Intelligent and Converged Networks ISSN 2708-6240
2021, 2(4): 277−294 DOI: 10.23919/ICN.2021.0018

Blockchain-envisioned unmanned aerial vehicle communications in space-air-ground integrated network: A review

Zhonghao Wang, Fulai Zhang, Qiqi Yu, and Tuanfa Qin*

Abstract: Unmanned Aerial Vehicle (UAV) communications have recently entered a new period of interest, motivated by technological advances and the gradual emergence of the Space-Air-Ground Integrated Network (SAGIN). The current survey aims to capture the use of UAVs in the SAGIN while highlighting the most promising open research topics. The traditional UAV network architecture is not adequate to meet the challenges presented by the SAGIN, and an effective and secure space-air-ground integrated UAV network needs to be constructed. Given its well-distributed management and consensus mechanism, blockchain technology can make up for the deficiency of the traditional UAV network. In this work, we review the role of UAVs in the SAGIN. Then, three applications of the blockchain-envisioned UAV network are introduced through several classifications. Future challenges and the corresponding open research topics are also described.

Key words: Unmanned Aerial Vehicle (UAV); blockchain; Space-Air-Ground Integrated Network (SAGIN); security; Internet of Things (IoT)

1 Introduction

Since the 1980s, the mobile communication system has changed dramatically. The massive demands and new applications of the communication industry are constantly expanding, and innovation is breaking the bottlenecks in traditional communication. As the number of people and machines connected to mobile communication networks grows[1], the demand for Quality of Services (QoS) increases, thereby putting pressure on the efficiency and productivity of the existing networks. Current networks are no longer sufficient to meet these new challenges, and a new communication architecture should be established to break through the traditional data exchange limitations[2]. Relative to the fourth generation (4G) Long-Term Evolution Advanced (LTE-A) system with increasingly high rates, large broadband applications continue to emerge, and one such application is the fifth generation (5G) network, which enables the connections of massive devices and is able to meet requirements, such as high traffic flow capacity and customized user service experience[3]. These applications involve High-Definition (HD) videos, Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR). A variety of applications and customization requirements engender new communication evolution with low latency, high throughput, low error rate, intensive computing performance, and Artificial Intelligence (AI) capabilities[4]. The explosive growth of the demand for these services is obviously far beyond that of previous communication modes and thus stimulates the development of different technologies. The number of mobile internet users is expected to reach 6.5 billion by 2025, with 80% of them using mobile broadband and thus, driving the growth of applications on mobile devices. The secure connections of distributed communication infrastructures and the effective transmission of massive data promote the development

• Zhonghao Wang, Fulai Zhang, Qiqi Yu, and Tuanfa Qin are with the School of Computer and Electronic Information and the Guangxi Key Laboratory of Multimedia Communications and Network Technology, Guangxi University, Nanning 530004, China. E-mail: w_z_h_n@126.com; flzhang@st.gxu.edu.cn; kate_yu@st.gxu.edu.cn; tfqin@gxu.edu.cn.
∗ To whom correspondence should be addressed.
Manuscript received: 2021-10-17; accepted: 2021-11-05

of comprehensive networks that maximize the advantages of communication resources from different dimensions[5, 6].

5G brings the concept of the Internet of Everything (IoE), while the sixth generation (6G) network is expected to evolve into a platform for the intelligent IoE[7−9]. Through this platform, mobile networks can connect a large number of smart devices to achieve intelligent interconnection. Through AI and Machine Learning (ML), the physical world and the digital world can be connected in real-time, and people can capture, retrieve, and access a large volume of information and knowledge in real-time as a step forward to the intelligent and fully connected era[10]. At the same time, Integrated Sensing And Communication (ISAC)[11, 12], distributed computing, Mobile Edge Computing (MEC)[13, 14], short-range wireless communication technology[15], and advanced Space-Air-Ground Integrated Network (SAGIN)[7, 16, 17] will lay a foundation for the future intelligent mobile communication.

In response to the demand for 6G network, efforts have been exerted to introduce terrestrial networks into the new mobile technologies so as to solve the unprecedented challenges, such as in the case of spectrum scarcity, for which intelligent spectrum sensing and dynamic spectrum sharing are used to adapt to the rapid growth of traffic flow[18−20]; the upgrading of the large-scale Internet of Things (IoT), and the transformation of the whole internet protocol network environment. The function of a network is no longer limited to the transmission of information, and it now covers the full dimension of integrated communication, sensing, and computation. Traditionally, the aforementioned problems have been mitigated to some extent by scaling up and adding terrestrial communication infrastructure. However, increasing the scalability of these entities can lead to complex network structures, redundancy of system information, and other complex problems[16]. Some areas are not even qualified to build terrestrial communication infrastructure (e.g., high mountains, forests, and oceans).

By integrating satellite networks and near-ground networks into terrestrial cellular systems, the 6G network can achieve true global coverage and maintain high availability and robustness even in the event of natural disasters. The SAGIN helps to expand the coverage of cellular networks through nonterrestrial nodes, ensures that users can access the network anytime and anywhere, and provides mobile broadband services to unserved or underserved areas, thereby bridging the coverage gap[21]. For the benefit of users in urban and remote mountainous areas, the wide coverage advantage of nonterrestrial nodes can be used to enhance the service capability of multicast and various applications[22]. Satellites are more suitable for large-scale communication than terrestrial networks. Given their ubiquitous coverage and flexible intersatellite transmission capabilities, satellites provide access schemes and high-speed global connectivity. Typically, satellites provide coverage extensions to small cellular cities, functionally treating all nonterrestrial network nodes as Base Stations (BSs), and thus ensuring seamless access to terrestrial and non-terrestrial BSs. In this case, a Low-Altitude Platform (LAP) provides additional connectivity to underserved areas on the ground, while a High-Altitude Platform (HAP) and satellite communication benefit from backhaul links.

