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Space-Air-Ground Integrated Network: A Survey

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***Abstract*—Space-air-ground integrated network (SAGIN), as an integration of satellite systems, aerial networks and terrestrial communications, has been becoming an emerging architecture and attracted intensive research interest during the past years. Besides bringing significant benefits for various practical services and applications, SAGIN is also facing many unprecedented challenges due to its specific characteristics such as heterogeneity, self-organization, and time-variability. Compared to traditional ground or satellite networks, SAGIN is affected by the limited and unbalanced network resources in all three network segments, so that it is difficult to obtain the best performances for traffic delivery. Therefore, the system integration, protocol optimization, resource management and allocation in SAGIN is of great significance. To the best of our knowledge, we are the first to present the state-of-the-art of the SAGIN since existing survey papers focused on either only one single network segment in space or air, or the integration of space-ground, neglecting the integration of all the three network segments. In light of this, we present in this paper a comprehensive review of recent research works concerning SAGIN from network design and resource allocation to performance analysis and optimization. After discussing several existing network architectures, we also point out some technology challenges and future directions.**

***Index Terms*—space-air-ground integrated network, quality of service, network design and protocol optimization, resource allocation, performance analysis.**

I. Introduction

During the last years, it has been widely acknowledged that traditional terrestrial wireless communications are experiencing an explosive growth in terms of both the number of users and the services to be supported [1]. Future networks are expected to provide more resources than current ones so as to cope with the increasing traffic demands of various services. To support the emerging applications such as Internet of Things (IoT), cloud computing, and big data, new standards and technologies for next generation mobile systems (5G [2]), are being proposed and implemented. However, limited by the network capacity and coverage, only depending on the ground communication systems cannot provide wireless access services with high data rate and reliability at any place on the earth, especially in the environmentally harsh areas like ocean and mountains [3]. It is imperative to exploit new network architectures to accommodate diverse services and applications with different quality of service (QoS) requirements in various scenarios.

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Utilizing modern information network technologies and interconnecting space, air, and ground network segments, the space-air-ground integrated network (SAGIN) has attracted many attentions from academia to industry. In recent years, more and more organizations have been starting their projects on SAGIN such as the Global Information Grid (GIG) [4] [5], Oneweb [6], SpaceX [7], etc. Thanks to the inherent advantages in terms of large coverage, high throughput and strong resilience, SAGIN can be used in lots of practical fields, including earth observation and mapping, intelligent transportation system (ITS) [8], military mission, disaster rescue [9], and so on. In particular, satellites can provide seamless connectivity to rural, ocean and mountain areas, air segment networks can enhance the capacity for covered areas with high service demands, while densely deployed ground segment systems can support high data rate access. The integration of these network segments would bring lots of benefits for the future 5G wireless communications.

As a multidimensional network, SAGIN adopts different communication protocols in each segment or the integration of different segments to achieve high throughput and high reliability data delivery. Unlike traditional ground or satellite networks, SAGIN is affected by limitation simultaneously from all three segments, from the aspects of traffic distribution, spectrum allocation, load balancing, mobility management, power control, route scheduling, end-to-end (E2E) QoS requirement, etc. Thus, it is critically necessary for network designers to achieve optimal performances in E2E data transmission, given various practical network resource constraints from each segment. However, in SAGIN, a specific heterogeneous network (HetNet) consisting various kinds of communication systems, it is difficult to use the limited network resources to obtain the best performances for information exchanging, especially for the inter-operating among different network segments. Therefore, the network design and system integration in SAGIN are of great significance. Toward this end, we provide in this paper a detailed survey for the latest research progress in SAGIN, with the emphasis on protocol optimization, resource allocation, performance analysis, mobility management, and inter-segment operation.

Until now, there have been several survey papers published on general aspects of space, air and space-ground networks, such as handover schemes, small satellite systems, unmanned aerial vehicle (UAV) communication issues, and QoS provisioning. Earlier in 2006, K. chowdhury *et al.* [10] provided a comprehensive review of handover schemes in low earth orbit (LEO) satellite networks, and compared the handover schemes using different QoS criteria. In 2016, Radhakrishnan *et al.* [11] reviewed various research in the small satellite systems for implementing inter-satellite communications

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focusing on physical, data link and network layer of the open system interconnection model. Gupta *et al.* in [12] surveyed some important issues about high mobility, dynamic topology, intermittent links, energy constraints, and changing link quality in UAV communication networks. While in [13], from a communications and networking viewpoint, Hayat *et al.* reported the characteristics and requirements of UAV networks for envisioned civil applications over the period 2000-2015. Also in 2016, Niephaus *et al.* [14] analyzed the current state-of-the-art of converged satellite and terrestrial networks and focused on the QoS provisioning when parallel satellite and terrestrial links existed.

The above existing surveys, although providing insights into diverse perspectives about satellite networks, UAV systems, and the integration of satellite-terrestrial communications, have one common limitation: all of them focused on either only one single network segment in space or air, or the integration of space-ground, gave no attention to the integration of space-air-ground network segments. **Due to the inherent characteristics of heterogeneity, self-organization, and time-variability, it will reveal lots of challenges for network design and protocol optimization in SAGIN. Specifically, operation in heterogeneous network must take into account collaborative control and management, cooperative data transmission, inter-connection and inter-communication. The time-varying dynamic mobile network will affect propagation channel modeling, mobility management, traffic distribution and routing mechanism. While the self-organization characteristic brings the challenging issues such as service discovery, cross-layer design and optimization, network security, and load balancing. Therefore, having a comprehensive knowledge of the space-air-ground communication system is of great importance and necessity**. To the best of our knowledge, we are the first to present the state-of-the-art of the space-air-ground integrated network. This paper mainly concerns the aspects of system integration, protocol design, performance analysis and optimization in the integrated networks. Besides, recent research works, existing network architectures, technical challenges and future directions are also presented in this paper.

The remainder of the paper is structured as follows. Section II introduces some existing systems and presents an architecture for SAGIN. We provide a comprehensive but not exhaustive overview of the related works in recent years from Section III to Section V. In particular, Section III reviews the physical layer characteristics and spectrum allocation. The mobility management and traffic offloading as well as routing are discussed in Section IV. Section V lists some proposed integrated architectures and analyzes the network performance metrics. We identify several existing network architectures applicable for SAGIN in Section VI and then point out some technical challenges and future directions in Section VII. Finally we conclude the whole paper in Section VIII. For convenience, abbreviations used in this paper are listed in Table I.

II. Background

In this section, we first provide a brief introduction of existing integrated systems and then we give an overview of the integrated network architecture.

A. Existing Systems

In the past decades, several space-air-ground, especially space-ground integrated systems were proposed and applied into wireless communications. A well known space-air-ground integrated network is the GIG. Among the space-ground integrated systems, there are mainly two kinds of network architectures, one is geostationary orbit (GEO) satellite system such as the transformational satellite (TSAT) system, and the other is non-GEO (NGEO) system such as O3b, Iridium, Globalstar, etc.

1) GIG: As an all-encompassing communications project of the United States Department of Defense (DoD), GIG is the integration of communication networks, sensor networks and operation networks. GIG mainly consists four layers containing the communication devices and nodes required to support seamless global communications [4]: ground layer, aerospace layer, near-space layer and satellite layer.

2) TSAT: The TSAT system is a future generation GEO satellite system which is designed for military applications by National Aeronautics and Space Administration (NASA), the U.S. DoD, and the Intelligence Community [15]. The TSAT system is composed of 5 GEO satellites, and these satellites communicate with each other using laser links, forming a 10 Gbps backbone network, which allows ground terminals to access optical and radar imagery from UAVs and satellites in real-time.

3) O3b: O3b satellite system is a medium earth orbit (MEO) constellation which has been developed by O3b Networks and is current being deployed [16]. The meaning of O3b is "the other 3 billion", that is, the goal of O3b is to help 3 billion people in Africa, Asia and South America access the Internet through satellite network. The O3b network has proposed the O3b constellation of 12 to 20 MEO satellites at an altitude about 8000 km and four satellites have been already launched in the operational orbits.

4) Iridium: The Iridium system is a satellite-based, wireless personal communications network which is designed to provide full earth coverage for date and voice services [17]. The constellation consists of 66 LEO satellites at a height of approximately 780 km. Every satellite of the Iridium system has the same capacities of on-board processing, routing and delivering. Each satellite has four inter-satellite links (ISLs) through which the satellites can connect to their neighboring satellites.

5) Globalstar: Globalstar cellular telephone system uses 48 LEO satellites to provide users with seamless connectivity, low cost and full coverage satellite mobile communication services. These 48 satellites are distributed in 8 circular orbital planes (1400 km altitude), inclined 52 degrees with respect to the equator with six satellites in each orbital plane [18].

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TABLE I
LIST OF ABBREVIATIONS

1G	1^{st} generation	2G	2^{nd} generation
3G	3^{rd} generation	3GPP	3^{rd} generation partnership project
4G	4^{th} generation	5G	5^{th} generation
AF	amplify-and-forward	ARM	architectural reference model
ATM	asynchronous transfer mode	ATSP	advanced transport satellite protocol
BER	bit error rate	BS	base station
CoMP	coordinated multipoint	D2D	device-to-device
DF	decode-and-forward	DIPS	distributed IPv6 solution
DoD	department of defense	DoS	denial of service
DSRC	dedicated short range communication	E2E	end-to-end
EE	energy efficiency	ELB	explicit load balancing
eNB	evolved Node B	FANET	flying ad hoc network
FSR	fuzzy satellite routing	GBSCM	GB stochastic channel model
GEO	geostationary	GIG	global information grid
GPS	global position system	HAP	high altitude platform
HCN	heterogeneous cellular network	HetNet	heterogeneous network
HSAT	hybrid satellite-aerial-terrestrial	HTS	high throughput satellite
ILL	inter-layer link	IoT	Internet of things
IP	internet protocol	IPSec	IP security
ISL	inter-satellite link	ITS	intelligent transportation system
ITU	international telecommunication union	LAP	low altitude platform
LEO	low earth orbit	LTE	long term evolution
LTE-A	LTE-advanced	LTE-V	LTE-vehicular
MANET	mobile ad hoc network	MEO	medium earth orbit
MIMO	multiple input multiple output	MIP	mobile IP
MLSN	multi-layered satellite network	mmWave	millimeter wave
NASA	national aeronautics and space administration	NB-IoT	narrow band IoT
NC	network coding	NFC	near field communication
NFV	network function virtualization	NGEO	non GEO
OBP	on-board processing	OLSR	optimized link-state routing
OSI	open systems interconnection	PDR	packet drop rate
PEP	performance enhancing proxy	PER	packet error rate
PDR	public protection and disaster relief	PR	perfect reconstruction
QoS	quality of service	RFID	radio frequency identification
RLNC	random linear NC	RTT	round trip time
RWP	random way-point	SAGIN	space-air-ground integrated network
SDN	software defined network	SE	spectrum efficiency
SER	symbol error rate	SGD	smart gateway diversity
SNR	signal-to-noise ratio	SRLNC	systematic RLNC
ST	satellite terminal	TCP	transmission control protocol
TDD	time division duplex	TLR	traffic-light-based intelligent routing
TSAT	transformational satellite	UAV	unmanned aerial vehicle
UDN	ultra-dense network	UDP	user datagram protocol
UE	user equipment	VANET	vehicular ad hoc network
WANET	wireless ad hoc network	WiMAX	worldwide interoperability for microwave access
WLAN	wireless local area network	WMN	wireless mesh network
WSN	wireless sensor network		

B. System Architecture

As shown in Figure 1, the SAGIN comprises three main segments: space, air, and ground. These three segments can work independently or inter-operationally, by integrating heterogeneous networks among the three segments, it is easy to build a hierarchical broadband wireless network.

1) Space Network: The space network is composed of satellites and constellations as well as their corresponding terrestrial infrastructures(e.g., ground stations, network operations control centers). These satellites and constellations are in different orbits and with different characteristics. Based on the altitude, satellites can be classified into three categories: GEO, MEO, and LEO satellites [9]. We can also categorize satellite networks into narrowband and broadband according to their channel bandwidth.

- **narrowband satellite network.** Narrowband satellite networks refer to the MEO/LEO satellite systems, such as Iridium and Globalstar, which primarily provide global users with voice and low-rate data services.
- **broadband satellite network.** Broadband is a general term in fixed or wireless communications that can carry a lot of data, using a wide band of frequencies. It can offer high speed data transmission rate of up to 10Gbps [19], and is expected to have capacity of 1000 Gbps by the year of 2020 [20].
- **multi-layered satellite network.** As a practical architecture for next-generation satellite network, multi-layered satellite network (MLSN) is constructed by integrating several satellite networks and have hierarchical structures [21]. MLSN is constructed with several types of links such as inter-satellite links and inter-layer links (ILLs).

