to the wide coverage of the satellite, it has inherent merits for broadcasting. If a satellite further possesses the caching ability, it can achieve great improvements for HSTNs, especially in terms of content delivery [239]. In addition, as the RTT of SatComs is much longer than that of cellular communications, caching strategies can improve the performance of timely transmissions. In [240], the authors studied the caching techniques both in the satellite and the user. The authors of [241]–[243] introduced a caching-enabled LEO satellite network where the topology is time-varying. Considering this, the authors of [241] proposed a back-tracing partition based on path caching algorithm, and the authors of [242] designed a caching node selection scheme as well as an in-network caching mechanism to reduce the overheads and access delay. The authors of [243] jointly optimized the content placement, power allocation, and cache sharing to maximize the energy efficiency. By leveraging reinforcement deep learning, the authors of [244] optimized content placement to reduce the long-term averaged network delay.

In addition to caching in a satellite, other caching nodes can also provide a promising direction to achieve timely and efficient delivery. In [245], the authors proposed a QoE-driven caching placement scheme for video streaming in the HSTN, considering the social relationship among users. In [246], the authors intended to implement MEC techniques in HSTNs and discussed a task offloading model in detail to improve the QoS of mobile users. In [247], the authors provided the main overview of the SHINE project and presented a secure hybrid in-network caching scheme for multimedia content streaming in the HSTN. Furthermore, satellite delivery models, the SHINE architecture and caching mechanisms were analyzed in [248] to evaluate the feasibility of the satellite-enabled caching scheme. The authors of [249] designed a new task-oriented intelligent networking architecture including space, air, ground, aqua components. By introducing edge-cloud computing, intelligent methods and information center networks, the network has the potential to tackle the challenges of intelligent networking, heterogeneous network interactions, intermittent network interruptions, long latency, and load unbalance. However, the authors provided only a macro outlook of this heterogeneous architecture and many detailed schemes have not yet been discussed.

E. Summary

In this section, works on the network layer of HSTNs have been reviewed, including mobility management, routing, caching, and security issues. The topology of the HSTN changes rapidly with the movements of mobile users and MEO/LEO satellites. Unlike existing terrestrial networks, the communication mechanism of HSTNs must adapt not only to the dynamics of users but also to the dynamics of MEO/LEO satellites. The existing schemes mainly perform real-time resource scheduling based on the current state to adapt to the dynamic topology, which lowers the resource efficiency. For example, considering the long distance of satellite links and the operation process of mobile Internet protocols, the real-time broadcast communications of a user group will result in a large delay or even service interruption during the handover of users. Therefore, unlike the passive switching of terrestrial networks, the system must actively focus on dynamic user groups with efficient path planning to provide dynamic services on
demand and facilitate cost-effective information services. In the future, network resources can be actively planned using service process information, such as delay requirements and satellite/user trajectories. For example, satellite-aided content distribution should be based on the dual dynamics of satellite networks and terrestrial networks for content scheduling to improve the utilization of wireless resources and the dynamic service capabilities of HSTNs.

VI. Open issues

To date, the 3GPP has finished all standardization work of NTNs in release 16. New normative solutions of 5G new radio (NR) in NTNs are under investigation in release 17, and a long-term study of the NR for NTNs in release 18 as well as release 19 is being carried out by the standard setting working group [250]. Although new 5G infrastructures are currently being deployed, which would bring excellent performance improvements in practical networks, there still exist many challenges in meeting the upsurge communication requirements. The seamless, ultrareliable and high capacity demands all call for the integration of satellite and terrestrial components to construct a cost-friendly, security-guaranteed, demands all call for the integration of satellite and terrestrial components to construct a cost-friendly, security-guaranteed, intelligence-oriented and demand-satisfied integrated network based on novel techniques from the physical layers to the application layers.

With these concerns, some studies focus on the HSTN for 5G and beyond. Luglio et al. reviewed satellite service delivery models to efficiently extend terrestrial content delivery services to satellite-enabled scenarios [248]. Guidotti et al. presented the architecture of 5G NTNs and analyzed the main technical challenges caused by satellite channel impairments, such as large path losses, delays, and Doppler frequency shifts [251]. Chien et al. introduced the architecture and challenges of HSTNs for IoT applications, where 5G, WiFi, Bluetooth, LoRa and other transmission technologies are jointly exploited [252]. Huang et al. presented the wireless evolution towards 6G communications and gave a whole architecture of the future green networks of ground, aerial, space and underwater components [253]. Charbit et al. gave a system design of the narrowband IoT air interface for NTNs, aiming to construct a backward compatible interface for future IoT systems [254]. In addition, the authors of [255] investigated the feasibility of mmWave communications through satellites to enhance the role of satellites in 5G and 6G.