Recently, airborne communication networks, which comprise of satellites, HAPs, and LAPs, have received considerable attention[23−25]. Nevertheless, the key technologies of HAPs and LAPs in the SAGIN need to be discussed from a novel perspective, including the flexible application of Unmanned Aerial Vehicles (UAVs) to space-HAP/LAP-terrestrial networks. Specifically, IMT-2020 is a novel communication network for UAVs. Recommendation ITU-T Y.4421 provides a functional architecture for UAVs and UAV controllers using IMT-2020 networks and functionalities defined in the application layer, service and application support layer, and security capabilities[26]. 6G aims to satisfy a variety of use cases with different types of traffic from many devices. Therefore, UAVs are used to set up 6G wireless communication infrastructure, mobile devices, and end users from terrestrial networks[9]. The flexibility and scalability of mobile networks need to be improved. Such requirements can be met by the autonomous flight of UAVs. The next step in achieving flexibility in this direction is to use mobile infrastructure to provide necessary services, such as building flight BSs using UAVs that can be further integrated into wireless networks[27]. As shown in Ref. [28], integrating such a system into a mobile network can be an effective alternative to ultra-dense small cell deployments and enhance the coverage, capacity, reliability, and energy efficiency of wireless networks, especially in scenarios where users move in groups. From a data processing perspective, the SAGIN integrated with UAVs can efficiently process large amounts of data and provide high data rate connections for devices. It also contributes to various types of applications, such as military[29, 30], agriculture[31−33], delivery of goods and medical services[34], disaster forecast[35, 36], and information security[37, 38].

On the basis of the literature survey[6, 39−41], we further discuss the application of UAVs to communication security. Zhang et al.[42] proposed to exploit the high mobility of UAVs to proactively establish favorable and degraded channels for legitimate and eavesdropping links through their trajectory design. Similarly, Cui et al.[43] formulated an optimization problem, which maximizes the average worst-case secrecy rate of a system by jointly designing the robust trajectory and transmit power of the UAV over a given flight duration. With these results, Mamaghani and Hong[44] proposed to jointly optimize a UAV's trajectory, network transmission power, and noise power allocation over a given time horizon to enhance the average secrecy rate performance. Moreover, Yang et al.[45] presented two typical network architectures in which each UAV serves as either a flying BS or aerial user equipment, and proposed a spectrum sharing strategy to fully exploit the interference incurred by spectrum reuse for improving secrecy performance. We realized that although the deployment of UAVs in the SAGIN greatly improves the flexibility of the system and can enhance the safety performance through some means of trajectory planning, channel allocation, and power control, whether fundamental architecture can resolve the aforementioned problems to some extent so as to achieve fair and universal security remains largely unknown.

The blockchain has been considered as one of the key enablers of UAV communication in the 6G network. As a secure distributed storage structure, a blockchain has special advantages in managing distributed systems[46, 47]. First, in a blockchain system, participants can reach global consensus without the need for centralization; the same is needed for a key management scheme that does not require any trusted third parties. Second, the block design ensures that the ledger recorded on the block is immutable and that any malicious behavior is permanently recorded in the block and viewed globally, thus greatly improving security. Third, blockchain is traceable. Key updates can be traced using a blockchain, and the participants and time of participation can be viewed for any recorded behavior. UAVs equipped with blockchain technology could transform the use of traditional UAVs in many scenarios. The communication among satellites, HAPs (e.g., airships, balloons), UAVs, and terrestrial mobile users can be connected tightly, and the UAV communication can be secured by the blockchain. Hence, blockchain-envisioned UAVs in the SAGIN are useful in many fields, such as supply chain retrospection[48], product delivery[49], and smart grids[50]. Motivated by the aforementioned facts, we focus on and discuss blockchain-envisioned UAV applications in the SAGIN and will discuss them in detail.

The objective of the current survey is to describe in a structured way the technological advances of space-air-ground UAV networks from a blockchain perspective and to highlight key research challenges and open questions. In this direction, Section 2 introduces the SAGIN and discusses the applications of UAVs to network construction at three deployment levels. These requirements drive SAGIN's continued innovation. Section 3 presents the main applications and use cases of blockchain-envisioned UAV networks and discusses them from three aspects. Section 4 highlights open research topics that are timely and challenging. Section 5 draws the conclusions.

The flowchart of the research methodology is shown in Fig. 1. The common acronyms used in this study are summarized in Table 1.

2 Space-air-ground integrated UAV networks

The integration of a satellite network and a near-space network into a terrestrial cellular network will produce a heterogeneous network containing multiple levels. Figure 2 shows the blockchain envisioned UAV communications in the SAGIN. The main goal of such an integrated network is to improve its overall performance of the network through efficient multilink sharing, flexible function sharing, and fast physical layer link switching[51]. The network consists of three types of satellite orbits, HAPs and LAPs, and other air or terrestrial access points. Given its heterogeneity and diversity, it can provide users with multiple cross-layer links, thus improving network coverage and flexibility. A monolayer network, when used alone, cannot achieve the desired overall performance. That is, a user can freely select any layer network to access a single service, but the link is not always a reliable service as it is time varying and diverse[52]. Therefore, fast detection and switching to the best access link are crucial. As the most flexible auxiliary means in the network, UAVs

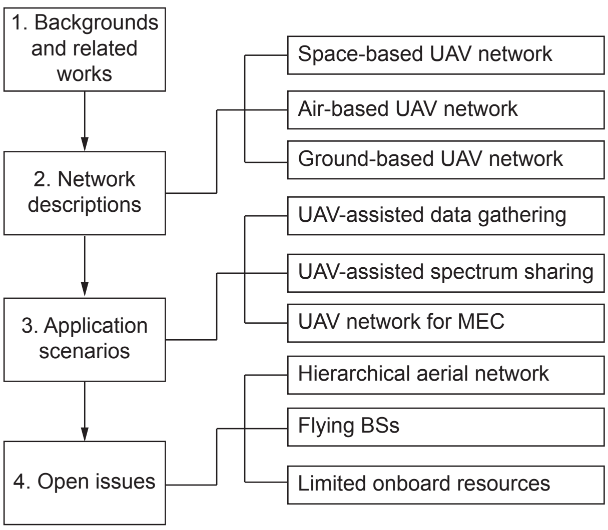

Fig. 1 Framework and major topic organization.