2) Air Network: The air network is an aerial mobile system which uses aircraft as carriers for information acquisition, transmission, and processing. UAVs, airships and balloons are the main infrastructures making up the high and low altitude

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TABLE II
COMPARISON OF DIFFERENT NETWORKS

Segment	Objects	Hight above earth	One way delay	Data rates	Advantages	Disadvantages
space	GEO	35,786km	about 270ms	least performance	large coverage, broadcast/multicast	long propagation latency, limited capacity, high mobility
	MEO	2000-35,786km	about 110ms	up to 1.2Gbps		
	LEO	160-2000km	less than 40ms	up to 3.75Gbps		
air	airship balloon UAV	17-30 km (HAP), less than 10 km (LAP)	medium	high data rates	wide coverage, low cost, flexible deployment	less capacity, unstable link, high mobility
ground	cellular Ad Hoc WiMAX WLAN	N.A.	lowest	high data rates	rich resources, high throughput	limited coverage, vulnerable to disaster

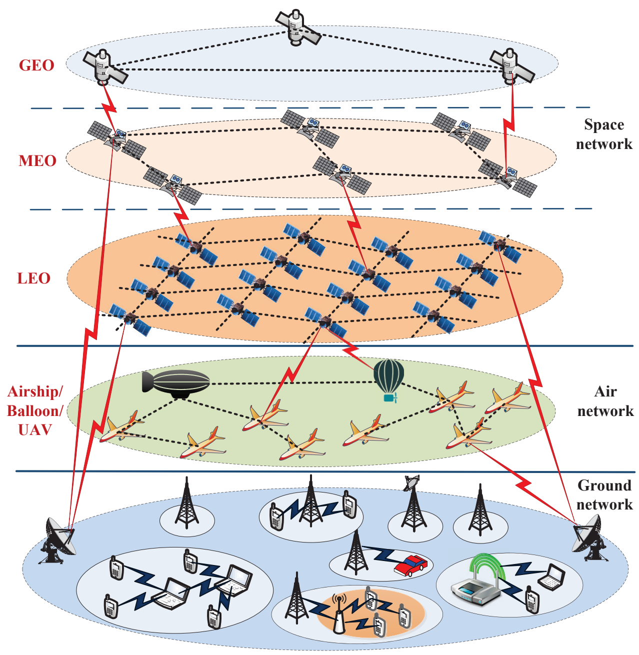

Fig. 1. An architecture for space-air-ground integrated network.

platforms (HAPs & LAPs) which can provide broadband wireless communications complementing the terrestrial networks [22]. Compared with base station (BSs) in terrestrial network, air network has the features of low cost, easy deployment, and large coverage to offer wireless access services on a regional basis.

3) Ground Network: The ground network mainly consists of terrestrial communication systems such as cellular network, mobile ad hoc network (MANET) [23], worldwide interoperability for microwave access (WiMAX) [24], wireless local area networks (WLANs), and so on. In particular, cellular network has evolved through the first generation (1G), to the second generation (2G) and third generation (3G) through the fourth generation (4G) or Long-Term Evolution-Advanced (LTE-A) [25], and now it is evolving to 5G wireless network, to support various services. As for standardization, the Third Generation Partnership Project (3GPP) has developed a set of specifications for cellular/mobile network. The ground network is able to provide high data rates to users, but the network coverage in rural and remote areas is limited.

4) Comparison of Different Networks: Table II gives some comparisons of different networks in these three segments [26]. As can be seen, satellite networks can provide global coverage on the earth but have long propagation latencies. Although ground networks have the lowest transmission delay, they are vulnerable to natural disasters or artificial infrastructure damages. Air networks have advantages in terms of low latency and wide coverage, but their limited capacity and unstable link must be well accounted when such networks are deployed.

III. PHYSICAL LAYER CHARACTERISTICS AND SPECTRUM ALLOCATION

Due to the long distance between satellites and aerial or ground terminals, wireless communications in SAGIN are affected by several propagation effects such as frequency, delay, fading, and so on. These factors seriously affect the communication quality and the system performance. In order to guarantee reliable communications in SAGIN, it is crucial to understand the physical propagation characteristics of the space-air-ground wireless channel. In this section, we focus on the physical layer characteristics of the SAGIN, and present a review of available existing literature concerning propagation channel, spectrum allocation, as well as the cross-layer design considerations.

A. Physical Layer Characteristics

Physical layer is the infrastructure of wireless transmission systems, in which some characteristics including frequency band, propagation channel, multipath fading and shadowing should be well accounted when a wireless network is designed and optimized.

1) Frequency Bands: Most operating frequencies for space-air-ground communications are assigned by the International Telecommunication Union (ITU), which coordinates with various other communication agencies. Table III lists the main frequency bands and their corresponding services in space-air-ground communications. As can be seen in the table, L-band can be used in both space-ground and space-air [27] as well as air-ground channels [28]. Ku-band is not prone to interference from terrestrial microwave radio communication systems. However, it is easily affected by rain attenuation [29]. Ka-band can be used in MEO satellite systems to provide high-speed data transfer for interactive traffic including voice and

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TABLE III
FREQUENCY BAND IN SPACE-AIR-GROUND COMMUNICATIONS.

Frequency band	Frequency range (GHz)	Intended services
L	0.39 - 1.55	GPS, satellite phone, space-air and air-ground communications
S	1.55 - 3.4	weather radar, NASA, deep space research
C	3.4 - 8	full-time satellite TV, air-ground communications
X	7.925 - 12.5	radar applications
Ku	12.5 - 16	broadcast satellite services
K	18 - 26.5	broadcast satellite services
Ka	26.5 - 36	close-range targeting radars on military aircraft
Q	36 - 46	high throughput satellite services
V	46 - 56	high throughput satellite services
W	75 - 110	high throughput satellite services

video [16]. Also, ISLs between GEO satellites typically use such a frequency band [30]. Q/V and W-bands are considered for high capacity satellites communications [31] [32].

What should be noted is that, Ku-, Ka-, Q/V-, and other so-called millimeter wave (mmWave) bands are usually suffered both larger free-space path loss and tropospheric attenuation, therefore, it will be difficult for these higher frequency bands to be operated in air-ground communications.

2) Propagation Channel: Wireless propagation channel is the real environment in which the propagation medium shows high variance in time, frequency, and space. In SAGIN, the propagation channel characteristics are distinctly different from those of the well studied terrestrial communication channels in virtue of long propagation distance and high node mobility. For instance, the high bit error rate (BER), bandwidth asymmetry, intermittent interruption and other factors in satellite channel will affect the user experience. Especially, in satellite-based communication system, it is necessary to consider the influence of the propagation delay, and it is of great significance to optimize the delay in the transmission process. Therefore, knowledge of the characteristics of propagation channel is the foundation of the design and analysis of the space-air-ground communication system.

Liu *et al.* in [33] analyzed a satellite propagation channel model built on C.Loo model and Corazza model to describe the received signals, multipath fading and shadowing effects of the channel. Considering the estimator error and propagation delay, Cioni *et al.* [34] devised a channel estimation scheme on the satellite link with time-variant interference, to address the physical adaptation problem in the multibeam satellite-terrestrial integrated network. The authors jointly analyzed the design of physical layer adaptation algorithm and the impact of physical layer channel estimation on the overall system capacity. Simulation results showed that the proposed adaptation methods could track critical Ka-band fading time series and satisfied the link outage probability requirement, with a limited impact on the system capacity.

According to [27], most characteristics in space-air propagation channel using L-band are similar to those in space-ground channel, and the air-ground communications with UAVs have new characteristics due to arbitrary mobility patterns and diverse types of communication applications [35]. Focusing on accurate quantitative characterization of air-ground propagation channel for UAV communications, W. Matolak *et al.* presented detailed descriptions of the measurement campaigns, measured results, and complete air-ground channel models for most of the typical ground site local environments, including over water [36], hilly/mountainous [37], suburban, and near-urban [38]. The authors provided statistical wide-band and tapped delay line models based on L- and C-band measurement campaigns to investigate the channel characteristics such as path loss, small scale fading, spatial correlations and delay spreads. Furthermore, they extended their results to study the airframe shadowing characteristic of the air-ground channels for a medium-sized aircraft [39]. They modeled the shadowing loss as a function of aircraft roll angle and proposed a time- and vector-based algorithm to simulate a random shadowing event. Simulation results verified that the modeling shadowing statistics replicated the measured shadowing fairly well.

3) Cross-layer Design Considerations: In space-air-ground communications, data packets transmitted from sources to destinations will traverse via various nodes in space, air and ground networks. Any change of these interconnected networks will affect not only the physical layer channels but also the higher-layer decisions of flow control and routing, thus impacts the performances such as delay, throughput and reliability of the whole integrated system. For example, the network throughput depends on the bandwidth in physical layer, packet switch algorithm in data link layer, and the routing path in the network layer. In summary, we use Table IV to highlight the relationship between the factors in physical layer, data link layer as well as network layer and some indicators of the network performance. As shown in the table, the adopted techniques and mechanisms in each layer will produce an impact on the QoS of the communication system. Therefore, the principle of cross-layer optimization spanning from physical layer to the network layer should be considered for space-air-ground network design.

There have been lots of research works on the cross-layer design for the wireless communications in terrestrial network [40] [41] [42], and some comprehensive surveys on the cross-layer design in wireless networks have been provided in [43] [44]. And recently, such research works in space-air-ground communication systems are presented in several literature. P. Choi *et al.* [45] presented a cross-layer design of physical layer, link layer, and network layer in high throughput satellite (HTS) systems with ISLs and space-ground links. Taking into account channel conditions and inter-beam interference, the authors developed a joint policy of packet routing and beam scheduling to maximize the total

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TABLE IV
RELATIONSHIP BETWEEN NETWORK PERFORMANCE AND NETWORK FACTORS.

Performance	Physical layer factors	Data link layer factors	Network layer factors
delay	signal processing delay, propagation delay	handover delay, link scheduling, congestion control, retransmission protocol	handover delay, IP mobility management, routing algorithm
throughput	frequency band, bandwidth, multi-carrier modulation, antenna technology, network coding	packet switching algorithm, automatic repeat request protocol,	topological structure, routing algorithm
reliability	channel conditions, path loss, bit error rate, interference	forwarding mechanism, error correction coding	topological structure
energy efficiency	power control, channel conditions, interference	forwarding mechanism, frame length control, packet retransmission count	routing protocol

weight of packets switching for on-board processing (OBP) satellites equipped with phased array antenna. Performance evaluation showed that, compared to the conventional multiple beam antenna, the throughput gain with phased array antenna was able to reach as high as 40, and that the proposed scheme with beamforming outperformed both time-sharing and power-splitting methods without beamforming.

When a routing protocol is designed, the forwarding decisions should be made based on the link quality information available from both link and physical layer, so as to avoid selecting an actually poor link as the "best" path. To this end, a cross-layer routing protocol was proposed in [46] to improve the routing performance in a UAV-aided ground MANET. The authors added a UAV to a connected backbone to combat link failures and wireless link effected at physical/link layers before the changes of routing table and introduced a cross-layer routing metric as well as a UAV load-balancing algorithm. Experimental results manifested that the proposed routing and load balancing method could significantly improve the throughput and delivery ratio of both transmission control protocol (TCP) and user datagram protocol (UDP).

B. Spectrum Allocation

Much progress in the variety and performance of telecommunications systems at different levels have been observed in the last decade that include system conception, resource allocation, and advanced techniques for bandwidth exploitation. Aiming at redeploying scarce spectrum, improving energy efficiency (EE), and balancing user demands, resource allocation has been widely dug in the terrestrial wireless networks, and some detailed surveys have already been provided in [47] [48] [49]. Indeed, spectrum allocation is a key factor to avoid interference among telecommunications devices, which can significantly impact the entire ecosystem of the satellite-aerial-terrestrial communications.

As an increasing number of satellites continue to orbit around the Earth, developing a vast ground stations network has appeared as a critical theme so that the ground stations can receive the satellite transmitted data. Therefore, space-ground spectrum allocation is an important topic for developing efficient mobile satellite communication terminals and ground stations. Li *et al.* [50] developed a spectrum allocation scheme in satellite-terrestrial integrated networks to improve spectrum efficiency (SE) by addressing the underutilized spectrum resource and the overall user demands. The authors used a multibeam GEO satellite working at Ka-band and devised a game theory based method to optimize bandwidth efficiency by achieving the Bayesian equilibrium through spectrum competition among cognitive satellite users. Simulation results given from diverse perspectives showed that, the proposed algorithm was able to allocate the optimal spectrum to satellite systems by fixing Bayesian equilibrium, which could be achieved after 15 times of elimination operator.

The key challenges to space-air communications are discussed in [51] whereby the satellite-UAV spectrum allocation can be considered as a formidable research problem due to different frequencies used by satellites and UAV-based systems. Tsuji *et al.* [52] pioneered the concept of satellite-UAV spectrum allocation whereby the Ka-band of the fixed satellite service is exploited for facilitating the feeder commands and other non-communication loads required for the UAV operation. In this vein, the work developed a Ka-band satellite tracking antenna on-board the UAV. Furthermore, a resource allocation optimization method was proposed in [53] to minimize mean packet transmission delay in multi-layer UAV-aided cellular network. The authors used Poisson-Voronoi system model to formulate the problem in M/G/1 queue. Numerical results demonstrated that the proposed spectrum and power allocation algorithm could provide minimum packet transmission delay.