The evolution to 5G has brought a number of new challenges. First, frequency resources are still the main bottleneck restricting satellite-terrestrial integration. With the large-scale deployment of LEO constellations, the problem of frequency conflicts will become more serious. Exploring new technologies for frequency planning and frequency reuse is the primary problem that needs to be solved [256]. In addition, moving the functions of terrestrial BSs to satellites can effectively reduce the processing delay and improve the user experience, and the air interfaces of satellites and 5G will gradually converge. However, the adaptive transformation and optimization of 5G new air interfaces in satellite systems is still a major issue that needs to be addressed. It is a trend that the HSTN is fully IP-based, and technologies such as NFV/SDN will play a prominent role in satellite-terrestrial integration [257]. To address these concerns, some frontier technologies can be applied, such as dynamic spectrum sharing, network virtualization, artificial intelligence and blockchain technologies. These technologies are considered promising ways to achieve high-speed and ultra-reliable HSTNs.

A. Dynamic spectrum sharing

Cognitive radio is considered an efficient way to tackle spectrum scarcity problems. However, although this issue has been widely investigated for decades, there is still a lack of supportive mechanisms to effectively implement it in practice [65]. The accuracy of spectrum sensing directly influences the performance of cognitive cooperation. To improve the ability of spectrum sensing, the authors of [258] proposed a sensing scheme in dual polarized fading channels for cognitive SatComs. In [259], the author designed a cooperative SU sensing network and optimized the energy detection threshold to maximize the energy efficiency. More recently, the author of [260] addressed the issue of spectrum misuse detection in HSTNs to protect satellite networks from potential impairment. The impact of imperfect channel estimation was analyzed in [87]. Furthermore, to exploit the spectrum opportunity for SUs, the authors of [261] exploited the SU bandwidths for multimedia content delivery in the 5G-HSTN. The authors of [262] optimized the beam width and proposed a beam sharing scheme to improve the spectral efficiency of the SU network. The authors of [263] presented a dynamic integrated backhaul network operating on the SU band for the HSTN to overcome the limitations of the fixed backhaul.

Recently, the authors of [264] applied an intelligent method of spectrum sensing, prediction and allocation to improve the utilization efficiency of frequency. The intelligent scheme may be a breakthrough for tackling spectrum scarcity. But to achieve the win-win cooperation of HSTNs, novel designs of accurate spectrum awareness, intelligent spectrum decisions and agile spectrum exploitation need to be employed for dynamic spectrum sharing [65]. Furthermore, frequencies above 100 GHz are promising bands for the development of beyond 5G networks, while how to cooperatively manage these frequencies with reduced computational complexity and simplified signal processing in the HSTN is still an open issue [265].

B. Network virtualization

The existing networks are almost closed and not renewable. To facilitate the deployment of new techniques and keep pace with the fast evolution of communication systems, SDN and NFV techniques are considered effective ways. The authors of [266] pointed out that network programmability, openness, and virtualization is a new trend for HSTNs. Concerning this, the authors of [246] and [267] investigated some possible ways to improve the QoS of HSTNs using edge computing. The authors of [268] estimated the end-to-end delay of the SDN-based HSTN, including the time required for the transfer of SDN control actions. The authors of [269] proposed a new HSTN architecture with virtual spectrum allocation techniques.
to satisfy various QoS requirements from heterogeneous devices. The authors of [270] presented a SDN-based architecture of HSTNs to enable dynamic traffic offloading and improve the user QoE. Based on the virtualization technology, the authors of [271] introduced a resource cube to depict the minimum unit of multidimensional resources and designed a service-matching scheme to minimize the total system delay. In [272], the authors assumed that virtual resources could be embedded into any physical nodes of the space-air-ground network and proposed a multiple intersection traffic scheduling scheme to effectively allocate multidimensional resources. By introducing SDN techniques into LEO satellites, controller placement and satellite-to-controller assignment issues were investigated in [273] to overcome the impact of topology changes and traffic variations.

Although many techniques have been proposed to support software and virtualization, the challenging issues of the SDN-based HSTN, including mobility management, resource allocation, and security, still require further investigation [267]. For example, conventional internet protocols have large signaling overhead and handover delay due to the frequent changes in the point of attachment (PoA) of LEO satellites in SDN-based HSTNs, and methods of for installing mobility logic in the SDN controller to address the PoA variation are still lacking.