Table 1 Summary of abbreviations.

Abbreviation	Description
QoS	Quality of Service
4G	Fourth Generation
LTE-A	Long Term Evolution Advanced
5G	Fifth Generation
HD	High-Definition
AR	Augmented Reality
VR	Virtual Reality
MR	Mixed Reality
AI	Artificial Intelligence
IoE	Internet of Everything
6G	Sixth Generation
ML	Machine Learning
ISAC	Integrated Sensing And Communication
MEC	Mobile Edge Computing
SAGIN	Space-Air-Ground Integrated Network
IP	Internet Protocol
BS	Base Station
LAP	Low-Altitude Platform
HAP	High-Altitude Platform
UAV	Unmanned Aerial Vehicle
GEO	Geostationary Earth Orbit
MEO	Medium Earth Orbit
LEO	Low Earth Orbit
BLoS	Beyond Line-of-Sight
GPS	Global Positioning System
DF	Decode-and-Forward
3D	Three-Dimensional
MDP	Markov Decision Process
mMTC	massive Machine-Type Communication
D2D	Device-to-Device
LoS	Line-of-Sight
NLoS	Non-Line-of-Sight
CoMP	Coordinated MultiPoint
CR	Cognitive Radio
SLA	Service Level Agreement
NOMA	Non-Orthogonal Multiple Access
SE	Spectrum Efficiency
GBD	Generalized Bender Decomposition
SCA	Successive Convex Approximation
OMA	Orthogonal Multiple Access
AoI	Age of Information
MNO	Mobile Network Operator
SSS	Spatial Spectrum Sensing
ASE	Area Spectral Efficiency
CS	Compressed Sensing
PLS	Physical Layer Security
VLC	Visible Light Communication
MAC	Medium Access Control
URLLC	Ultra-Reliable and Low-Latency Communication

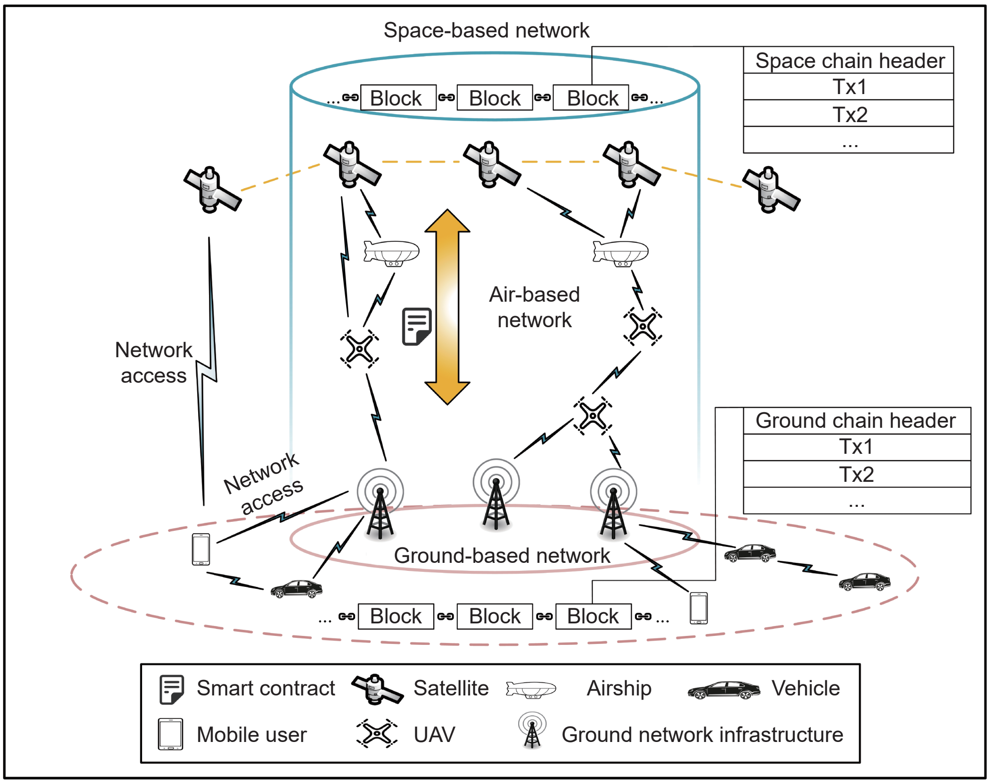

Fig. 2 Blockchain-envisioned UAV communications in SAGIN.

play an essential role. In the 5G network, each network layer still functions independently. In 6G plans, satellite networks, near-earth networks and ground mobile networks will be integrated. Next, we discuss the important role of UAVs in each network layer from the perspective of UAV assistance.

2.1 Space-based UAV network

The space-based network consists of a variety of orbiting satellites, which can be categorized into three different orbits according to their height: (1) Geostationary Earth Orbit (GEO) satellite (35 786−36 000 km coverage area), (2) Medium Earth Orbit (MEO) satellite (2 000−20 000 km); (3) Low Earth Orbit (LEO) satellite (200−2 000 km)[53]. In intersatellite laser communication, the optical frequency range broadcasts and multicasts the techniques to improve the network infrastructure and provides high-bandwidth, high-speed communication services. Meanwhile, satellites communicate with the terrestrial infrastructure.