In satellite-UAV-ground heterogeneous network, Si *et al.* [54] proposed a dynamic spectrum allocation scheme based on navigation data and routing information to achieve optimal spectrum utilization. By adopting a unified communication protocol stack is adopted in the communication component of each UAV and ground station, the authors formulated the spectrum allocation process as an optimization problem to maximize the data delivery rate. Simulation results demonstrated that, with total 40 subbands available in the network, the proposed scheme could significantly improve the SE by over 75%, and was able to almost double the SE performance of the existing algorithm without optimization of subband management. In [55], Hosseini *et al.* considered a satellite emulation of C/Ku-bands, and stressed on the point that satellite-ground links are extremely susceptible to terrestrial interference because of relatively weak satellite stations. To

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alleviate this shortcoming, the authors introduced a cognitive software defined radio as cognitive relays for satellite ground stations suffering from terrestrial interference. The work further envisioned the future use of UAVs, which may act as relays, to improve the performance of the ground-satellite communications. Thus, the work in [55] opens up the much anticipated direction for practical satellite-air-ground communications.

Summary: This section covers various physical layer characteristics in the space-air-ground communication systems. Propagation channel, cross-layer design and spectrum allocation in such networks have been investigated in detail. Table V summarized the related works and the mainly considered factors in their solutions. From the table, we can see that, in available works, most factors in physical and higher layers have been taken into account for network design and performance optimization. However, these works mainly focused on the cases of space-ground and air-ground communication systems, few of them pay attention to the full integration of the three segments including space, air and ground. To support data delivery with low latency, high throughput and reliability in satellite-aerial-terrestrial communication, comprehensive mechanisms coordinating three parts of path routing, link scheduling, and spectrum allocating on the space-air-ground propagation channel are expected to be further explored. Especially, regarding spectrum allocation, existing works usually adopt a static channel model, which assumes that the satellite and/or the ground terminals are motionless. In fact, the high mobility of LEO satellites and UAVs in SAGIN will change the propagation channel state all the time. In order to achieve higher SE, dynamic and flexible spectrum allocating schemes based on the varying channel conditions, are still deserving further investigation.

IV. Mobility Management and Routing Algorithms

Mobility management and routing mechanism are two of the key techniques to satisfy the QoS requirements of users in mobile communications, especially in SAGIN where various moving NGEO satellites and aircraft are deployed. Many research efforts have focused on mobility management, traffic offloading and routing algorithms in integrated networks. In this section, we bring these works together in a common framework and give a detailed description.

A. Mobility Management

Mobility management is the management of the mobile user equipment (UE)'s location information, security, and the service continuity, with the objective of ensuring the uninterrupted connection between UE and the network. It contains two components: location management and handover management. Mobility management in terrestrial wireless network had been comprehensively surveyed in [56]. In this subsection, we mainly review existing works about the location management in satellite and integrated networks and leave the handover management as the next subsection.

1) Mobility Management in Satellite Network: In LEO satellite network, most available mobility management schemes mainly borrow the idea from the Internet Protocol (IP) mobility solutions [57], such as mobile IP (MIP) [58] and MIPv6 [59]. However, these schemes, which are based on a centralized management architecture, have exposed some shortcomings such as resulting in a large number of binding update requests. To this end, Han *et al.* [60] proposed a distributed mobility management based IPv6 mobility solution, named DIPS, by deploying the distributed anchors to handle the traffic from mobile terminals in LEO satellite network. Based on ground gateways, the proposed approach highlighted a distributed location management architecture. The authors compared the DIPS with centralized scheme and obtained the conclusion from simulation results that DIPS was able to decrease the management cost and transmission delay with the number of gateways increasing.

Considering the limited flow table size and satellite link handover, Li *et al.* [61] proposed a heuristic timeout strategy-based mobility management algorithm to reduce the drop-flows in the software defined satellite network, which adopted delay tolerant network for data transmission and OpenFlow for network control. The experimental results verified that the proposed algorithm was able to achieve the good performance in terms of transmission quality, an 8.2%-9.9% decrease in drop-flow rate, and a 6.9%-11.18% decrease in flow table size during the handover.

2) Mobility Management in Integrated Network: Compared to the single segment of satellite or terrestrial system, mobility management is more complex in the integrated network since it has to consider the moving nodes from all integrated segments.

Taking into account the efficiency of mobility management, Chiew Foong [62] discussed different mobility management strategies in the satellite-terrestrial integrated network. The author used Hata model in terrestrial system and the statistical shadowing model in satellite links to create an efficient seamless ubiquitous communication. Considering multiple performance metrics, a fuzz mobility management scheme was proposed in [62] to reduce the unnecessary handover, thus the reliability of the integrated network was increased.

When a spacecraft equipped IP address move from a GEO satellite coverage area to another, ground router cannot change the routing path automatically, with the result that the forwarding data cannot be routed to user spacecraft. With regard to this, Xu *et al.* [63] analyzed the mobility management problem generated from forward-communication between spacecraft and ground user in the GEO satellites based space-ground integrated IP network. The authors proposed a centralized routing control method to solve the location management and automatic routing maintenance problem considering the high mobility of spacecraft. Simulation results showed that the proposed mechanism in [63] was able to fulfill the requirements of switching time and achieve the performance of 100% routing handover success rate.

In the UAV-aided air-ground communication system, the high mobility of UAVs may bring unique benefits to improve the network performances. Zeng *et al.* [64] discussed two key techniques for wireless communications with UAV controlled

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TABLE V
RELEVANT REFERENCES RELATED TO PHYSICAL LAYER CHARACTERISTICS AND SPECTRUM ALLOCATION

Objective	References	Network scenario	Solution	Considered factors
channel analysis	[33]	space-ground	a dynamic fading channel model	multipath fading, shadowing effect, frequency band
channel estimation	[34]	space-ground	a physical layer adaptation algorithm	estimator errors, propagation delay
channel modeling	[36] [37] [38] [39]	air-ground	a time and vector based algorithm	path loss, delay spread, small-scale fading,multiple antennas, shadowing
maximizing weight of packet switching	[45]	space-air	a cross-layer OBP design	packet routing, beamforming, user scheduling, phased array antenna
improving routing performance	[46]	air-ground	a cross-layer routing metric and a load balancing algorithm	packet error rate, bandwidth, frame size
maximizing bandwidth efficiency	[50]	space-ground	a game theory based spectrum allocation method	interference, channel fading, bandwidth, antenna systems
minimizing packet transmission delay	[53]	air-ground	a spectrum and power allocation algorithm	path loss, fading, packet arrival rate, packet transmission delay
maximizing data rate	[54]	space-air-ground	a dynamic spectrum allocation scheme	navigation data, routing information

mobility, i.e., UAV-enabled mobile relaying and device-to-device (D2D)-enhanced UAV information dissemination. The UAV-enabled mobile relaying strategy used flying UAV as mobile relaying to reduce the link distances between the source and destination on the ground. Performance evaluation showed that the proposed mobile relaying strategy always enjoyed a shortest link distance and could achieve significant throughput improvement over the fixed UAV location relaying. D2D-enhanced UAV information dissemination aimed to achieve efficient information dissemination to a large number of ground nodes by exploiting both D2D communications and the UAV mobility. It was able to reduce the number of UAV retransmissions and the total flying time of the UAV, and thus the energy of UAV was saved.

In the past decades, location of wireless sensor networks (WSNs) has gained increasing attention [65]. However, the conventional localization systems have several deficiencies including difficulty of obtaining unbiased distance estimations and aggravation of communication burdens and battery consumption. In light of this, Gong *et al.* [66] proposed a new location framework for UAV-assisted air-ground integrated WSNs. The authors employed the moving UAV to serve as virtual anchors and designed a Newton iteration method to analyze the positioning error and estimation error. Numerical results represented that, the computational complexity of the proposed positioning system was acceptable, and that, using the mobility of UAV, the positioning error was less than 3.5 m with only 16 virtual anchors available.

B. Handover Management

In wireless communications, handover means the transfer of an ongoing connection from an original connected cell to a new one. In SAGIN, due to the high mobility of NGEO satellites, aircraft, and ground users, handover will happen frequently, thus its management is of great significance.

1) Handover in Satellite Network: In contrast to GEO systems, NGEO, especially LEO satellites move quickly around the earth, resulting in frequent handing over among satellites. According to [10], handover schemes in LEO satellite networks can be broadly classified into **link-layer** and **network-layer** schemes. Link-layer handover schemes mainly consist three types: **spotbeam handover schemes**, **satellite handover schemes**, as well as **ISL handover schemes**, and network-layer handover schemes can also be classified depending on connection transfer strategies. Considering service time correlation of inter and intra-satellite handover procedure in the LEO satellite systems, Musumpuka *et al.* [67] presented an analytical framework to efficiently evaluate the performance of services handover between spotbeams. The authors modeled the system as a queuing system with correlated service time and derived a closed-form solution of the correlated queue service time. Performance evaluation validated that the service time distribution and the handover blocking probability for the correlated case were higher than that for the uncorrelated case.

As an MEO system, O3b ensures seamless handovers between satellites by adopting a make-before-break mechanism [16], which makes a terrestrial terminal temporarily connected to two satellites simultaneously.

2) Handover Between Satellite Gateways: By using of high frequency bands such as Ka and Q/V on the feeder link, the multi-beam and multi-gateway satellite systems could provide high data-rate services [20]. In the case of satellite links quality becoming worsened under poor meteorological conditions, data flow should be transformed from one satellite gateway to another, which is called gateway diversity and results in a full handover between gateways.

Many research works have focused on the handover procedure and developed various smart gateway diversity (SGD) solutions to guarantee network performances. Kyrgiazos *et al.* [68] [69] investigated different SGD architectures and presented an analytical framework to evaluate the performance of the N-active SGD schemes. Considering a time switched payload architecture to introduce more flexibility and reduce the total number of gateways, they proposed three resource allocation schemes which took into account the uplink propagation conditions and the users demands. Bertaux *et al.* [70] developed an SDN-enabled gateway diversity architecture. They suggested that satellite gateways may be replaced by software defined network (SDN) enabled switches and SDN controllers could determine when and how to execute the handover between gateways according to the network QoS indicators.

The gateway handover in SGD systems requires efficient coordination strategies between gateways and precise predic-

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tion algorithms, so as to enable high data transmission rate and efficiently manage the satellite resources. To this regard, Mongelli *et al.* [71] designed a novel feeder link outage prediction algorithm based on machine learning concepts to orchestrate the gateway handover operations in the SDN-enabled HTS systems. Muhammad *et al.* [72] introduced a channel prediction algorithm and applied network coding to cope with packet losses caused by inaccuracies on the prediction of the handover time in the SGD systems. They used Buffer-Split handover benchmark technique to avoid packet losses and Delayed-Routing to control bandwidth waste. The results obtained via simulations confirmed that the proposed algorithm could protect the system from packet losses and efficiently save the system bandwidth.

3) Handover in Integrated System: Due to the movements of satellites, aircraft as well as terrestrial users, several issues need to be addressed in SAGIN when involving the space, air, and ground segments. An efficient inter-segment handover scheme is viewed as one of the most important issues to ensure seamless transition between segments.

In the satellite-LTE integrated systems, the movements of UEs cannot be predicted in advance, especially when the UEs are not able to relay on terrestrial networks, they must be able to shift to the service provided by the satellite. Therefore, a transparent handover is required. Based on this, Casoni *et al.* [9] described two kinds of handover procedures, i.e., S1 and X2 handover. S1 handover happened when a UE moved between satellite cells or between a satellite cell and a terrestrial eNB (evolved Node B or eNodeB), while X2 handover was required when a UE was moving between terrestrial eNBs. Similarly, to ensure seamless communication in LTE system, Crosnier *et al.* [73] presented a handover optimization mechanism in the hybrid satellite-terrestrial architecture. The authors focused on the handover between a terrestrial eNB with a satellite S1 interface and an eNB with a standard S1 interface. Experimental results validated that the proposed handover optimization procedure could save half of the satellite bandwidth and avoid an additional satellite transmission delay.

In the air-ground integrated networks, especially in the UAV-based communication systems, handover management is also a challenging issue. During prolonged flying, UAVs may be periodically out of service, or their communication interfaces may also be shut down to save power. In all these cases, communications must be seamlessly handed over to maintain the ongoing network services such as voice, video or data transmission.

A detailed survey on the types of handover and existing handover schemes in UAV networks had been given in [12]. The authors elaborated that handovers in UAV networks could be classified as hard and soft handovers, or horizontal and vertical handovers. Considering various handover challenges raised by the movement of UE and the changing of its cell, Sharma *et al.* [74] proposed an SDN enhanced UAV-based wireless network architecture, to efficiently handle the problem of managing and providing fast handover with a solution aimed at a fast transition of services. In their proposed model, a UAV module, which decided to shift traffic according to the network load and the active users' number, was invoked only when needed to reduce the burden of the controller. Performance evaluation showed that the proposed approach was able to decrease the overall signaling overheads, E2E delay, and handover latency in the UAV-aided communication system.

C. Traffic Offloading

Traffic offloading has gained much research attention recently as this concept offers complementary network technologies to deliver mobile data originally targeted for cellular networks [75]. Through traffic offloading, the data volume on the network bands is significantly reduced which frees bandwidth to other connected users. In SAGIN, there are several access approaches such as satellite communication, air network, and terrestrial mobile system. By offloading data traffic from the original network to other networks, network operators are able to add more capacity in an affordable and flexible manner.