C. Artificial intelligence and blockchain

Future networks will integrate caching, computing and communication into an indivisible whole and miscellaneous services require intelligent management to handle multidimensional tasks [274]. Artificial intelligence may play an important role in future networks due to its unique self-learning ability, endowing heterogeneous networks with decision-making power. To enable fully intelligent network orchestration in 5G networks, a novel framework based on quantum machine learning was proposed in [275]. By combining networking, caching and computing, a joint resource allocation scheme using the deep Q-learning technique was proposed in [276]. Furthermore, a deep learning based traffic control method was proposed to improve network throughput and reduce the packet loss rate in [277]. The authors of [278] devised a mobile pointing and tracking model to implement satellite selection and antenna adjustment through unsupervised learning, and it was proved to greatly improve the transmission quality. In addition, the authors of [279] investigated a task scheduling and resource allocation scheme based on the deep reinforcement learning method to reduce the delay and energy cost in a MEC-aided IoT network.

In addition, blockchain technology has rapidly evolved and has impacted the economy. The extensive applications of blockchains also promote some new technical requirements for communication infrastructures:

1) Broadcasting: In the basic model of blockchain technology, transaction information and blockchain data should be broadcast to all nodes.

2) Mass data: In blockchains, the data need to be broadcast to other nodes. If all data are broadcast to all the nodes, the total amount of data is very massive.

3) Global decentralization: For public chains, nodes are distributed around the world.

Because SatComs have the characteristics of global coverage and broadcasting, it could be applied in blockchains for data broadcasting. In [280], the authors first introduced the blockchain reputation system into space networks and proposed a reputation aware routing protocol. More recently, the authors of [281] considered a blockchain scenario and designed a Nash bargaining framework to implement power allocation for caching, computing and communication under fairness and security awareness. However, many issues such as service offloading and performance evaluation criteria have not been considered. The applications of HSTNs require further investigation.

D. Intelligent cooperation of Model X, L & V

The cooperative model plays an important role in the performance of HSTNs due to the significant differences between SatComs and TerComs in wireless channels, transmission delay, mobility, and coverage performance. To date, most existing works on Model X have focused on the differences in wireless channels and coverage performance, ignoring the delay difference, and a general statistical channel model instead of a particular channel for certain scenarios is still lacking. In the future, the interference mechanism suitable for different scenarios needs to be clarified. On that basis, the signal waveform can be intelligently optimized from time, space and frequency domains to match the characteristics of interference. In particular, the delay and coverage differences between SatComs and TerComs need to be addressed in the time domain and the spatial domain, respectively. For Model L, the dynamic topology of MEO/LEO satellites requires beams to equip dynamic tracking capabilities and adaptive processing for the relay. The existing AF/DF relaying schemes may result in high delay due to the high signal processing complexity in dynamic topology scenarios. In the future, intelligent AF/DF schemes will be needed to improve the performance of Model L while minimizing the power consumption and complexity. For example, by learning the network node mobility such as the attitude of MEO/LEO satellites, the network topology evolution model could be built for position prediction. On this basis, the HSTN can be dynamically and intelligently configured for higher efficiency and wider coverage. High inter-system communication complexity, additional overhead, and high delay problems also exist in Model V. In the future, intelligent multi-system cooperative interactions with lower overhead are required. In a word, the satellite-terrestrial differences in wireless channels, transmission delay, mobility, and coverage performance need to be emphasized, learned, and predicted for more intelligent cooperation in HSTNs.

VII. Conclusions

In this paper, we have provided a survey on the basic cooperative models and technologies for HSTNs. The complicated topology of HSTNs has been categorized into three basic cooperative models: Model X, Model L, and Model V. The core problems and solutions therein, with respect to
performance analysis and resource management, have been summarized separately, focusing on the differences between SatComs and TerComs. Works on the network layer of HSTNs, such as mobility management and security issues, have also been presented, focusing on the differences between HSTNs and a separated terrestrial or satellite network. Finally, works and open issues on the utilization of the latest technologies for 5G-HSTNs have been summarized from the perspective of SDN, cognitive radio, artificial intelligence, and blockchain technologies. For future works, intelligent cooperation techniques for the three cooperative models, as well as some open research topics, have been suggested, to envision an agile, smart, and secure HSTN for 6G ubiquitous IoT.

REFERENCES

[1] Z. Zhou, C. Zhang, C. Xu, F. Xiong, Y. Zhang and T. Umer, “Energy-efficient industrial internet of UAVs for powerline inspection in smart grid,” IEEE Trans. Ind. Informat., vol. 14, no. 6, pp. 2705–2714, Jun. 2018.