In spatial distribution, the active range of UAVs is located between the satellite network layer and the terrestrial cellular network layer, and links can be established up and down. Given the large free space path loss, high attenuation of the troposphere, and high transmission delay of satellites directly to ground stations or high-speed mobile users, UAVs are used as a relay in satellite-terrestrial networks based on integrated UAV networks to provide ultra-high throughput service for end users. The effective and efficient transmission of satellite-to-ground and satellite-to-UAV information is an important part of the infrastructure of space-air-ground integrated UAV networks. The satellite-to-UAV channel relies mainly on Beyond Line-of-Sight (BLoS) and Global Positioning Systems (GPS)[54]. These channels are used by UAVs for navigation and trajectory prediction purposes. The rest of the time, UAVs can autonomously detect and establish satellite-to-UAV links to reduce network link redundancy and improve spectrum sharing efficiency. The successful and continuous path connection between satellites and UAVs is a crucial component. Given the flexibility of UAVs in a three-dimensional active space, UAVs need to constantly adjust the beam orientation toward satellites or to the ground and adjust the beam receiving range to maintain and control communication links[55−57].

2.2 Air-based UAV network

The air-based network is a mobile network composed of balloons, aircraft, UAVs, etc., and provides opportunistic data transmission services. It has a shorter delay than the space network and broader coverage than the terrestrial network; in addition, it can provide seamless wireless communication and complement the terrestrial network[58]. Existing platforms may be limited by operating altitudes depending on their flight constraints, service objectives, and design specifications. They are usually equipped with transceivers (for establishing stable and continuous communication links), multiple sensors (for sensing high-resolution images, sensing the spectrum, and scanning the surrounding flight nodes), rotors (providing stable flight control), batteries, electronic speed controllers, and UAV units. To manage and avoid UAV collisions, and to provide an optimal path for data transmission, research has mainly focused on the trajectory planning and prediction of UAVs combined with different communication services. In Ref. [39], Sharma and Kim proposed a novel Decode-and-Forward (DF) based secure three-Dimensional (3D) mobile UAV relaying for the SAGIN in the presence of an aerial eavesdropper lying around a serving UAV relay in a circular plane. Savkin et al. optimized the online 3D trajectory of a UAV to minimize its energy expenditure subject to the its aeronautic maneuverability; ground nodes can effectively capture transmitted data, whereas eavesdroppers are not able to[59]. Similarly, Hu et al.[60], from the perspective of channel security and the existence of eavesdroppers, developed a suboptimal scheme, in which a UAV’s position and jamming power are alternately optimized by leveraging the successive convex approximation and block coordinate descent. From the perspective of avoiding collisions, in Ref. [61], Gan et al. constructed a cylinder static protection zone model of a UAV to detect the flight conflict trend and near midair collision trend between the UAV and an intruder and proposed a dynamic collision avoidance zone modeling method on the basis of the emergency collision avoidance trajectory of the UAV in a 3D space. Yu et al.[62] proposed a Markov Decision Process (MDP) based algorithm combined with a backtracking method to create a safe trajectory in the case of hostile environments. In Ref. [63], Baca et al. proposed a novel approach to optimal trajectory tracking for UAVs; by sampling the states of a virtual UAV, the method can create a control command for fast non-linear feedback, which is capable of performing agile maneuvers with high precision. In Ref. [64], Sharma et al. evaluated the outage probability of the considered system under opportunistic UAV relay selection on the basis of a novel analytical framework for 3D mobile UAV relaying. In Ref. [65], Zhang et al. proposed a power allocation scheme and UAV trajectory, which are designed to maximize system energy efficiency. In Ref. [66], Hoseini et al. modeled the trajectory optimization of UAVs as an MDP problem and solved it using a Q-learning algorithm to optimize the energy transfer gain. Jin et al. formulated a joint trajectory, sensing location, and sensing time optimization problem to minimize the overall completion time for all the sensing tasks[67]. The literature survey indicates that the trajectory prediction of UAVs is a hot research issue, which includes trajectory optimization problems brought by resisting channel interference and eavesdropping, improving relay capability, and reducing energy consumption.

2.3 Ground-based UAV network

The ground-based network is mainly composed of the cellular network, terrestrial internet, mobile ad hoc network, and so on. The topology is fixed relative to the air/satellite-based network, and the communication link is stable. However, the coverage of the ground-based network is limited, and UAVs with good mobility make up for this shortcoming. A ground-based UAV network covers all 6G wireless communication technologies, such as massive

Machine-Type Communication (mMTC), Device-to-Device (D2D) communication, energy harvesting, and high-frequency band millimeter-wave communication. UAVs connect to mobile ground users via Line-of-Sight (LoS) links and Non-Line-of-Sight (NLoS) links[68] in some cases. In Ref. [69], Mei and Zhang proposed a new UAV sensing-assisted design for UAV downlink and uplink communications for avoiding interferences with co-channel terrestrial communications. In Ref. [70], Hua et al. investigated a novel architecture of Coordinated MultiPoint (CoMP) transmission in a cognitive satellite-terrestrial network associated with a UAV and considered the downlink communication where the UAV and BS cooperatively serve terrestrial users by sharing the licensed satellite network spectrum. Huang et al.[71] investigated a new scenario of spectrum sharing between UAVs and terrestrial wireless communication, in which a cognitive UAV transmitter communicates with a ground receiver in the presence of a number of primary terrestrial communication links that operate over the same frequency band. In general, this type of network introduces the concept of Cognitive Radio (CR), focusing on the UAVs' sensing and allocation of spectrum and resources on the ground. In the 6G SAGIN, sensing will be tightly integrated to support autonomous systems.

Supporting diverse and heterogeneous access points is one of the new challenges faced by the 6G SAGIN. UAVs and other HAPs/LAPs are considered as a new BS for 6G because of their relatively close proximity to the ground that enables similar functions as ground BSs[72–74]. From the perspective of energy, this BS is different from the traditional BSs, which lack a stable energy supply, and battery life is an important problem that leads to the stable work of the BS. At the same time, although the UAV BS can use similar air interface and frequency bands for terrestrial communication, reasonable planning and switching of small cells are required to improve link stability[75]. Similar to ground nodes, UAV nodes require adaptive, dynamic backhauling that entails self-organization for seamlessly integrating reusable UAVs into the SAGIN without the additional cost of reconfiguration[76]. From the perspective of users on the ground, the UAV as an aerial BS should enable users to maintain continuous communication, i.e., they should not feel the cell switch. Therefore, related physical layer operation and upstream and downstream synchronization should be reasonably designed.