A detailed survey on the offloading approaches at different part of the terrestrial cellular network (access, gateway, and core) has been presented in [76], and many research works have put their attention into traffic loading about heterogeneous cellular network (HCN) [77] [78], ultra-dense network (UDN) [79], and vehicular ad hoc networks (VANETs) [80], etc. In this subsection, we mainly focus on the traffic offloading in satellite network as well as the integrated system.

1) Traffic Offloading in Satellite Network: An NGEO satellite typically moves at a high speed along its own orbit and its contact time with the terrestrial station is short. Therefore, it is difficult for the satellite to download all its data (collected in space for target surveillance, weather forecast, environmental monitoring, and so forth) to the ground servers. Toward this end, Jia *et al.* in [81] proposed a collaborative data downloading by employing ISLs in LEO satellite networks prior to their contact with the terrestrial station. An iterative optimization algorithm to jointly schedule data offload among the satellites and data downloading from the satellites to the terrestrial station was also proposed. The research work demonstrated that in many cases, the throughput through the collaborative offloading method achieved 100% of the capacity of the terrestrial station. A similar research work can be found in [82], which considered ISL offloading in LEO satellite networks aiming at data downloading to the terrestrial station.

2) Traffic Offloading in Integrated Network: In contrast with traffic offloading in single terrestrial network, data offloading in the integrated networks involving satellites and/or UAV based networks is an ongoing research area. In this subsection, several prominent offloading approaches are discussed.

In future 5G system, D2D communication is identified as an emerging technology for traffic offloading to meet the huge demand of multimedia services. However, the increasing number of D2D pairs will result in the complexity of interference and radio resources management. With significant advantages for bandwidth-hungry services [83], satellite networks could be a promising candidate for offloading traffic

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from the terrestrial 5G networks to overcome above issues. To this end, Araniti *et al.* in [84] presented a subgrouping approach exploiting satellite links for multimedia traffic offloading in the 5G-satellite integrated network. Based on the multicast subgrouping-maximum satisfaction index metric, the proposed approach aimed to measure the overall performance of multicast radio resource management strategies through a single mark. Simulation results demonstrated that the proposed approach could increase the channel and aggregated data rate, and was able to achieve a better radio channel exploitation compared to state-of-the-art multicast solutions.

In satellite-terrestrial integrated mobile backhauling network, satellite links divert traffic from congested areas so that the limited capacity in terrestrial links could be supplemented. In this context, Mendoza *et al.* [85] proposed developed an SDN-based traffic distribution strategy in the 5G-satellite integrated network. The authors exploited the dynamically steerable satellite link capacity to maximize the network utility function in the cases of both failure and non-failure of the terrestrial links. Obtained results showed that, by reallocating the satellite resources, the proposed approach was able to minimize the utility decrease in the BSs affected by terrestrial link failures.

Recently, UAV-aided traffic offloading has been regarded as a potential solution to the so-called "hot-spot" issue in 5G networks [86]. In this solution, the UAV is considered as aerial, mobile base BS which can assist ground BSs to offload the data traffic, so as to service the mobile terminals on the network edge. Combining D2D communication, the UAV-aided traffic offloading from 5G BS was considered in [87]. Focusing on the UAV trajectory optimization to offload traffic from ground BSs, Cheng *et al.* [88] proposed an iterative algorithm to maximize the user sum rate in the UAV-aided cellular network. In the network model with three ground BSs and a UAV, the authors transformed such a mixed-integer nonconvex problem into two convex problems. Simulation results showed that, by optimizing the UAV trajectory, the proposed algorithm could maximize the average sum rate of edge users and satisfy the rate requirements of all the users.

D. Routing Algorithms

Routing algorithms address the problem of finding the most connected E2E path to successfully transmit data traffic to the destinations with a reduced E2E latency. Because of the particular features of space and air segments in SAGIN, such as dynamic topology, non-homogeneous traffic distribution, limited power and processing capabilities, it is necessary to develop appropriate routing approaches to manage and optimize network resource. On one hand, the use of ISLs raises the issue of routing in the NGEO satellite networks. On the other hand, in an integrated space-air-ground network, different traffic flows should be routed to different space-ground, air-ground, and space-air links according to their different QoS requirements.

Early routing protocols in NGEO satellite systems were usually connection oriented, they assumed asynchronous transfer mode (ATM)-like switches in the satellites, and most routing algorithms in satellite systems were ATM-based [89] [90]. As Internet is becoming very popular and the efforts concerning the next generation satellite networks are on the way, there has been an initiative to use IP routing technology in satellite networks [91]. As discussed in [92], several connectionless routing problem had been proposed in NGEO satellite networks. Here, we mainly focus on two kinds of IP routing algorithms: traffic-based and QoS-based.

1) Traffic based Routing: Kandus *et al.* [93] developed a traffic-class dependent routing algorithm and considered three classes of traffic: i) *delay-sensitive*, ii) *throughput-sensitive*, and iii) *best-effort*. Rao *et al.* [94] presented a distributed agent-based load balancing routing algorithm to ensure an intelligent engineering of traffic in LEO satellite networks. The authors used two kinds of agents, mobile agent and fixed agent, to gather and evaluate ISL cost, finally update routing items. Song *et al.* [95] developed a traffic-light-based intelligent routing (TLR) scheme for NGEO satellite IP networks. The authors used traffic lights to indicate the congestion status at both the current node and the next node. Compared to other routing algorithms, TLR could achieve better performance in avoiding congestion, reducing queueing delay, lowering packet drops and increasing total throughput.

Routing scheme is required not only in single NGEO satellite networks, but also in MLSNs. To utilize the abundant network resources of the MLSNs, The authors in [21] focused on the load balancing problem among the satellite layers and proposed a short path based routing method for fair traffic distribution in a two-layered MLSN. They developed the traffic distribution scheme by the traffic generation and detouring model, and also optimized it using theoretical analysis.

For UAV-aided air-ground communications, appropriate routing schemes may significantly shorten the communication distance and thus is crucial for high-capacity performance. Sami Oubbati *et al.* [96] proposed a connectivity-based traffic density aware routing algorithm for VANETs using UAVs. By using UAVs as the relay nodes and by combining the real time traffic density based on the periodic exchange of messages, that algorithm could found the shortest stable connected path to forward packets to their destinations at each moment.

2) QoS based Routing: Generally, QoS metrics mainly include E2E delay, delay jitter and bandwidth. However, due to the high mobility of LEO satellites, some ISLs in the network are not always available. Therefore, there should be extra QoS elements to measure the network performances. Rao *et al.* [97] presented a source-based multi-path QoS routing for Polar-orbit satellite constellation, and thoroughly revealed the impact of some key ingredients on the observed QoS parameters. The authors employed genetic satellite ISLs routing to implement QoS routing. Based on genetic algorithm, they re-designed several key ingredients: fitness function considering both the traffic distribution on the earth and the characteristic of Polar-orbit satellite constellation, mutation probability based on satellite congestion state, population diversity handling with simulated annealing.

In SAGIN, ground terminals should be able to work on different frequent bands so as to receive communications on forward link both from satellite and air network. Since satellite

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return link is a very expensive resource, Pace *et al.* [98] proposed an inter HAPs-satellite routing algorithm to minimize the maximum link usage and obtain a network load balance in the satellite-HAP-terrestrial integrated system. Simulation results showed that, the proposed algorithm could achieve the same performance of throughput over the inter-HAP links compared to the static minimum hop routing algorithm, while saving 30% of the satellite return link.

Summary: In this section, approaches for handover and mobility management, traffic loading, and routing in satellite- and UAV-based communications have been discussed. Figure 2 summaries and classifies the reviewed research works on these issues in different network scenarios. On one hand, we can clearly see from the figure that, most of existing works have focused on the satellite network, space-ground and air-ground integrated network, and have presented lots of significant methods to handle the problems of mobility management and routing. On the other hand, Figure 2 also shows that, few available works considered the network scenario integrating space, air, and ground, for example, only the study [98] put its attention into the SAGIN scenario. Note that in SAGIN, especially in LEO satellite-based case, both satellites and aerial components as well as terminals on the ground are moving with high speed, which will require comprehensive mechanisms coordinating three network segments of handover and mobility management. In addition, with the rapid growth of mobile data traffic in future terrestrial 5G wireless networks, it is expected to utilize the satellite capacity to offload as much traffic as possible so as to alleviate the burden of the terrestrial links. However, most related works concerning traffic offloading in space-ground network mainly focused on the multimedia content delivery. What's more, there are various services with different QoS requirements in SAGIN, some services are time sensitive while some are bandwidth-hungry. How to distribute the traffic flows of these services to the corresponding terrestrial or satellite or air-ground links according to their different QoS requirements and the actual link quality is well worth studying. Therefore, designing efficient traffic offloading schemes and routing mechanisms in SAGIN with different QoS requirements deserve further exploration.

V. System Integration and Performance Analysis

Up to now, there have been plenty of research works on the integration of space, air, and ground network, and various aspects related to the performance of these networks have been well discussed. In this section, we present a review of available literature concerning the integrated architectures and their performance analysis.

A. System Integration

As described in Section II-A, there have been several commercial integrated systems in the past decades. Besides, scholars have proposed their own integrated architectures about space-ground, space-air and space-air-ground, they also presented some open issues of these architectures in their research works.

The concept of space-ground integrated networks was introduced in [99] while the hybrid systems had been presented in [100]. Kota *et al.* [101] provided detailed definitions and examples concerning satellite-terrestrial integrated and hybrid networks. The authors focused on the design of integrated/hybrid systems taking into account physical, link, and network layers issues. They discussed some issues related to the interworking operation between the satellite and terrestrial networks. The work [101] also considered different integration levels such as data transmission, resource allocation, and service provisioning.

As an attractive complement to terrestrial and satellite systems, HAP in air network can provide telephony and direct access to broadband services. Based on Google Loon [102], Thai Hoang *et al.* [103] discussed the optimal energy allocation problem for the balloons in HAP to maximize network performance and the revenue for service providers. The authors formulated the problem as a Markov decision process and proposed a simulation-based learning algorithm. Numerical results indicated that the average EE obtained by the learning algorithm was always greater than that of the greedy policy. Cianca *et al.* [104] presented two integrated space-air architectures, in which the HAP was used to overcome some shortcomings of satellites like E2E TCP/IP throughput degradation and capacity in point-point model. For the provision of services ranging from communication to localization and data relay, the proposed integrated architectures could noticeably improve the TCP/IP connections throughput with respect to a pure satellite-based system.

Recently, addressing the separation of the LTE network and the mobile satellite system in current public protection and disaster relief (PPDR) network, Wang *et al.* [105] proposed a hybrid satellite-aerial-terrestrial (HSAT) system for the large-scale emergency scenarios which added LAP as a complementary component. In 2017, they surveyed the LAP and the HSAT networks in [106] and discussed the promising technologies from several aspects such SDN, D2D and software defined radio. Some practical challenges of the HSAT networks like interoperability and security were also outlined in [106].

To satisfy different QoS requirements imposed by diverse services in various vehicular networking scenarios in a cost-effective and flexible manner, Zhang *et al.* [26] proposed an SDN-enabled space-air-ground integrated vehicular network, in which ground network provided individual vehicular users high data rate unicast services in urban/suburban areas, while satellite helped achieve ubiquitous coverage in rural and remote areas, and HAPs were utilized to boost capacity at areas with poor or congested terrestrial infrastructure deployment.

B. Performance Analysis and Optimization

Compared to traditional terrestrial communications, SAGIN is affected by resource limitations, including limited frequency spectrum, limited bandwidth, unreliable wireless link, and so on. Thus, it is of critical necessity for network operators to provide optimal network performances so as to build communication conditions with high bandwidth, high reliability, and high throughput. Toward this end, lots of existing publications

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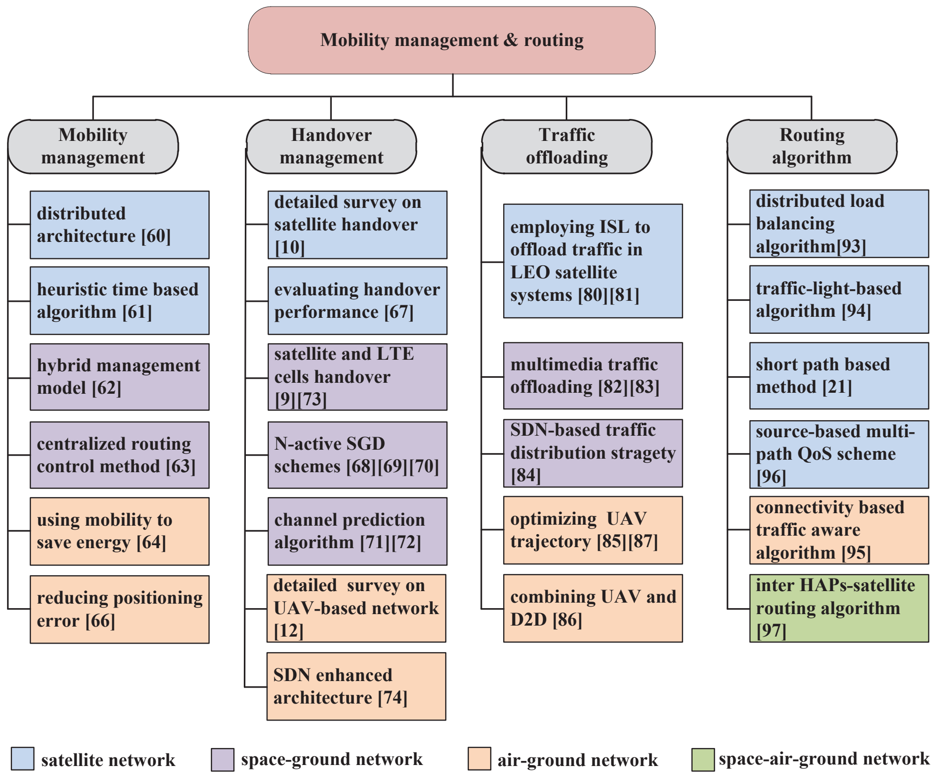

Fig. 2. Classification of the related works on mobility management, traffic offloading, and routing algorithm in different network scenarios.

focus on this issue to improve bandwidth, reliability and throughput of the integrated network.