[2] Z. Zhou, J. Gong, Y. He and Y. Zhang, “Software defined machine-to-machine communication for smart energy management,” IEEE Commun. Mag., vol. 55, no. 10, pp. 52–60, Oct. 2017.

[3] R. Girau et al., “Coastal monitoring system based on social Internet of Things platforms,” IEEE Internet Things J., vol. 7, no. 2, pp. 1260–1272, Feb. 2020.

[4] A. Salam and S. Shah, “Internet of Things in smart agriculture: Enabling technologies,” in Proc. 2019 IEEE 5th World Forum on Internet of Things (WF-IoT), Limerick, Ireland, 2019, pp. 692–695.

[5] H. Lu, Q. Liu, D. Tian, Y. Li, H. Kim and S. Serikawa, “The cognitive internet of vehicles for autonomous driving,” IEEE Netw., vol. 33, no. 3, pp. 65–73, May/June 2019.

[6] M. A. Mahmud, K. Bates, T. Wood, A. Abdelgawad and K. Yelamarthi, “A complete Internet of Things (IoT) platform for structural health monitoring (SHM),” in Proc. 2018 IEEE 4th World Forum on Internet of Things (WF-IoT), Singapore, 2018, pp. 275–279.

[7] J. J. Wellington and P. Ramesh, “Role of Internet of Things in disaster management,” in Proc. 2017 Int. Conf. Innov. Inf., Embedded Commun. Syst. (ICHECS), Coimbatore, 2017, pp. 1–4.

[8] Z. Zhou, H. Liao, B. Gu, S. Muntaz and J. Rodriguez, “Resource sharing and task offloading in IoT fog computing: A contract-learning approach,” IEEE Trans. Emerg. Topics Comput., vol. 4, no. 3, pp. 227–240, Jun. 2020.

[9] W. Feng, J. Wang, Y. Chen, X. Wang, N. Ge and J. Lu, “UAV-aided MIMO communications for 5G Internet of Things,” IEEE Internet Things J., vol. 6, no. 2, pp. 1731–1740, Apr. 2019.

[10] C. Liu, W. Feng, Y. Chen, C. Wang and N. Ge, “Cell-free satellite-UE networks for 6G wide-area internet of things,” IEEE J. Sel. Areas Commun., early access, doi: 10.1109/JSAC.2020.3018837.

[11] H. Wei, W. Feng, C. Zhang, Y. Chen, Y. Fang and N. Ge, “Creating efficient blockchains for the internet of things by coordinated satellite-terrestrial networks,” IEEE Wireless Commun., vol. 27, no. 3, pp. 104–110, Jun. 2020.

[12] X. Li, W. Feng, J. Wang, Y. Chen, N. Ge and C. Wang, “Enabling 5G on the ocean: A Hybrid satellite-UAV terrestrial network solution,” IEEE Wireless Commun., early access, doi: 10.1109/MWC.2001.2000076.

[13] Y. Fujino, A. Miura, N. Hamamoto, H. Tsuji and R. Suzuki, “Satellite terrestrial integrated mobile communication system as a disaster countermeasure,” in Proc. URSI General Assembly & Scientific Symp., Istanbul, Turkey, Aug. 2011, pp. 1–4.

[14] A. Kapovits et al., “Satellite communications integration with terrestrial networks,” China Commun., vol. 15, no. 8, pp. 22–38, Aug. 2018.

[15] J. K. Chamberlain and R. G. Medhurst, “Mutual interference between communication satellites and terrestrial line-of-sight radio-relay systems,” in Proc. Institution Electrical Engineers, vol. 111, no. 3, pp. 524–534, Mar. 1964.

[16] J. K. Chamberlain, “Interference between an earth station of a communication-satellite system and the stations of terrestrial line-of-sight radio-relay systems,” in Proc. Institution Electrical Engineers, vol. 112, no. 2, pp. 231–241, Feb. 1965.

[17] P. B. Johns, “Interference between terrestrial line-of-sight radio-relay systems and communication-satellite systems,” Electronics Lett., vol. 2, no. 5, pp. 177–178, May 1966.
A. H. G. Swalem, J. V. M. Halim and H. Elhennawy, “Performance analysis of MIMO AF CDMA hybrid satellite-terrestrial cooperative networks using multiple relays strategy for downlink,” *IET Commun.*, vol. 13, no. 14, pp. 2155-2162, Aug. 2019.

M. K. Arti, “Imperfect CSI based AF relaying in hybrid satellite-terrestrial cooperative communication systems,” in *Proc. IEEE Int. Conf. Commun. Workshop*, London, UK, Jun. 2015, pp. 1681–1686.