3 Blockchain-envisioned UAV communication in SAGIN

Over the past decade, blockchain technology has exploded in popularity and has exerted a profound impact on today's digital society. The core concept of blockchain technology provides a reference for the development of bitcoin. With blockchain technology, bitcoin is decentralized so that no single user can control it, hence the absence of a single point of failure. Smart contracts are based on predefined logical processing ledger records, their execution is secure and fully automated, and their execution continues as long as predefined conditions are met. The combination of blockchain and smart contracts allows business logic and business processes to be integrated into blockchain. Today, blockchain has evolved into a common technology, and UAV architecture designs can take advantage of these features to create an open and collaborative ecosystem.

Extensive research relates to the application of blockchain in UAV networks. According to the literature survey[77–79], UAVs and blockchain can already be effectively combined. In Ref. [80], Jensen et al. explored a blockchain framework known as the Hyperledger Fabric that could potentially be applied to a swarm of UAVs to increase its security. With the Hyperledger Fabric as a framework for discussion, Khan et al.[81] stressed the selection of UAVs for the desired quality of network coverage and the development of a distributed and autonomous real-time monitoring framework for the enforcement of service level agreement (SLA). In Ref. [82], Keshavarz et al. proposed a trust management framework based on blockchain time-stamped series that can detect not only UAVs' abnormal behavior in a real-time manner but also the compromised distributed observers. In Ref. [83], Ge et al. proposed a lightweight blockchain architecture that mitigated the computation and storage overhead and designed a novel reputation-based consensus protocol. Hassija et al.[84] proposed a framework for secure and reliable energy trading among UAVs and charging stations to create a distributed network of UAVs and charging stations. The integration of blockchain technology into space-air-ground UAV networks helps meet the new design principles and enables the transparency and decentralization of network functions, which are in line with the characteristics of UAV networks. However, blockchain technology also has limitations. If a large amount of data and information need to be shared, blockchain may bring problems, such as ground throughput, high latency, and high energy consumption. Hence, much room for improvement is needed. Nonetheless, UAVs remain good relay nodes in the SAGIN thus far, and blockchain-envisioned UAV communication in the SAGIN provides a secure, scalable, and reliable environment to many applications. The detailed classification is discussed below. The solution taxonomy of blockchain-envisioned UAV communication is shown in Table 2.

3.1 UAV-assisted data gathering

Given their good mobility and flexibility, UAVs provide an effective way to gather data from wireless sensor nodes scattered in forests, suburbs, and other hard-to-reach areas. In addition, UAVs' ability to maintain LoS connections with sensors at certain altitudes greatly improves the quality of the wireless channesl between UAVs and the ground sensors, thereby increasing data rates and reducing power consumption. In many applications, sensor nodes perform data sensing and package the collected information to sink nodes for processing directly or through multiple hops. When sensors are deployed on a large scale, innovative data collection solutions are inevitably needed to save energy further and safeguard the survival and longevity of sensor networks. UAV data collection is regarded as a logical solution. The procedure for data collection, preprocessing, classification, and index evaluation was described by Cermakova and Komarkova[85]. To improve the safety and efficiency of UAV-assisted data gathering, Xu et al.[86] introduced blockchain into the scene of UAV-assisted IoT and proposed a data gathering system with consideration of security and energy efficiency. In Ref. [87], Islam and Shin presented a two-phase validation utilizing the pi-hash bloom filter and the digital signature algorithm to validate a sender when a UAV is receiving data. Their performance results showed that UAVs assist IoT devices' data gathering both in terms of connectivity and energy consumption and provide security against threats.

Non-Orthogonal Multiple Access (NOMA) has been regarded as a promising candidate in 5G and 6G networks for providing high Spectrum Efficiency (SE) and supporting massive connectivity[88]. In Ref. [89], Chen et al. proposed a general NOMA-enabled UAV-assisted data collection protocol to maximize the sum rate of a wireless sensor network where the location of UAVs, sensor grouping, and power control are jointly considered. Considering the integration of NOMA into the UAV collection network, Zhao et al.[90] proposed an optimization algorithm to minimize the total energy

Table 2 Solution taxonomy of blockchain-envisioned UAV communications.

Application	Taxonomy of research	Related work
Data gathering	Blockchain-envisioned UAV's data collection	[85−87]
	NOMA	[88−91]
	Energy consumption and resource allocation	[92−94]
	Data freshness and trajectory	[95−99]
Spectrum sharing	Blockchain-envisioned UAV's spectrum management	[100]
	Spectrum sensing and efficiency	[101−104]
	Interference and eavesdropper	[45,105,106]
MEC	Blockchain-envisioned UAV communications for MEC	[107−109]
	Power consumption	[110, 111]

consumption while ensuring data collection by applying the Generalized Bender Decomposition (GBD) and Successive Convex Approximation (SCA) techniques. Mu et al.[91], from the perspective of NOMA and Orthogonal Multiple Access (OMA), developed a penalty-based algorithm and reported that NOMA yields a higher performance gain than OMA when ground nodes have sufficient energy.

Given the limited endurance of UAVs, the reasonable planning of resource allocation is very important to reduce UAV energy consumption. In Ref. [92], Ye et al. investigated the energy-efficient trajectory planning and speed scheduling problem with the goal of minimizing the total energy consumption of UAVs by determining their flight trajectory and speed while completing the task of data collection. Yang et al.[93] found that a tradeoff exists between the UAV data collection location and the outage probability and that the optimal UAV data collection location for achieving maximum energy efficiency needs to be closer to the tags for lower UAV transmit power. Fu et al.[94] proposed a reinforcement learning based approach to plan the route of UAVs in collecting sensor data from sensor devices scattered in the physical environment and designed a reward function with consideration of the energy efficiency of UAV flight and data collection.