1) Bandwidth Allocation: Bandwidth allocation aims at obtaining specific network performances, such as minimum data loss, delay, and power consumption [107]. For bandwidth is scare resource having multipurpose utility in the area of wireless communications, the bandwidth allocation problem has been discussed in articles for several years. Early in 2007, Bisio *et al.* in [108] proposed a minimum distance bandwidth allocation algorithm in space communication systems. The authors formalized the bandwidth allocation process as a multi-objective programming problem and assigned the bandwidth to the ideal case in which each ground station had the overall channel bandwidth available. Performance evaluation showed that the proposed algorithm followed the channel behavior and could provide more bandwidth to the faded station.

In current space-ground integrated networks, multi-beam satellites exploiting frequency reuse have been used to enhance the SE. However, the high frequency reuse systems are mainly limited by the aggregate interference, which had been neglected in many studies. Taking this into account, the authors in [109] proposed a joint power and carrier allocation technique for the cognitive satellite uplink and terrestrial fixed service co-existence scenario. Especially, an ad-hoc bandwidth allocation algorithm was designed to dynamically allocate the satellite bandwidth to the satellite terminals based on the rate demands of users. The results obtained with the proposed technique validated that the bandwidth allocation scheme presented in [109] satisfied the user rate requirements and prevented an unnecessary waste of bandwidth by maximizing its utilization.

To address the inefficiency of fixed bandwidth allocation caused by uneven user distribution and dissimilar content requirement, Kawamoto *et al.* in [110] proposed a dynamic bandwidth allocation method to provide context-aware contents to many network users in the satellite-terrestrial frequency sharing networks. The authors exploited the superiority of satellite multicasting and broadcasting to achieve high capacity of the cooperative network. Numerical results showed that the proposed method could achieve the highest number of users and utilized the bandwidth efficiently, and as a consequence was able to serve a large number of uses.

Since the hover time of each UAV will significantly affect the performance of UAV-based air-ground communication systems, it is necessary to analyze and optimize the performance of such systems based on the hover time of UAVs. To this end, Mozaffari *et al.* [111] investigated the hover time and load constraints in UAV communications, and considered a network in which multiple UAVs were deployed as aerial BSs to provide wireless service to ground users. Given the load requirements of ground users, the authors introduced an optimal bandwidth allocation scheme and an iterative cell partitioning algorithm to minimize the average hover time. The results showed that the average hover time could be reduced by 64% by adopting the proposed optimal bandwidth allocation and cell partitioning approach.

It is noted that increasing bandwidth means consuming more power, the wider the bandwidth, the larger the transmission capacity, and the less the EE. There should be trade-offs between power and information transfer when the bandwidth

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allocation strategy is performed.

2) Network Reliability: Since satellites and aircraft in SAGIN are moving and the network topologies are dynamically changing, so setting up E2E delivery paths and ensuring reliable message delivery are of great challenges. In all existing transport protocols, it is assumed that the network is always connected and that there exists E2E paths in the networks all the time. However, in SAGIN, due to the high mobility of satellites and aircraft, complete E2E paths rarely or never exist between sources and destinations, and the E2E transmission delays are much greater than that in terrestrial networks.

In the frequency reuse case, many studies only adopt the cooperative transmission mode to analyze the performance of the integrated satellite-terrestrial network from a single perspective such as symbol error rate (SER), EE and capacity, neglecting the direct transmission model and the interrelationship among the performance metrics. In light of this, Ruan *et al.* [112] proposed an EE adaptive transmission scheme with SER constraints for integrated satellite-terrestrial networks while taking into account the requirements of both EE and reliability in satellite communications, and modeled satellite downlinks and terrestrial links as generalized-K fading channels. The authors evaluated the exact SERs in closed-form expressions and then approximated the exact SERs at high signal-to-noise ratio (SNR) value, finally derived the linear form SERs as constraints to guarantee the reliability requirement of satellite communications. Simulation results verified that when the network demanded relatively high reliability in data transmission, the cooperative mode achieved considerably larger EE than the direct mode, while lower EE when SER was large.

Differing from other works mainly focusing on the relaying distance of UAV, Chen *et al.* [113] studied the optimum altitude of the UAV as a relaying station to improve the reliability metrics in terms of power loss, outage probability and BER. Considering static and mobile UAVs, the authors used the Nakagami-m fading channel model and numerical search to calculate these metrics by approximating the exact E2E SNR under the conditions of decode-and-forward (DF) and amplify-and-forward (AF), respectively. Simulation results identified that the altitude optimizing the relaying reliability was significantly different from the altitude optimizing the distance from the ground user to UAV and that DF performed better than AF.

As is well known, all the network performance metrics cannot be optimized simultaneously, when the network reliability is maximized, latency or data rate must be compromised. For example, A.Sabti *et al.* [114] used wireless sensor network module to analyze the link performance by recording the data and traffic lost on different runners and for different transmitter. The experimental results showed 62% reliability at 2 Mb/s, while 98% resulted when using a data rate of 250 kb/s.

3) Throughput: Delivery of high data throughput content with strict delay constraint is a constant challenge in many wireless communication systems. In available literature, the method most commonly used to analyze and improve network throughout is network coding (NC), which was first proposed in [115]. NC is mainly used in the multicast/broadcast network, where the nodes are coded to improve the information transmission rate and to save bandwidth.

Using independent time division duplex (TDD) channels with packet error rates (PERs) between the satellite and ground users, Esmaeilzadeh *et al.* [116] proposed a joint optimization problem of maximizing throughput and minimizing the packet drop rate (PDR). They first presented a systematic framework to study random linear network coding (RLNC) for delay sensitive applications, and then formulated the mean throughput and PDR for RLNC and systematic RLNC (SRLNC) schemes, and compared these schemes under feedback-free or feedback scenarios. Numerical results represented that, using the proposed framework, the feedback-free NC schemes provide better performances, in terms of the mean throughput and PDR; and that by optimizing the NC design parameters, performances very close to those of the idealistic scheme could be achieved even without using feedback.

Compared with fixed-wing UAV, rotary-wing UAV can take off or land vertically, and is easier to be deployed. However the research on rotary-wing UAV relaying system is still in infancy and existing works in the fixed-wing UAV relaying system cannot offer too much guidance. To this end, Fan *et al.* in [117] studied a joint optimization problem of transmission power, bandwidth, data rate and the position of UAV, with the objective of maximizing the network throughput in a rotary-wing UAV relaying system. The authors transformed such a non-convex problem to a monotonic optimization problem and proposed a Polyblock algorithm. Numerical results showed that the proposed method could achieve the global optimal solution with short running time, and that with system bandwidth, transmission power growing, the maximal network throughput increased.

Summary: This section elaborates several integrated systems and network performance metrics. The related works which discuss the system integration and the performances from the perspective of bandwidth, reliability, and throughput are summarized in Table VI. We can easily see from the table that, the space-air-ground integrated architectures have been well investigated in these reviewed references. As also shown in Table VI, although the performance analysis in most available works have focused on typical challenges faced in space-ground or air-ground integrated network, few of them concerned the cases in SAGIN. As described in Section I, the new challenges brought by the heterogeneity, self-organization, and time-variability in SAGIN will seriously affect the network performances such as latency, reliability, and throughput for data transmission. That is, we wish existing research works may concern such issues involving all the three network segments. This aspect, however, is missing in the aforementioned references.

VI. Applicability of Existing Network Architectures

In this section, we introduce several contemporary network architectures applied in terrestrial systems with respect to their extensibility and feasibility to support integrated space-air-ground networks.

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TABLE VI
SUMMARY OF RELATED WORKS ON SYSTEM INTEGRATION AND PERFORMANCE ANALYSIS

Objective	Related works	Network scenario	Problem formulation	Key contributions
system integration	[99] [100]	space-ground	not applicable	introducing the concept of integrated/hybrid satellite-terrestrial network
	[101]	space-ground	not applicable	definitions and examples of the integrated/ hybrid satellite-terrestrial network, and discussing interworking issues
	[103]	SAGIN	optimizing energy allocation	a simulation-based learning algorithm
	[104]	SAGIN	improving TCP/IP connections throughput	using HAP in space-ground architecture
	[105] [106]	SAGIN	not applicable	a HSAT system for emergency scenario
	[26]	SAGIN	not applicable	an SDN-enabled space-air-ground integrated vehicular network
bandwidth allocation	[108]	space-ground	a multi-objective programming problem to provide more bandwidth to the faded station	a minimum distance based allocation algorithm
	[109]	space-ground	maximizing bandwidth utilization, jointl allocating power and carrier	an ad hoc bandwidth allocating algorithm
	[110]	space-ground	maximizing the number of serving users	a dynamic allocation method exploiting the superiority of satellite broadcasting
	[111]	air-ground	minimizing the average hover time of UAV	an optimal bandwidth allocation scheme and an iterative cell partitioning algorithm
reliability	[112]	space-ground	jointly optimizing SER, EE and capacity	an EE adaption transmission scheme with SER constraint
	[113]	air-ground	minimizing BER, power loss and outage probability	a numerical search calculation method
throughput	[116]	space-ground	maximizing throughput and minimizing PDR	a systematic framework using RLNC and SRLNC
	[117]	air-ground	joint optimization of transmission power, bandwidth, data rate and the position of UAV	a Polyblock algorithm

A. TCP/IP Model

Although the TCP/IP protocol has been widely used in terrestrial fixed and mobile networks to provide high speed and reliability data delivery, it reveals many challenges and performs poorly in satellite, aerial network and the integrated environments [118]. These stem from the inherent characteristics of SAGIN, such as high mobility, long propagation delay, high heterogeneity, asymmetric bandwidth, and so on. To well apply TCP/IP protocols into space or air networks, various solutions based on the basic model have been proposed for many years, which include direct TCP performance enhancements [119] and advanced link optimization [120].

1) TCP/IP Basic Model: The first definition of the TCP/IP model was introduced in 1974 [121], and was adopted by ARPANET in 1983. Unlike the seven layers of the Open Systems Interconnection (OSI [122]) reference model, TCP/IP model has only four layers, in which the Network Access layer is sometimes called the Network Interface or Link layer [123] [124]. It should be noted that, TCP/IP protocol suite was developed for wired global Internet as the networking solution. Thus, when employed in wireless networks, it faces the new challenge of TCP performance degradation due to the high and unpredictable error rates on the wireless links [125] [126]. Toward this end, several new performance enhancement solutions like multipath transmission and cross-layer design, which can be found in the survey papers [127] and [43], respectively, have been proposed and applied.

Based on the basic TCP/IP model, several new network communication reference models are proposed and have been implemented. Among these reference models, the most arrestive and successful one is the Architectural Reference Model (ARM) for IoT [128]. Although ARM is not able to address the interoperability issues between heterogeneous objects, such as security and QoS, it can be layered on top of another model with new vision to form a new model. For instance, according to the ARM, [123] proposed a new IoT communication reference model as illustrated in Figure 3. In this IoT model, two new layers, i.e., QoS layer and Security layer were introduced and classified as Layer 2 and Layer 3, respectively.

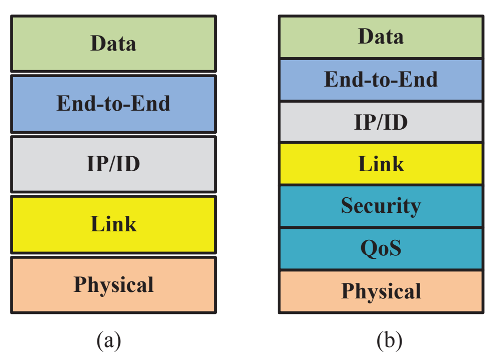

Fig. 3. Illustration of ARM and new model for IoT, (a) ARM, (b) a new reference model proposed in [123].

2) TCP/IP in Integrated Network: In Transport layer of the TCP/IP model, TCP adopts some schemes like slow start, congestion avoidance, fast retransmit and recovery to control congestion. These schemes are based on the premise that the network congestion results in packet loss. In SAGIN, especially in satellite communication systems with a relatively high

BER, TCP cannot identify whether the packet loss is caused by BER or network congestion, thus the TCP transmission performance deteriorates. What's more, the congestion control mechanism of TCP does not allow full utilization of satellite bandwidth due to the large bandwidth-delay product [129]. Besides, TCP considers segment losses as congestion signal, thus forcing the data transmission rate to be unnecessary reduced, and the congestion window has to be halved, which lead the satellite link into under-utilizing.