P. K. Upadhyay and P. K. Sharma, “Multituser hybrid satellite-terrestrial relay networks with co-channel interference and feedback latency,” in *Proc. European Conf. Netw. Commun.*, Athens, Greece, Jun. 2016, pp. 174–178.

K. Guo, B. Zhang, Y. Huang, and D. Guo, “Performance analysis of two-way satellite terrestrial relay networks with hardware impairments,” *IEEE Wireless Commun. Lett.*, vol. 6, no. 4, pp. 430–433, Aug. 2017.

W. Zeng, J. Zhang, D. W. K. Ng, B. Ai, and Z. Zhong, “Two-way hybrid-terrestrial-satellite relaying systems: Performance analysis and relay selection,” *IEEE Trans. Veh. Technol.*, vol. 68, no. 7, pp. 7011–7023, Jul. 2019.

V. Singh, P. K. Upadhyay, D. B. da Costa, U. S. Dias, “Hybrid satellite-terrestrial spectrum sharing systems with RF energy harvesting,” in *Proc. IEEE Int. Symp. Personal, Indoor Mobile Radio Commun.*, Bologna, Italy, Sep. 2018, pp. 306–311.

K. An, Y. Li, X. Yan, and T. Liang, “On the performance of cache-enabled hybrid satellite-terrestrial relay networks,” *IEEE Wireless Commun. Lett.*, vol. 8, no. 5, pp. 1506–1509, Oct. 2019.

P. K. Sharma, B. Yogesh, D. Gupta, and D. Kim, “Overlay satellite-terrestrial networks for IoT under hybrid interference environments,” Arxiv: 2003.12950, Mar. 2020.

S. Sreng, B. Escrig, and M. L. Boucheret, “Outage analysis of hybrid satellite-terrestrial cooperative network with best relay selection,” in *Proc. Wireless Telecommun. Symp.*, London, UK, Apr. 2012, pp. 1–5.

S. Sreng, B. Escrig, and M. L. Boucheret, “Exact symbol error probability of hybrid/integrated satellite-terrestrial cooperative network,” *IEEE Trans. Wireless Commun.*, vol. 12, no. 3, pp. 1310–1319, Mar. 2013.

S. Sreng, B. Escrig, and M. L. Boucheret, “Exact outage probability of a hybrid satellite terrestrial cooperative system with best relay selection,” in *Proc. IEEE Int. Conf. Commun.*, Budapest, Hungary, Jun. 2013, pp. 4520–4524.

Y. Zhao, L. Xie, H. Chen, and K. Wang, “Ergodic channel capacity analysis of the hybrid satellite-terrestrial single frequency network,” in *Proc. IEEE Int. Symp. Pers., Indoor Mobile Radio Commun.*, Hong Kong, China, Aug. 2015, pp. 1803–1807.

N. Varsheyn and A. K. Jagannatham, “Hybrid satellite-terrestrial cooperative communication with mobile terrestrial nodes,” in *Proc. Nat. Conf. Commun.*, Hyderabad, India, Feb. 2018, pp. 1–6.

Y. Zhao, H. Chen, L. Xie, and K. Wang, “Exact and asymptotic ergodic capacity analysis of the hybrid satellite-terrestrial cooperative system over generalised fading channels,” *IET Commun.*, vol. 12, no. 11, pp. 1342–1350, 2018.

K. An and T. Liang, “Hybrid satellite-terrestrial relay networks with adaptive transmission,” *IEEE Trans. Veh. Technol.*, vol. 68, no. 5, pp. 4586-4601, May 2019.

A. Garg and P. Kumar, “Analysis of variable bit rate SOFD transmission scheme over multi-relay hybrid satellite-terrestrial system in presence of CPO and phase noise,” *IEEE Trans. Veh. Technol.*, vol. 68, no. 5, pp. 35103-35112, Mar. 2019.

A. Garg and P. Kumar, “Analysis of variable bit rate SOFD based integrated satellite-terrestrial broadcast system in presence of CPO and phase noise,” *IEEE Syst. J.*, vol. 13, no. 4, pp. 3827-3835, Dec. 2019.

K. An, J. Ouyang, M. Lin, and T. Liang, “Outage analysis of multi-antenna cognitive hybrid satellite-terrestrial relay networks with beamforming,” *IEEE Commun. Lett.*, vol. 19, no. 7, pp. 1157–1160, Jul. 2015.

X. Tang, K. An, K. Guo, Y. Huang, and S. Wang, “Outage analysis of non-orthogonal multiple access-based integrated satellite-terrestrial relay networks with hardware impairments,” *IEEE Access*, vol. 7, pp. 141258-141267, Sep. 2019.