In a UAV-assisted data acquisition network, sensing data change rapidly over time. Therefore, UAVs must maintain "freshness" through frequent data sensing and gathering. A metric called the Age of Information (AoI) was proposed in Ref. [95]. AoI over a time period is defined as the time elapsed since the most recent data update occurred, and it increases linearly if sensing data are not updated. The total AoI reflects the average delay of data update and quantifies the freshness of sensing data. Using the AoI concept, the fuzzy data freshness tracking problem of the UAV-assisted data gathering network can be transformed into a mathematical problem and be solved by an optimization method. In Ref. [96], Zhang et al. proposed an iterative algorithm to optimize the sensing time, transmission time, and UAV velocity for completing a specific task and designed the order in which the UAV performs data updates for multiple sensing tasks. In Ref. [97], Liu et al. formulated two optimization problems of AoI data collection. The simulation results showed that the proposed strategy could improve the freshness of information. Abd-Elmagid and Dhillon[98] formulated an optimization problem to jointly optimize a UAV's flight trajectory and energy and service time allocations for packet transmissions and found that in some cases, the UAV's trajectory cannot be altered on the basis of the locations of IoT devices. In Ref. [99], Ahani et al. studied the route scheduling of a UAV for data collection from sensor nodes with battery recharging and proved that optimum could be computed in polynomial time.

UAVs have clearly become an essential part of data gathering under various constraints, e.g., channel, energy consumption, data freshness, and many other sources. They are one of the fastest and cheapest methods for gathering data from different ground nodes.

3.2 UAV-assisted spectrum sharing

The selection of an appropriate spectrum is a significant problem to be considered in a wireless communication system. First, the existing mobile allocations which can be used by communication systems have some limitations due to coexistence with other services in the frequency band, these systems crave more spectrum to increase their data rates and network capacity. Second, a globally harmonized spectrum would facilitate the implementation of new space-air-ground communication systems, and provides good economics in terms of infrastructure and terminals[112]. With the continuous evolution of wireless technology, multiband wireless communication technology will enable us to effectively use existing and new spectra. Finally, uniform spectrum allocation and regulatory rules are particularly important and unique challenges for spectrum use. UAVs are envisioned to be widely deployed as an integral component of 6G spectrum management networks, where spectrum sharing among spacial, aerial, and terrestrial communication systems will play an important role. Some core technical challenges remain and require resolution to fully reap the benefits of deploying UAVs for spectrum management purposes. On the one hand, most UAVs basically operate on unlicensed frequency bands, which are often unreliable and subject to interferences with limited data rates and thus severely limit the potential performance of UAVs[113]. On the other hand, UAV-assisted wireless communication has always been a major security and privacy threat because of the broadcast characteristics of UAV-assisted networks and the easy monitoring of wireless transmission. These problems urge us to consider security and privacy issues while studying the spectrum sharing management of UAV-assisted cellular networks.

Qiu et al.[100] proposed a novel privacy-preserving secure spectrum trading and sharing scheme based on blockchain technology to resolve the security issues. To address the potential security issues, they proposed a spectrum blockchain framework for illustrating the detailed operations of how the blockchain helps to improve spectrum trading. A Stackelberg game was also formulated to jointly maximize the profits of the Mobile Network Operator (MNO) and the UAV operators with consideration of uniform and nonuniform pricing schemes.

With the lack of dedicated spectra, UAVs always need to share spectra with existing communication systems, e.g., licensed spectrum, cellular spectrum, and satellite spectrum. Efficient spectrum-sharing policies need to be designed for UAV communications to enhance SE and control interference-to-ground communication. In Ref. [101], Shang et al. considered Spatial Spectrum Sensing (SSS), which enables devices to sense spatial spectrum opportunities and reuse them aggressively and efficiently by controlling the SSS radius. They later perfected their work in Ref. [102]. The objective of the considered 3D spectrum sharing networks is to maximize the Area Spectral Efficiency (ASE) of UAV networks while guaranteeing the required minimum ASE of D2D networks. Similarly, Shen et al. investigated the issue of joint spatial-temporal spectrum sensing in a 3D spectrum-heterogeneous space by leveraging the location flexibility of flying UAV spectrum sensors[103]. They designed a temporal fusion window and a spatial fusion sphere to address the composite spatial-temporal data fusion, called 3D spatial-temporal sensing. In Ref. [104], Xu et al. investigated the application of Compressed Sensing (CS) technology in CR to UAV communication network to provide high-capacity, reliable communication, and opportunistic and timely spectrum access. However, traditional spectrum sharing mechanisms through spectrum sensing may not be effective in space-air-ground integrated UAV networks because spectrum sensing is generally imperfect and prone to sensing errors.

In Ref. [105], Li et al. suggested that although mutual interference due to spectrum sharing could reduce spectrum efficiency, the impact of eavesdropping could also be mitigated by the fact that two UAVs are essentially cooperative jammers. From the perspective of Physical Layer Security (PLS), Yang et al.[45] investigated PLS performance via spectrum sharing in device-to-device-enabled UAV networks. They proposed a spectrum sharing strategy to fully exploit the interference incurred by spectrum reuse for improving secrecy performance. In Ref. [106], Tang et al. discussed the case where UAVs share spectrum with the core network and eavesdroppers try to wiretap the communication. The joint optimization of the 3D trajectory and power distribution of UAVs was proposed to maximize the worst-case average secrecy sum rate.

UAV-assisted spectrum sharing is clearly unsafe when conducting large-scale spectrum trading in an unreliable and opaque trading environment. Eavesdroppers and malicious UAVs may seriously threaten the security of cellular networks by means of forging and issuing fraudulent spectrum demands. At the same time, in the traditional centralized spectrum trading, the trading between operators is managed by intermediaries, which suffer from problems such as single point of failure and privacy disclosure. Given its distributed management and consensus mechanism, blockchain has a good prospect in UAV spectrum sharing management. With 3D spectrum sensing and trajectory prediction, spectrum sharing technology is gradually maturing.