TCP throughput is mainly affected by PER, which can distinctly raise performance degradations in satellite networks. To this end, several new architectures and protocols such as TCP Hybla [130], New Reno [131], and advanced transport satellite protocol (ATSP) [132], have been proposed to improving the throughput on satellite links. Besides, another specific network architecture, called Performance Enhancing Proxy (PEP) [133], has been carried out to take the advantages of advanced TCP version over satellite links without changing the protocol stack of end-users. PEP uses a suit of techniques usually based on TCP spoofing/splitting techniques which break off TCP connections, transparently to end-users, and establish new ones using optimized transport protocols to efficiently deliver data over the satellite links [134]. It can be located in devices like satellite modems and be implemented at link and/or higher layer(s). Recently, several evolutionary PEP solutions have been proposed to improve the performance in the satellite networks, like Mobile-PEP [135], network-coding-enhanced PEP [136], 3-segment splitting PEP [137], and A-PEP [138]. The comparisons of these solutions are listed in Table VII.

B. Ad hoc Network

Ad hoc network, also called MANET or wireless ad hoc network (WANET), is a temporary, nonstandard, and self-organizing network formed by a collection of wireless mobile terminals. This kind of network does not need the aid of any established infrastructure or centralized administration. In ad hoc networks, an individual node should dynamically discover which other nodes it can directly connect with. Limited by wireless transmission range of each node, it is necessary for one mobile node to enlist the help of other ones to forward packets to its destination [139].

Ad hoc network can be built by leveraging any wireless access technology, such as infrared and radio frequency. For the past decades, several new kinds of ad hoc network architectures have been proposed and applied, including terrestrial networks such as VANET [140], wireless mesh network (WMN) [141], WSN [142] and aerial networks like flying ad hoc network (FANET) [143]. By definition, FANET is a formation of MANET, and can also be classified as a subgroup of VANET. This affiliation is shown in Figure 4.

1) Ad hoc in Integrated Network: Ad hoc network is suited to special environments, such as military mission, disaster relief, and field expedition, where infrastructure is either not available, not trusted, or should not be relied on in times of emergency [144]. Integrating with satellite and/or aerial network, it will provide reliable communications with the advantages of wide coverage and high flexibility.

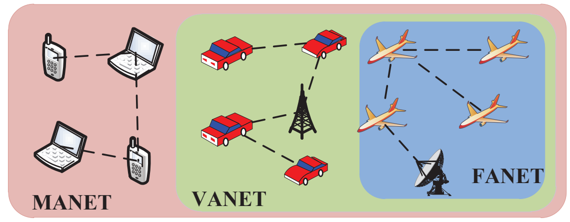

Fig. 4. Relationship between MANET, VANET and FANET.

- **UAV-enhanced VANET.** VANET aims at enhancing safety and efficiency in future ITS. Currently, the potential candidates for VANET wireless communication mainly include IEEE 802.11p based dedicated short range communication (DSRC) [145] and LTE based LTE-V [146]. As an emerging technology, UAV communication has exhibited valuable features such as flexible deployment, broadband wireless access, and dynamic networking, which can enhance the performance and applications of VANET [147]. UAV-enhanced VANET can not only improve infrastructure coverage and vehicle-to-vehicle connectivity, but also provide better safety and security on the road, and bring more comfort to the driver [148].
- **Satellite-based WSN.** WSN is usually used for remote monitoring applications where data is collected by sensors and then transmitted to a remote destination. Limited by transmission distance, it needs to leverage other communication technologies to set up connections between sources and the remote destination. Integrated with satellite, the employment of terrestrial WSN will be further strengthened for various applications [149]. Especially, the satellite backhaul allows remotely controlling and monitoring WSN data over long distances. At the same time, to efficiently integrate satellite and WSN networks, some essential issues such as sink selection [150], data security, and performance evaluation should be well considered.
- **Satellite/UAV-enabled WMN.** WMN, also called multi-hop wireless networks, consists of mesh routers and mesh clients. It can be utilized in many practical scenarios including environmental monitoring, surveillance activities, remote telemedicine, and so on. Unfortunately, WMN is easily affected by the unavailability Internet connections, especially when the infrastructures are destroyed in natural disasters. Leveraging the immunity of satellite/UAV to infrastructure damages, the satellite/UAV-enabled WMN is able to provide wireless access services to users in the disaster areas [151] [152]. However, when such an integrated network deployed, the gateway placement problem in WMN must be taken into account.

2) FANET: In air network, with the number of UAVs increasing in the same systems, it is necessary to design an efficient network architecture for multi-UAV communications. In general, there are four alternative architectures, as shown in Figure 5, to solve the communication problems among multiple UAVs [153]. According to Figure 5(a), the operation area is limited to the communication range between UAVs

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TABLE VII
COMPARISONS OF PROPOSED PEP SOLUTIONS

Proposed PEP	Operating layer in TCP/IP model	Splitting connections	Main parameters	Algorithm
mobile PEP [135]	network layer & link layer	mesh connection	sequence number of transmitted packets	none
network-coding-enhanced PEP [136]	network layer & link layer	PEP-NEC	throughput, PER, overhead	RLNC
3-segment splitting PEP [137]	transport layer	TCP Hybla	token generating rate, size of bucket	token bucket filter
A-PEP [138]	cross-layer	customer TCP and file transfer framework with application layer forward error correction	PER, round trip time	adaptive selection algorithm

and the ground station; in the case of (b), such a system will not be suitable for extreme weather conditions; and the architecture depicted in (c) is vulnerable for disaster application scenarios. Another communication architecture is FANET, which is shown in Figure 5(d). This architecture establishes an ad hoc network among UAVs and thereby can resolve the communication range restriction problem. In this architecture, some UAVs connect with the ground station or satellite, other UAVs can employ their communication through FANET structure [154].

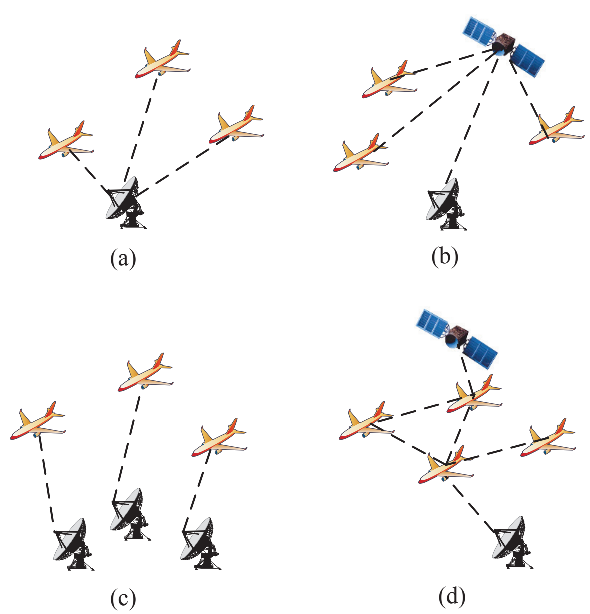

Fig. 5. Architectures for multiple UAVs communication, (a) single ground station, (b) single satellite, (c) multiple ground stations, (d) FANET.

Due to the high mobility of UAVs, it is of great challenge to maintain a communication link between them. What's more, the topology of FANET is more dynamic than that of MANET and typical VANET, the available routing protocols applied in MANET, such as optimized link-state routing (OLSR), may partly fail in tracking network topology changes. There must be some modification or extension of these protocols in order to be adapted in FANET [155]. As an example, [156] proposed an extended OLSR, named P-OLSR, which took the advantages of the Global Positioning System(GPS) information to predict how the quality of the wireless links will evolve.

C. SDN/NFV

There is an urgent necessity to enhance the SAGIN through intelligence, to deploy and realize a powerful wireless communication system. Leveraging the concepts of software and virtualization, SDN [157] and Network Function Virtualization (NFV) [158] are redefining the network architecture to support the new requirements of an eco-system in the future networks. On one hand, SDN decouples control entity (called the *controller*) from the switch for a centralized control in the data plane [159], as shown in Figure 6. The controller has an overview of the network so it is able to give a global management on the network. On the other hand, by separating software instance from hardware resources, NFV implements network functions through visualization technologies and runs them on commodity hardware [160], which is depicted in Figure 7.

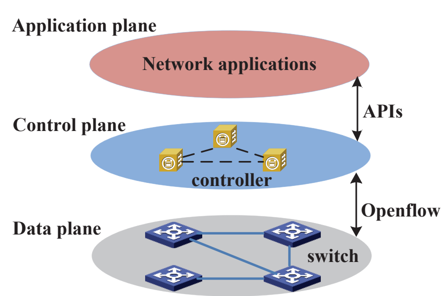

Fig. 6. Architecture for SDN.

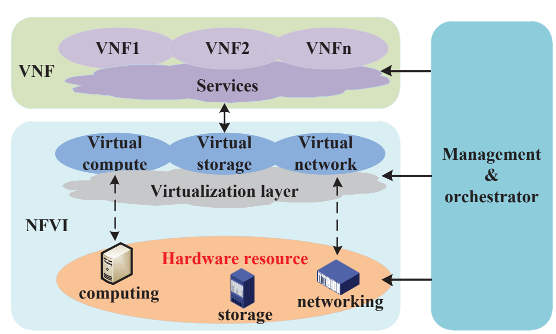

Fig. 7. NFV architectural framework.

It is expected that the future 5G network will be open, more flexible, able to support HetNets, and able to evolve more easily than the traditional networks [161] [162]. Introduction of SDN and NFV can address numerous challenges in 5G networks, including inconsistent interfaces, frequent handovers, extensive backhauling [163], and complicated heterogeneity, by specifying and providing intelligent and flexible management and orchestration systems [164]. SDN and NFV technologies are also being considered as central technology enablers towards improved and more flexible integration of space, air and ground segments, providing further service innovation and business agility by advanced network resources management strategies.

1) SDN/NFV in Satellite-based Network: In general, the application modes of SDN/NFV in satellite networks can be categorized into three types according to the specific objectives: SDN/NFV in satellite, SDN/NFV in satellite ground components, and SDN/NFV in satellite backhauling network.

- **SDN/NFV in satellite.** Current satellite systems have the capacities of on-board processing and routing, thus they can be turned into SDN-enabled switches that execute simple forwarding rules from the controllers. According to this, a multi-path TCP (MPTCP)-aware SDN controller which could identify MPTCP subflows, and compute the subflows with disjoint satellite paths, was developed in [165]. Based on SDN and NFV, Li *et al.* [166] presented a multi-layer SDN-enabled satellite network. In such a network, the NFV based service deployment method could provide flexible and reconfigurable satellite services delivery.
- **SDN/NFV in satellite ground components.** The ground components of satellite networks mainly consist of multiple satellite gateways and satellite terminals (STs). The gateways are interconnected via dedicated backbone network with some points of presence to the Internet. NFV can be used to virtualize some functions in gateways, such as firewalling, PEP, network address translation, media transcoding, and so on [167]. By applying SDN-enabled gateways and STs, inter-gateway handover and flow-based packet forwarding in satellite-terrestrial integrated network can be executed with intelligence [168].
- **SDN/NFV in satellite backhauling network.** In the space-ground integrated/hybrid systems, one of the most noticeable scenarios is mobile backhauling, in which satellite capacity can be used as a complementary part to the ground backhauling infrastructure. However, in the integrated/hybrid backhauling network, usually there will be multiple available paths along which data traffic can be routed, when and how to select path while avoiding network congestion and obtaining the best resource utilization must be carefully considered [169]. The SDN controller has an overview of the network so it is able to make decisions of global path selection according to the whole network states [170].

2) SDN/NFV in Integrated Network: SAGIN is composed of different types of network devices, resulting in HetNets. The communication system in each network segment is closed due to the dedicated hardware equipments, which significantly limit the system reconfigurability and interoperability and increase the complexity to manage these networks. Left only data forwarding functionality, SDN-enabled devices in HetNets need not to understand various protocols but merely to receive instructions from the controller, which paves the way to manage these devices with great flexibility and programmability. Decoupled from proprietary hardware devices, network functions can be dispatched to a service provider as an instance of plain software, which break through the barrier caused by closed hardware resources. In [26], an SDN-enabled space-air-ground integrated vehicular network architecture, which mainly consisted of three layers: infrastructure, control, and application layers, was proposed to address the challenges like inter-operation, network management and QoS provisioning in the integrated network. In such a network, many benefits, including simplified network management and cost-effective network upgrade/evolution, optimized network operation and resource utilization, flexible and agile network behavior control, could be achieved.

D. Other Emerging Architectures and Technologies

1) IoT: By leveraging smart devices, sensors, radio-frequency and wireless technologies, IoT has been a newly emerging architecture to build powerful systems and applications in various fields including industry, agriculture, energy, and health care [171]. It can transparently and seamlessly merge different and heterogeneous networks to process, store, and represent tremendous amount of data in an efficient, flexible, and interoperable way.