H. Wu, Y. Zou, W. Cao, Z. Chen, T. Tsiftsis, M. R. Bhatnagar, and R. D. Lamare, “Impact of hardware impairments on outage performance of hybrid satellite-terrestrial relay systems,” *IEEE Access*, vol. 7, pp. 35103-35112, Mar. 2019.

K. Guo, K. An, B. Zhang, Y. Huang, D. Guo, G. Zheng, and S. Che, “Outage analysis of the uplink satellite multi-relay terrestrial relay networks with hardware impairments and interference,” *IEEE Syst. J.*, vol. 13, no. 3, pp. 2297-2308, Sep. 2019.
S. Kittiparasrol, Z. Sun, and H. Cuckshank, “Performance evaluation of on-board QoS support for multiservice applications on the integrated next generation satellite-terrestrial network,” in Proc. Advanced Satell. Mobile Syst., Bologna, Italy, Aug. 2008, pp. 311–316.

S. Yang, H. Li, and Q. Wu, “Performance analysis of QUC protocol in integrated satellites and terrestrial networks,” in Proc. Int. Conf. Wirel. Commun. Mobile Commun., Limassol, Cyprus, Jun. 2018, pp. 1425–1430.

J. Cloud, D. Puin Calmon, W. Zeng, G. Pau, L. M. Zeger, and M. Medard, “Multi-path TCP with network coding for mobile devices in heterogeneous networks,” in Proc. IEEE 76th Veh. Technol. Conf. (VTC Fall), Fall 2013, pp. 1–5.

P. Du, S. Nazari, J. Menas, R. Fan, M. Gerla, and R. Gupta, “Multipath TCP in SDN-enabled LEO satellite networks,” in Proc. IEEE Military Commun. Conf. (MILCOM), Baltimore, MD, USA, Nov. 2016, pp. 354–359.

Chen Hui, Wang Jun and Feng Xiaolin, “New strategy of improving stream control transmission protocol performance over satellite link,” in Proc. 2008 27th China Control Conf., Kunming, 2008, pp. 307–310.

G. G. Giambene, D. K. Luong, T. De Cola, V. A. Le and M. Shaat, E. Lagunas, A. I. P.-Neira, and S. Chatzinotas, “Integrated terrestrial-satellite mobile systems,” IEEE Trans. Veh. Technol., vol. 68, no. 8, pp. 8117–8132, Aug. 2019.

V. Roseti, F. Zampognaro, and M. Luglio, “Enhancing TCP performance over hybrid wireless terrestrial-satellite networks,” in Proc. Int. Conf. Advances Satell. Space Commun., Colmar, France, Jul. 2009, pp. 19–23.

T. K. Saini and M. K. Dhaka, “Performance simulation of Tahoe, Reno, New Reno and SACK over terrestrial and geostationary satellite links,” in Proc. Int. Conf. Methods Models Comput. Sci., Delhi, India, Dec. 2009, pp. 1–5.

E. Lagunas, L. Lei, S. Chatzinotas and B. Ottersten, “Power and flow assignment for 5G integrated terrestrial-satellite backhaul networks,” in Proc. 2019 IEEE Wireless Commun. Netw. Conf. (WCNC), Marrakech, Morocco, 2019, pp. 1–6.

M. Shaat, E. Lagunas, A. I. P.-Neira, and S. Chatzinotas, “Integrated terrestrial-satellite wireless backhauling: resource management and benefits for 5G,” IEEE Veh. Tech. Mag., vol. 13, no. 3, pp. 39–47, Sep. 2018.

B. Li, Z. Fei, C. Zhou, and Y. Zhang, “Physical layer security in space information networks: A survey,” in Proc. IEEE Internet Things J., vol. 7, no. 1, pp. 33–52, Jan. 2020.

K. An, M. Lin, T. Liang, J. Ouyang, C. Yuan, and Y. Li, “Secure transmission in multi-antenna hybrid satellite-terrestrial relay networks in the presence of eavesdropper,” in Proc. Int. Conf. Wireless Commun. Signal Process., Nanjing, China, Oct. 2015, pp. 1–5.

K. An, M. Lin, J. Ouyang, and W. P. Zhu, “Secure transmission in cognitive satellite terrestrial networks,” IEEE J. Sel. Areas Commun., vol. 37, no. 11, pp. 2025–2037, Nov. 2016.

V. Bankey and P. K. Upadhyay, “Physical layer security of multiuser multirelay hybrid satellite-terrestrial relay networks,” IEEE Trans. Veh. Tech., vol. 68, no. 3, pp. 2488-2501, Mar. 2019.