3.3 UAV network for MEC

MEC is a popular technological domain in the market because of the latency and cost issues with big cloud servers. To alleviate computing capacity constraints and reduce transmission and computing latencies, MEC has emerged as a promising platform for providing high-capacity and low-latency computing resources at the mobile network edge. Given their flexible and rapid deployment capabilities, UAVs are the ideal MEC platform for performing computation-intensive tasks for terrestrial users. UAV networks can play an essential role in MEC implementation, especially in emergency situations such as disasters when fixed ground infrastructure is unavailable or in edges of forests and mountains where infrastructure is difficult to build. Blockchain can be used to improve the reliability of MEC communication, including its connectivity, availability, and survivability, by using UAV caches.

In Ref. [107], Islam and Shin presented a blockchain-based data collection process in which information is gathered using a UAV as a relay and is securely kept in a blockchain at the MEC server. With the help of UAVs, data are encrypted before being transmitted to MEC servers. Upon receiving the data, the MEC servers validate the data and the identity of the sender. Guan et al.[108] proposed a blockchain-based MEC architecture to build a UAV system of mutual trust, fairness, openness, and stability in this scenario. In Ref. [109], Sharma et al. used UAVs as on-demand nodes for efficient caching and presented a novel neural blockchain-based UAV caching approach designed to ensure ultra-reliability and provide a flat architecture. The results demonstrated that the connection probability could reach 0.99, the survivability is greater than 0.90, the energy consumption is reduced by 60.34%, and the reliability can reach 1.0 even for a large number of users.

Several issues need to be addressed to apply blockchain to increase the security of MEC and reduce the cost and administration of MEC. Some of the problems involve the upper limits of memory for blockchain communication, the limited onboard capability of UAVs, and the excessive computing that leads to the memory redundancy of UAVs and to the decline of survivability and failure analysis ability. Some solutions in this area can be found in the literature. In Ref. [110], Wang et al. designed an open UAV-based airborne computing platform with advanced onboard computing capability and tested the performance by executing real UAV onboard computing tasks. Several results verified the feasibility and potentials of the proposed UAV computing platform. Faraci et al.[111] proposed a framework where a system controller can switch on and off the onboard elements to maximize an objective function defined in terms of power consumption, job loss, and incurred delay. These measures are needed to make blockchain-based UAV networks suitable for MEC applications.

4 Future and open topic

This section aims to cover the open research topics and the future trends of blockchain-envisioned UAV communication in the SAGIN while highlighting the challenges to be addressed.

4.1 Hierarchical aerial networks

As the technology of microminiaturized satellite platforms advances, an intermediate layer of various communication systems has emerged between terrestrial and traditional satellite segments. Hierarchical area networks with multiple flying layers are a promising solution to provide great coverage and improve the security of communication in the SAGIN. In this architecture, multiple types of flying layers cooperate to improve the reliability and capacity of SAGIN links. We realize that UAVs have the potential to serve terrestrial users at medium and low levels, while HAPs can serve both UAVs and ground users from high up and act jointly as relay nodes for satellites when necessary.

However, HAPs and UAVs may be frequently disconnected because of differences in height and velocity that directly affect link connections between intermediate layers. Therefore, flights between UAVs and HAPs should be coordinated to maintain reliable connections when existing routing protocols are not suitable for vertical space networks[114, 115]. Note that the routing protocol required by a vertical area network should consider the heterogeneous connection between links; in this case, Visible Light Communication (VLC) will be a good solution[116]. For integration, this includes not only the layout design of UAVs and HAPs but also the orbit optimization of each layer. It remains an open subject of research.

4.2 Flying BSs

Flying BSs could be mounted on general-purpose UAVs that could be further integrated into the SAGIN. Reference [117] reported that integrating such a system into a mobile network can be an effective alternative to ultra-dense small cell deployments, especially in scenarios where users move in groups. In Ref. [38], the challenges and opportunities of using UAV-based flying relays and BS-assisted cellular communication were reviewed. The wide application of UAV onboard processing in the SAGIN paves the way for the realization of the flying UAV BSs. Onboard regeneration is the key to achieving this capability. Processing is not limited to the physical layer as it also requires the addition of a Medium Access Control (MAC) layer and network layer capabilities. This feature is similar to CoMP scenarios in cellular networks, where the capacity of multiple BSs is used for data transmission, thus resulting in improved network performance and utilization. Another key aspect worth considering is power budget analysis. In Ref. [118], Wang et al. presented an efficient joint transmit power and trajectory optimization algorithm. The simulation results revealed that the optimized transmit power shows a water-filling characteristic in the spatial domain.

4.3 Limited onboard resources

If a blockchain is used to deploy a network of UAVs and perform the consensus algorithms, UAV miners need considerable processing power. Moreover, integrating such systems on UAVs is a challenging task. First, most UAVs are used as relays for frequency conversion, amplification, and forwarding. Second, the path loss is large, and the power supply is limited; these characteristics are closely related to the quality and deployment cost of UAVs[119, 120]. This problem may become common for all blockchain-envisioned UAV systems in the future. In addition to batteries and flight mechanism systems, UAVs already have complex payloads to carry. In addition, if they have to act as core nodes in the blockchain, then considerable processing and storage power should be integrated into their hardware.

5 Conclusion

UAV communication has entered a critical phase of development in recent years mainly because of UAVs' flexible deployment, strong joint service capabilities, diverse functions, and the growing demand for broadband high-speed, heterogeneous, Ultra-Reliable and Low-Latency Communication (URLLC) as the SAGIN matures and a variety of internet-based applications and services emerge. Given the unique characteristics and technological advances of UAVs in this field, either as a standalone solution or as a participant in the SAGIN, they can be a cornerstone to meet existing requirements. With its distributed management mode and flexible consensus mechanism, blockchain technology is suitable for the networking and security of the UAV networks. To this end, this study, to some extent, captures the new technological progress in the field of UAV communication. Some important applications and use cases under the current research focus of UAV communication are emphasized. In addition, a review is provided covering the latest contributions of UAVs in systems, integrated networking, data gathering, and spectrum management. Finally, some important future challenges and corresponding open research topics are described.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (Nos. 61563004 and 61761007).