The major difference between IoT and WSN is that WSN need not to be connected to Internet. There are three key techniques in IoT: sensor technology, radio frequency identification (RFID), and embedded system. According to communication distance, IoT can be classified into long distance transmission IoT and short range communication IoT. The main wireless technologies in the former includes LoRa, narrow-band IoT (NB-IoT), and sigfox, while that in the latter consists of WiFi, Bluetooth, Zigbee, and near field communication (NFC).

For most IoT applications, long distance and wide coverage for services with demands of anytime, anywhere, and anything are required. In recent years, satellite-based IoT is found to be of paramount importance in such applications as smart grid, environmental monitoring, and emergency management [172]. Satellite is able to serve a huge number of smart objects by exploiting broadcast/multicast connectivity, and could provide true alternative communication links to the terrestrial systems when both fixed and wireless infrastructures are disabled or destroyed. However, to build an effective IoT via satellite, several challenging issues need to be considered and solved including HetNets interoperability, QoS management, and cooperative resource allocation [173].

With ubiquitous usability, UAVs are also foreseen as an importantly integral part of IoT ecosystem. On one side, they can act as aerial BSs or relays to provide wireless access services to the smart devices. On the other side, UAVs can offer new value-added service when they are equipped remotely controllable IoT devices such as sensors, cameras, and actuators [174]. In such a way, a UAV-based IoT platform

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will be formed in the air. When involving UAV into IoT, there must be several technical challenges to address such as routing scheme, data collection, communication and networking.

2) D2D Communication: D2D communication is a very flexible communication technique in LTE-A and 5G network to realize data transmission between mobile UEs. By the definition, it does not need to leverage the eNB or core network while directly forwarding data traffic from one mobile UE to another spatially closely located one. Thanks to the short communication distance between UEs, D2D communication can be widely used in peer-to-peer communication, machine-to-machine communication, and multicasting communication. And it is believed to be of the capability to improve system capacity, throughput, spectrum efficiency [175] [176], and EE in cellular network.

The concept of 5G technology has been introduced as a futuristic solution to meet the excessive consumer demand for wireless data access. As an allied technology of 5G, D2D communication has been envisioned for providing services that include live videos and pictures sharing, traffic offloading [177], gaming, disaster relief, connectivity extension, etc. Recently, focusing on the challenging issues of D2D communication in 5G system including interference management, network discovery, network coding, and network security, lots of research works have been done, which can be found in the detailed surveys [178] [179] [180].

Undoubtedly, D2D communication will bring great benefits to the forthcoming 5G cellular network. However, due to the unavailability or insufficiency of infrastructures in rural, remote, and disaster damaged areas, it is still difficult to construct wireless communication networks. As mentioned before, deployed as aerial BSs, UAVs are able to rapidly form a flexible wireless network, and thus can be a good candidate to build the D2D-enhanced wireless system [181]. Similar to UAV-based IoT, in the combined UAV and D2D-based network, UAVs can be considered as both local content servers or relays to provide wireless access services and D2D nodes [87]. In this context, conventional channel assignment mechanisms may be no longer suitable, and tractable analytical frameworks for coverage and rate analysis are also required.

VII. Technical Challenges and Future Directions

In this section, from aspects of network design, protocol optimization, and performance enhancement, we identify several technical challenges and future directions in SAGIN.

A. High Latency in Satellite Network

In general, latency, which can be defined as the time it takes data packet to be transferred from source to destination, mainly consists of four parts: transmission delay, propagation delay, processing delay and queuing delay. Different from terrestrial systems, the high latency plays a key role in satellite networks for QoS purposes, especially when considering the usage of satellites as backhauling network. According to [14], the latency in satellite systems can be divided into two parts: fixed one and dynamic one. The former refers to propagation delay and the latter includes transmission delay, processing delay and queuing delay.

In satellite systems, it is expected that the fixed propagation delay is dominated. GEO satellites are at fixed positions of 35,786km altitude in the sky, even if all other signaling delays could be eliminated, it still takes radio signals about 125ms to travel from the satellite to the earth's surface. In the case of MEO/LEO satellites, the propagation delay is determined by the satellite altitude above the earth, for example, increasing the satellite height of 1000 km will add roughly 20 ms to the one-way delay for a single hop, and additional satellite hops will add to the latency [182]. Due to the high mobility, the propagation delay in an LEO satellite system actually varies with the changing of satellite's positions.

Every network device on the E2E communication path may process information and slow the transmission, thus contributing some visible amount to the overall processing delay. To reduce the processing delay, a direct solution is to improve the computing and storage capacities of devices, which results in the cost increasing as well. It is also noted that many devices can be highly configured to serve a wide range of applications, and different configuration may lead to lower latency.

1) Latency of GEO Network: There is no way to eliminate latency in GEO satellite systems, but the problem can be somewhat mitigated in Internet communications by adopting specialized TCP acceleration algorithms which can shorten the apparent round trip time (RTT) and alleviate the TCP throughput suffering from the high latency over the satellite links. As discussed in Section VI-A2, by breaking off the E2E connection at the satellite modem and/or ground station, TCP PEPs separate the satellite link from the rest of the communication path, thus the E2E connection is split into three intermediate segments. Introducing PEPs in TCP allows for developing different technologies to optimize the high latency in the embedded satellite equipment, at the same time, it reveals other new issues like security problems in the network layer.

2) Latency of NGEO Network: Unlike GEO satellites, MEO/LEO satellites have no stationary positions in the space, as a consequence, ground stations cannot easily locked into connection with any one specific satellite. In satellite footprints, due to the user density and climatic conditions, the traffic distribution is nonuniform, which leads to some ISLs in satellite systems getting into congestion and others remaining underutilized. Thus the queuing delay and PDR are significantly increased, and the QoS of the entire networks will be ultimately affected. To avoid such congestion so as to reduce the queuing delay, developing an efficient routing solution taking the network traffic distribution into account is needed. Several routing algorithms like Fuzzy Satellite Routing(FSR) [183], Explicit Load Balancing (ELB) scheme [184] have been proposed to guarantee a better distribution of traffic among satellites. These methods are based on multipath forwarding strategy, which transmits packets of the same flow over different links. Therefore, the traffic in the satellite systems can have better distribution, accordingly congestion in some ISLs will be alleviated and packet drops are avoided.

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However, such method requires a full knowledge of current network status, which is difficult to obtain.

Remarks: In-network caching has been studied to improve the performance of satellite-terrestrial networks for recent years. **By caching video content or television live streams at radio access node, the long propagation latency may be largely shortened**. Besides, it is expected that more and more satellites will be equipped with OBP in the near future, which can move the communication and networking functionalities from ground stations to satellites. Thus **the overall E2E latency will be reduced by removing unnecessary round-trip control signals delays**.

B. *Traffic Offloading in Integrated Network*

As discussed in Section IV-C, there have been many study works focusing on traffic offloading in terrestrial, satellite, space-ground, and air-ground networks, and several efficient architectures and approaches have been already proposed to address such an issue. Besides, a proof-of-concept prototype has been introduced in [185] to show how data offloading can be carried out in satellite-terrestrial integrated networks. However, unlike terrestrial network, in which the traffic offloading methods are significantly mature, moving traffic form terrestrial cellular system to satellite and/or air based networks still faces following changes.

- **Long propagation latency.** When satellite links are used to offload traffic from terrestrial networks, the long latency introduced by the long propagation distance from the earth surface to satellite should not be neglected. Therefore, deciding which kind of traffic may be offloaded via satellite links is necessary. For instance, it is not suitable for traffic flow of delay-sensitive services to be transmitted through satellite networks. Fortunately, as described in Section VII-A, the long latency can be reduced with the aid of intelligent caching.
- **Link selection.** In SAGIN, there usually exist multiple links including terrestrial links, satellite links, and air-ground links, which have different link cost. Thus, selecting different kind of links will lead to different usage cost. When the traffic offloading decision is made, it should take into account the comprehensive factors such as network capacity, performance degradation caused by congestion, queueing delay, and link cost. To address such a problem, competition and cooperation mechanisms between resource providing and utilizing are required, and game theory [186] and auction theory [187] should be introduced.
- **Channel allocation.** When using UAV to offload traffic from terrestrial network, due to the limited number of channels, one UAV cannot provide wireless access services for all users in its covered area simultaneously, especially when there are a large number of users. Thus, an efficient channel allocation scheme is necessary. Fair or competitive? Polling or interrupt? Queueing or setting priority? These issues must be well considered when designing the channel allocation algorithm in UAV-aided traffic offloading context.

Remarks: The architecture of future 5G is based on ultra-densely deployed smalls, which leads to the increase in the amount of needed control signals. To address this problem, the concept of control (C) plane and data (U) plane splitting has been proposed so that the control traffic can be delivered via macro cell while the small cells just deliver data on the U plane [188]. It is suggested that **satellite backhaul be used to offload control traffic by regarding a satellite cell as the macro cell**, thus the terrestrial capacity and energy can be saved.

C. *Management of HetNets*

In SAGIN, different networks are supported by various communication protocols, and each network comprises vast devices with different interfaces for configuration and control, which lead the integrated network to become more complex to manage. Operated at different segments and designed for different purposes, network components in SAGIN show heterogeneous characteristics, which requires new techniques to solve the challenging coexistence problems including mobile nodes management, cooperative transport control, and so on.

1) Relativity of Mobile Nodes: In SAGIN, dense deployments of HetNets to all three network segments lead to more frequent handovers and need more efficient mobility management. The cross-segment handover rate and handover failure rate in SAGIN will be much higher than that in one single-segment networks. Frequent handovers in HetNets not only increase signaling overhead on the network, but also degrades the user experience [189]. Acquiring the nodes movement behavior, i.e., the relativity of mobile nodes, is of fundamental importance to reduce handover. Thus, to model the relativity of mobile nodes is an important building block in the HetNets. The choice of the mobility model and its parameters has a significant influence on the obtained performance of HetNets.

It is difficult to build and use the mobility models based on the actual characteristics of mobile nodes. At present, a very popular and frequently used mobility model is the random waypoint (RWP) model [190] in MANETs. It is a simple stochastic model describing the movement behavior of a mobile node in a two-dimensional system area. However, when utilized in HetNets of SAGIN, RWP may face many challenges due to the uneven nodes distributions, high speed node movement, and the interference from all other network segments.

2) Cooperative Transport Control: Cooperative transport in HetNets means not only allowing different communication systems to dynamically share wireless network resources, but also using the distributed collaboration of mobile nodes to improve resource utilization and transmission capacity. Specifically, in SAGIN, various heterogeneous communication systems such as satellite networks, FANETs, VANETs, and mobile communications are coexisting in a dynamic integration. To take full advantage of network resource and to improve the scalability and reconfiguration capability of the integrated communication systems, collaborative network transport control strategies for multi-segment HetNets are required.

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Currently, one of the most common methods of cooperative transport is coordinated multipoint (CoMP) or cooperative multiple input multiple output (MIMO) transmission in terrestrial LTE and mobile WiMAX [191]. CoMP mainly uses the coordination of BSs to avoid interference, thus, when such a method is adopted, the limited maximum distance of cooperation BSs and the cost of their synchronization must be taken into account.

Remarks: As described in Section VI-C, SDN/NFV can bring great flexibility and intelligence to the management of HetNets. Meanwhile comes an entirely new problem of controller placement in the integrated network. **Note that in such a network, SDN-enabled devices are distributed not only on ground but also in aerial and satellite network. Especially in SDN-enabled satellite-terrestrial communications, controller placement must take into account the placement of satellite gateway simultaneously** [192].

D. Multi-layered Satellite Networks

Consisting of multiple satellites constellations moving different orbitals, MLSNs have many special merits compared to single-layered satellite networks, such as high space spectrum utilization, low link congestion and high robustness. However, due to the rapidly changed topology and complex structure in MLSNs, there are also some challenging issues to be addressed, including QoS guaranteeing, handover management, and load balancing among the different satellite layers.

1) QoS Guaranteeing: In MLSNs, to avoid traffic congestion so as to guarantee the network QoS of lower satellite layer, a usually way is to route some packets from the lower layer to the upper one. Such a strategy, however, will lead to the increase of propagation delay due to the long communication distances between two layers [193]. Especially, if the upper layer is composed of MEO satellites, their altitude will affect the not only propagation delay but also the queueing delay. Low altitude will shorten the distance from MEO satellites to LEO satelliets thus reduce the propagation delay. Simultaneously, such an altitude results in limited coverage of MEO satellites, which increases the queueing delay of LEO satellites since most traffic from them has to be routed to the only one covering MEO satellite. As a consequence, there should be a trade-off between propagation delay and queueing delay when designing such MLSNs.

What's more, in MLSNs, the upper layer network may be congested since each satellite in this layer usually receives the traffic from more than one satellite in the lower layer, which results in the whole network throughput degradation, and increases the E2E communication delay. Therefore, to improve the network performance and guarantee QoS, it is urgently necessary to develop effective solutions to address such congestion for MLSN communications.

2) Load Balancing: In general, LEO satellites in bottom layer of MLSNs are responsible for the terrestrial network access services. Because of the uneven distributed ground users, the amount of traffic each LEO satellite received is inhomogeneous, leading to unbalance load at those LEO satellites. Moreover, the inhomogeneous traffic distribution in the LEO layer causes the biased converging of traffic at the satellites in upper layer [3]. Thus, the problem of balancing the inhomogeneous traffic so as to avoid congestion of intra-layer and inter-layer in MLSNs deserves to study. To this end, intelligent routing schemes based on load balancing to meet the QoS requirements are necessary. What needs to be emphasized that, when designing these routing algorithms, it will be better to optimize path selection and take the appropriate shunt measures according to different type of traffic in the satellite orbit period.