V. Bankey, et al., “Physical layer security of hybrid satellite terrestrial relay networks with multiple colluding eavesdroppers over non-identically distributed Nakagami-m fading channels,” IET Commun., vol. 13, no. 14, pp. 2115–2123, Aug. 2019.

V. Bankey et al., “Performance analysis of multi-antenna multiuser hybrid satellite-terrestrial relay systems for mobile services delivery,” IEEE Access, vol. 6, pp. 24729–24745, Apr. 2018.

C. Chen and L. Song, “Secure communications in hybrid cooperative satellite-terrestrial networks,” in Proc. IEEE Veh. Tech. Conf., Porto, Portugal, Jun. 2018, pp. 1–5.

C. Yuan, M. Lin, J. Ouyang, and Y. Bu, “Joint security beamforming in cognitive hybrid satellite-terrestrial networks,” in Proc. IEEE Veh. Tech. Conf., Nanjing, China, May 2016, pp. 1–5.

Q. Song, S. Zhao, and Q. Shi, “Secure satellite-terrestrial transmission via hybrid analog-digital beamforming,” in Proc. IEEE Int. Conf. Wireless Commun. Signal Process., Hangzhou, China, Oct. 2018, pp. 1–6.

J. Xiong, D. Ma, H. Zhao and F. Gu, “Secure multicast communications in cognitive satellite-terrestrial networks,” IEEE Commun. Lett., vol. 23, no. 4, pp. 632–635, Apr. 2019.

W. Lu, T. Liang, K. An, and H. Yang, “Secure beamforming and transmission with noise algorithms in cognitive satellite-terrestrial networks with multiple eavesdroppers,” IEEE Access, vol. 6, pp. 65760–65771, Oct. 2018.
[252] W.-C. Chien, C.-F. Lai, M. S. Hossain, and G. Muhammad, “Heterogeneous space and terrestrial integrated networks for IoT: Architecture and challenges,” *IEEE Netw.*, vol. 33, no. 1, pp. 15–21, Jan. 2019.

[253] T. Huang, W. Yang, J. Wu, J. Ma, X. Zhang and D. Zhang, “A survey on green 6G network: Architecture and technologies,” *IEEE Access*, vol. 7, pp. 175758–175768, Dec. 2019.

[254] G. Charbit, D. Lin, K. Medlès, L. Li and I. Fu, “Space-terrestrial radio network integration for 6G,” in *Proc. 2020 2nd 6G Wireless Summit (6G SUMMIT)*, Levi, Finland, 2020, pp. 1–5.

[255] M. Giordani and M. Zorzi, “Satellite communication at millimeter waves: A key enabler of the 6G era,” in *Proc. 2020 Int. Conf. Comput., Netw. Commun. (ICNC)*, Big Island, HI, USA, 2020, pp. 383–388.

[256] M. Hoyhtya, M. Hoppari, and M. Majanen, “Validation framework for building a spectrum sharing testbed for integrated satellite-terrestrial systems,” in *Proc. European Signal Process. Conf.*, A Coruna, Spain, Sep. 2019, pp. 1–5.

[257] E. Lagunas, L. Lei, S. Chatzinotas, and B. Ottersten, “Satellite links integrated in 5G SDN-enabled backhaul networks: An iterative joint power and flow assignment,” in *Proc. European Signal Process. Conf.*, A Coruna, Spain, Sep. 2019, pp. 1–5.

[258] S. K. Sharma, S. Chatzinotas, and B. Ottersten, “Spectrum sensing in dual polarized fading channels for cognitive SatComs,” in *Proc. IEEE Global Commun. Conf.*, Anaheim, USA, Dec. 2012, pp. 3419–3424.

[259] J. Hu, G. Li, D. Bian, S. Shi, R. Ge and L. Guo, “Energy-efficient cooperative spectrum sensing in cognitive satellite terrestrial networks,” *IEEE Access*, vol. 8, pp. 161396–161405, Sep. 2020.

[260] Y. Liu, B. Zhang, D. Guo, L. Zhang, B. Zhao and G. Ding, “Detection of spectrum misuse behavior in satellite-terrestrial spectrum sensing based on multi-hypothesis tests,” *IEEE Access*, vol. 8, pp. 50399–50413, Mar. 2020.

[261] A. Mudonhi, C. Sacchi, and F. Granelli, “SDN-based multimedia content delivery in 5G SU hybrid satellite-terrestrial networks,” in *Proc. IEEE Int. Symp. Pers., Indoor Mobile Radio Commun.*, Bologna, Italy, Sep. 2018, pp. 1–7.

[262] Q. Cao, et al., “Capacity enhancement for SU multi-beam satellite-terrestrial backhaul via beam sharing,” in *Proc. Int. Conf. Commun.*, Kansas City, USA, May 2018, pp. 1–6.

[263] X. Artiga et al., “Shared access satellite-terrestrial reconfigurable backhaul network enabled by smart antennas at SU band,” *IEEE Netw.*, vol. 32, no. 5, pp. 46–53, Sep. 2018.

[264] M. Jia, X. Zhang, J. Sun, X. Gu, and Q. Guo, “Intelligent resource management for satellite and terrestrial spectrum shared networking toward 5G,” *IEEE Wireless Commun.*, vol. 27, no. 1, pp. 54–61, Feb. 2020.

[265] T. S. Rappaport et al., “Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond,” *IEEE Access*, vol. 7, pp. 78729–78757, Jun. 2019.

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

[267] Y. Bi, et al., “Software defined space-terrestrial integrated networks: architecture, challenges, and solutions,” *IEEE Network*, vol. 33, no. 1, pp. 22–28, Jan. 2019.

[268] L. Boero, M. Marchese, and F. Patrone, “The impact of delay in software-defined integrated terrestrial-satellite networks,” *China Commun.*, vol. 15, no. 8, pp. 11–21, Aug. 2018.

[269] K. Lin, D. Wang, L. Hu, M. S. Hossain, and G. Muhammad, “Virtualized QoS-driven spectrum allocation in space-terrestrial integrated networks,” *IEEE Netw.*, vol. 33, no. 1, pp. 58–63, Jan. 2019.

[270] C. Niephaus, J. Modeker, and G. Ghinea, “Toward traffic offload in converged satellite and terrestrial networks,” *IEEE Trans. Broadcasting*, vol. 65, no. 2, pp. 340–346, Jun. 2019.

[271] D. Chen et al., “Resource cube: Multi-virtual resource management for integrated satellite-terrestrial industrial IoT networks,” *IEEE Trans. Veh. Technol.*, vol. 69, no. 10, pp. 11963–11974, Oct. 2020.

[272] G. Wang, S. Zhou, S. Zhang, Z. Niu and X. Shen, “SFC-based service provisioning for reconfigurable space-air-ground integrated networks,” *IEEE J. Sel. Areas Commun.*, vol. 38, no. 7, pp. 1478–1489, Jul. 2020.

[273] A. Papa, T. de Cola, P. Vizarretta, M. He, C. Mas-Machuca and W. Kellerer, “Design and evaluation of reconfigurable SDN LEO constellations,” *IEEE Trans. Netw. Service Manag.*, vol. 17, no. 3, pp. 1432–1445, Sep. 2020.

[274] S. Fu, F. Yang and Y. Xiao, “AI inspired intelligent resource management in future wireless network,” *IEEE Access*, vol. 8, pp. 22425–22433, Jan. 2020.

[275] S. J. Nawaz, S. K. Sharma, S. Wyne, M. N. Patwary, and M. Asaduzzaman, “Quantum machine learning for 6G communication networks: State-of-the-art and vision for the future,” *IEEE Access*, vol. 7, pp. 46317–46350, Apr. 2019.

[276] C. Qiu, H. Yao, R. Yu, F. Xu, and C. Zhao, “Deep Q-learning aided networking, caching, and computing resources allocation in software-defined satellite-terrestrial networks,” *IEEE Trans. Veh. Technol.*, vol. 68, no. 6, pp. 5871–5883, Jun. 2019.

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

[278] Q. Liu, J. Yang, C. Zhuang, A. Barnawi and B. A Alzahrani, “Artificial intelligence based mobile tracking and antenna pointing in satellite-terrestrial networks,” *IEEE Access*, vol. 7, pp. 177497–177503, Nov. 2019.

[279] G. Cui, X. Li, L. Xu and W. Wang, “Latency and energy optimization for MEC enhanced SAT-IoT networks,” *IEEE Access*, vol. 8, pp. 55915–55926, Mar. 2020.

[280] L. Clark, Y. Tung, M. Clark and L. Zapanta, “A blockchain-based reputation system for small satellite relay networks,” in *Proc. 2020 IEEE Aerosp. Conf.*, Big Sky, MT, USA, Mar. 2020, pp. 1–8.

[281] S. Fu, J. Gao, and L. Zhao, “Integrated resource management for terrestrial-satellite systems,” *IEEE Trans. Veh. Technol.*, vol. 69, no. 3, pp. 3256–3266, Mar. 2020.