Remarks: Besides the multi-layered satellite networks in space, UAVs, airships, and balloons at different altitudes can also form multi-layered aerial networks. Thus, **a fully layered GEO-MEO-LEO-HAP-LAP-ground integrated system may be constructed**. In such a layered system, QoS guaranteeing, load balancing, handover and management will become much more complex and difficult.

E. Digital Channelization in HTS Systems

Based on frequency division multiplexing, and time division multiplexing, the digital channelization technology is usually used to extract multi-channels signals for different wireless standards. By leveraging digital channelizer, it becomes easier to route sub-signals from any upstreaming channel to any downstreming one, control the gain of each sub-signal, and improve the channel capacity and the flexibility of bandwidth allocation.

Due to the fixed communication resource allocation, current HTS systems cannot flexibly change its channel resource like bandwidth during operation. Employing digital channelizer in the advanced HTS systems, which have the capability of on-board signal processing, can add flexibility to satellite communication systems [194] and provide broadband communications to commercial and military mobile users. Given the same capacity, digital channelizer can greatly reduce the complexity of the satellite payload and improve the reliability of the satellite payload. Especially, this technology can bring about the flexibility of channel resource allocation in HTS which solves the problem of bursty demands in a specific area like caused by disaster [195].

Obviously, equipping digital channelizer dose make it flexible to allocate the channel resources in HTS systems. However, with the fast increasing developments of wireless and satellite communication standards and related network bandwidth, the requirements of processing bandwidth, signal channel, and signal reconstruction performance for digital channelizers in HTS systems are becoming higher and higher. Therefore, how to design digital channelizers is a key technique for HTS systems and also a challenging issue. Up to now, the most common digital channelizer architectures are based on the Cosine modulated filter bank, per-channel filter bank and discrete Fourier transform filter bank. When designing digital channelizers, the most difficult task is to design the high-order perfect reconstruction (PR) prototype filters. The problem is that with the resolution of channelizer becoming higher, the number of sub-channels will rise. Thus efficient methods to overcome the difficulty of extreme high-resolution channelizer with high-order PR filter bank are necessary.

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Remarks: High-resolution digital channelizer is a key enabler for extraction and reconstruction of multichannel signals in HTS, and the high-order PR filter bank is an efficient structure for the channelizer. Generally speaking, it is of great difficulty to build an ideal high-resolution channelizer with high-order PR filter bank. **The best approximation approach is to achieve the near PR filter bank**, for example, using two-channel loss-less lattice and iteration design procedure with criterion of least mean square error [196].

F. Gateway Selection

In order to enable inter-segment communications in heterogeneous SAGIN, a common paradigm is to select several gateway nodes for each segment, these nodes serve as transfer stations and collectively establish inter-segment connections for information exchanging, which is similar to the inter-domain communications described in [197]. By selecting gateway nodes, it can enhance the manageability and controllability of convergent networks by implementing routing strategies for inter-segment communications.

On one hand, in space-ground integrated networks, the ground gateways play an important role in the traffic delivery process from terrestrial nodes to the satellites. Due to the impact of geographical locations and poor meteorological conditions, different placement of satellite gateways may result in totally different performances of network reliability and latency. Therefore, for the purpose of QoS, it is of great challenge to place these satellite gateways in optimal locations. On the other hand, in modern NGEO constellation systems, with the support of ISLs and networking technologies, it only needs to select a part of satellites which can be observed by the ground to establish the satellite-terrestrial links. Such satellites, which have direct links connecting with the ground stations, are named as *gateway satellites*. Similarly, in UAV-based communications, some superior nodes should be selected as gateways, so that other nodes in the network can connect the ground station or satellite through them rather than to establish a remote connection. How to select the gateway nodes with the minimum number in SAGIN to guarantee the best network performances is worth studying.

1) Satellite Gateway: In space-ground integrated networks, it is necessary for each ground node to communicate with satellites taking the least time. As has been discussed in Section VII-A, the propagation delay from GEO satellite to the ground is fixed, and most data traffic delivery between ground nodes and satellites must travel through the gateways, thus the latency between ground nodes and satellite gateways is especially critical. On the other hand, no matter the ground nodes or links or the satellite links are prone to failing due to lots of factors. Therefore, to improve the network performances of latency and/or reliability in the integrated networks [198], it is of fundamental importance to select geographical locations for the placement of satellite gateways.

2) Gateway Satellite/UAV: With the increasing number of satellites in outer space, the operation management on satellite systems in becoming more and more difficult. Only depending on the ground stations to establish a direct space-ground connection for each satellite is an unpractical solution, which will raise not only capital expenditure but also operation expenditure. Connecting to gateway satellites through ISLs, other satellites in the same constellation systems can also communicate with ground stations, thus the limitation of satellite services must be visible on the ground is broken through, and lots of ground station resources are saved. Therefore, how to select gateway satellites in NGEO constellation networks is of great significance and challenge. In general, when selecting gateway satellites, we should give much consideration to the forwarding hops between these satellites and others, since more hops will lead to longer latency and larger load in the satellite networks.

Finding the optimal set of gateway nodes in UAV networks is also challenging due to several reasons. Firstly, the high mobility of UAVs results in the frequent change of network topology, gateway nodes cannot be regularly selected from some specific UAVs. Secondly, when selecting gateway nodes in UAV networks, each UAV is inclined to assign the gateway node for its own unilateral benefit, neglecting the potential disadvantages over the whole network performance. What's more, for the absence of a trusted central authority in UAV networks, it will get much worse when a malicious node is selected as gateway.

Remarks: It should be noted that, when deciding how to select gateway nodes in SAGIN, **besides the geographical locations, the network topologies, overall traffic distributions, and the inter/intra-segment link quality as well as link capacity [199], must be taken into account**. In addition, efficient traffic offloading schemes should also be devised when the gateway selection is determined.

G. Channel Modeling

A general and accurate model of the space-air-ground channel is of great significance to design, test, and optimize the integrated systems. A propagation channel model of SAGIN allows the analysis of the integrated network independently from realistic experiments on satellites and UAVs which are usually very complex, cost intensive, and time-consuming. Leveraging channel models, communication systems can be evaluated using computer simulations, which allow the system testing and configuring to be performed in an economic and rapid way. For now, however, no suitable space-air-ground channel mode exists for the system performance analysis in SAGIN. Although several satellite-space and air-ground channel models have been proposed and applied [200] [35], due to the specific characteristics mentioned in Section I, modeling a space-air-ground channel is still of severe challenges.

1) Channel Measurement: Wireless channel measurement is the most simple and effective way to obtain the channel information. In general, to model a propagation channel of SAGIN, several physical parameter should be measured including channel sounding signal type, bandwidth, carrier frequency, transmit power, satellite/UAV speed, propagation distance, elevation angle, antenna type and gain, local ground environment characteristics, and so on. Proper selection of channel measurement parameters in a given environment is

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critical for obtaining accurate channel statistics for a given application. However, due to the long propagation distance in satellite-based communications, the received signals will be quite weak with large Doppler shift, it is challenging to acquire and process such signals. In addition, in UAV-aided space-air-ground network, due to the motion of UAVs, it is generally difficult to precisely obtain the link distance between the UAV and the ground station. What's more, the different application environments will result in violent difference of channel conditions, so that the measuring process and objective become more sophisticated.

2) Channel Non-stationarity: A general assumption in most channel models is that their distributions are stationary in space, time, and frequency [201]. However, because of the high moving speed of NGEO satellites, UAVs, and ground terminals in SAGIN environments, the time variation in space-air-ground propagation channels may be more rapid than that in fix-to-mobile channels of terrestrial wireless communications. In other words, this means that space-air-ground channels are mostly in statistically non-stationary situations, which will bring great difficulty to model such channels. For example, although the non-stationary characteristic of UAV-aided air-ground channels has been considered in GB stochastic channel models (GBSCMs) [36] by employing limited ray-tracing with stochastically distributed objects, the trade-off should be more comprehensively investigated between the model precision and complexity of the GBSCMs. Thus, how to properly incorporate the non-stationarity into space-air-ground channel models is still an open problem.

Remarks: In SAGIN, the propagation channel is time-varying with multiple paths. Many factors including node movement, propagation distance, meteorological condition, and antenna attitude, will cause the channel fading. It is expected the channel feedback delay be less than its correlation time to increase the channel capacity. Besides, channel modeling should take into account not only the large amount existing physical parameters, **but also some still unclear factors in new scenarios such as mmWave and high-speed terrestrial data transmission**. As a consequence, further measurement campaigns are required before validating the real model.

H. Security

SAGIN integrates various military and civil application systems, in which a large amount of sensitive data and resources must be secure, reliable, and real-time. However, because of the open links, moving nodes, dynamic network topologies, and diverse collaborative algorithms, it is difficult for SAGIN to provide high security level communications to efficiently resist jamming, message tampering, malicious attacking, and other security issues.

1) IP Protocol Security: SAGIN contains mobile and fixed network infrastructures, parts of which are dedicated nodes. It can be considered as a typical Internet and conventional security measures like Internet Protocol Security (IPSec), symmetric or asymmetric cryptographic mechanisms, authentication algorithms can be also applied at upper layers. However, in space-air-ground communications, some parameters at the transport layer or the IP layer have been changed by introducing other techniques to improve the overall network performances. That is, the original TCP/IP protocols have been modified by some introduced technologies, which bring new problems to implement security mechanisms on these layers. In particular, utilizing PEP on satellite link can use several mechanisms to improve TCP performance but the splitting will make it easy suffer snooping and spoofing. Additionally, how to efficiently couple PEPs mechanisms and IPSec protocols is a challenging issue. What's more, mobile users in SAGIN are expected to handover from cellular/non-cellular BSs to UAVs and/or to satellites. The frequent handover also produces new problems to existing IPSec protocols such as security routing, mobile IP, key management and exchange.

2) Link Security: Depending on the security requirements of the space-air-ground communications, link security may be applied at one or more levels. For instance, the application data can be secured via the existing encryption used in terrestrial networks. However, this would leave the rest of the communications stack unencrypted, i.e., potentially vulnerable. While applying encryption at the network layer can encrypt E2E traffic flows between the user and target applications in the integrated network, it may lead to network performance and security tradeoff. Particularly, for MEO and GEO satellites, the delay added by encryption operations may hamper real-time communications over the integrated networks. To alleviate this problem, the network flows may be encrypted across a single space or ground link given that it satisfies the security requirements. Furthermore, depending on the security requirements of the communication, different levels of quality of protection can be assigned [202]. For instance, for the communications requiring the highest levels of communication over the integrated network, even all routing information may require protection to prevent possible traffic analysis attacks by applying physical layer encryption.

3) Jamming: By transmitting noise with sufficient power at the same frequency band of the transmitter and receiver so as to reducer the SNR of their transmission, jamming may degrade the integrity of signals and even cut off the communication link between the transmitter and receiver in wireless communications. SAGIN contains different types of wireless links, either the satellite links, or the air-ground links, or the terrestrial links are vulnerable to jamming attacks. On one hand, satellite communications are susceptible to denial of service (DoS) attacks by adverse electromagnetic jamming, including downlink jamming and uplink jamming. It is relatively easily to find and handle downlink jamming. While dealing with uplink jamming is challenging because of the lack of special processing or filtering function on the satellite. On the other hand, the high mobility of UAV makes the UAV-aided SAGIN more vulnerable to jamming, especially when such a system is compromised by an adversary. Once the air-ground links are jammed, the communication between the UAV and ground station will be interrupted or unavailable.

Due to the tremendously huge area in SAGIN, it is difficult to find efficient countermeasures for anti-jamming. Currently, game theory based approaches have been proposed to study jamming attacks in satellite- and UAV- based communica-

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tions [203] [204]. However, these methods are under the assumption that the defender knows the attacking strategy, which is usually not true in practice. Furthermore, when suppressing jamming, there should be a complicated trade-off between the resisting efficiency and some network indicators such as transmit power.

Remarks: In addition to the available traditional cryptographic methods, physical layer security, which exploits the physical characteristics of propagation channels to enhance secured wireless links, has been emerging as a promising paradigm of the satellite and UAV communication security. How to enhance secure transmission in SAGIN by utilizing physical layer security mechanisms is an open issue and of great challenges. **In this context, jamming can play an important role by generating interference signals to prevent malicious eavesdroppers from decoding the transmitted messages, and significantly improves quality and reliability of secure communication links between legitimate terminals.**

VIII. Conclusion

In this paper, we have presented a comprehensive survey of recent studies related to SAGIN, which has attracted intensive attentions from both academia and industry. In particular, we first provided an extensive overview of the available research works on the three segments of the integrated network according to the major research topics, ranging from cross-layer design, resource management and allocation to system integration, network performance analysis and optimization. Then we discussed in details the existing network architectures applicable for SAGIN. Based on the above survey of existing works, we finally pointed out main technical challenges when designing such integrated networks and gave some future research directions which are believed to deserve further explorations.

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