References

[1] F. X. Tang, Y. Kawamot, N. Kato, and J. J. Liu, Future intelligent and secure vehicular network toward 6G: Machine-learning approaches, *Proc. IEEE*, vol. 108, no. 2, pp. 292–307, 2020.

[2] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, Five disruptive technology directions for 5G, *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 74–80, 2014.

[3] M. Agiwal, A. Roy, and N. Saxena, Next generation 5G wireless networks: A comprehensive survey, *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1617–1655, 2016.

[4] R. P. Li, Z. F. Zhao, X. Zhou, G. R. Ding, Y. Chen, Z. Y. Wang, and H. G. Zhang, Intelligent 5G: When cellular networks meet artificial intelligence, *IEEE Wireless Commun.*, vol. 24, no. 5, pp. 175–183, 2017.

[5] J. B. Ni, X. D. Lin, and X. S. Shen, Efficient and secure service-oriented authentication supporting network slicing for 5G-enabled IoT, *IEEE J. Sel. Areas Commun.*, vol. 36, no. 3, pp. 644–657, 2018.

[6] B. Li, Z. S. Fei, Y. Zhang, and M. Guizani, Secure UAV communication networks over 5G, *IEEE Wireless Commun.*, vol. 26, no. 5, pp. 114–120, 2019.

[7] Z. Q. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. G. Ding, X. F. Lei, G. K. Karagiannidis, and P. Z. Fan, 6G wireless networks: Vision, requirements, architecture, and key technologies, *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 28–41, 2019.

[8] B. F. Ji, Y. A. Wang, K. Song, C. G. Li, H. Wen, V. G. Menon, and S. Mumtaz, A survey of computational intelligence for 6G: Key technologies, applications and trends, *IEEE Trans. Ind. Informat.*, vol. 17, no. 10, pp. 7145–7154, 2021.

[9] G. Gui, M. Liu, F. X. Tang, N. Kato, and F. Adachi, 6G: Opening new horizons for integration of comfort, security and intelligence, *IEEE Wireless Commun.*, vol. 27, no. 5, pp. 126–132, 2020.

[10] H. Viswanathan and P. E. Mogensen, Communications in the 6G Era, *IEEE Access*, vol. 8, pp. 57063–57074, 2020.

[11] T. Wild, V. Braun, and H. Viswanathan, Joint design of communication and sensing for beyond 5G and 6G systems, *IEEE Access*, vol. 9, pp. 30845–30857, 2021.

[12] C. De Lima, D. Belot, R. Berkvens, A. Bourdoux, D. Dardari, M. Guillaud, M. Isomursu, E. S. Lohan, Y. Miao, A. N. Barreto, et al., Convergent communication, sensing and localization in 6G systems: An overview of technologies, opportunities and challenges, *IEEE Access*, vol. 9, pp. 26902–26925, 2021.

[13] Z. F. Liao, J. S. Peng, J. W. Huang, J. X. Wang, J. Wang, P. K. Sharma, and U. Ghosh, Distributed probabilistic offloading in edge computing for 6G-enabled massive Internet of Things, *IEEE Internet Things J.*, vol. 8, no. 7, pp. 5298–5308, 2021.

[14] Y. Xiao, G. M. Shi, Y. Y. Li, W. Saad, and H. V. Poor, Toward self-learning edge intelligence in 6G, *IEEE Commun. Mag.*, vol. 58, no. 12, pp. 34–40, 2020.

[15] R. Shafin, L. J. Liu, V. Chandrasekhar, H. Chen, J. Reed, and J. Z. Zhang, Artificial intelligence-enabled cellular networks: A critical path to beyond-5G and 6G, *IEEE Wireless Commun.*, vol. 27, no. 2, pp. 212–217, 2020.

[16] T. Hong, W. T. Zhao, R. K. Liu, and M. Kadoch, Space-air-ground IoT network and related key technologies, *IEEE Wireless Commun.*, vol. 27, no. 2, pp. 96–104, 2020.

[17] P. Wang, J. X. Zhang, X. Zhang, Z. Yan, B. G. Evans, and W. B. Wang, Convergence of satellite and terrestrial networks: A comprehensive survey, *IEEE Access*, vol. 8, pp. 5550–5588, 2020.

[18] A. Ivanov, K. Tonchev, V. Poulkov, and A. Manolova, Probabilistic spectrum sensing based on feature detection for 6G cognitive radio: A survey, *IEEE Access*, vol. 9, pp. 116994–117026, 2021.

[19] H. Song, J. N. Bai, Y. Yi, J. S. Wu, and L. J. Liu, Artificial intelligence enabled Internet of Things: Network architecture and spectrum access, *IEEE Comput. Intell. Mag.*, vol. 15, no. 1, pp. 44–51, 2020.

[20] Y. Feng, B. L. Jiao, and L. Y. Song, Satellite-based spectrum sensing for dynamic spectrum sharing in ground-located CRNs, *Wireless Pers. Commun.*, vol. 57, no. 1, pp. 105–117, 2011.

[21] J. J. Liu, Y. P. Shi, Z. M. Fadlullah, and N. Kato, Space-air-ground integrated network: A survey, *IEEE Commun. Surveys Tuts.*, vol. 20, no. 4, pp. 2714–2741, 2018.

[22] B. M. Mao, F. X. Tang, Y. Kawamoto, and N. Kato, Optimizing computation offloading in satellite-UAV-served 6G IoT: A deep learning approach, *IEEE Netw.*, vol. 35, no. 4, pp. 102–108, 2021.

[23] M. Helmy, Z. E. Ankarali, M. Siala, T. Baykas, and H. Arslan, Dynamic utilization of low-altitude platforms in aerial heterogeneous cellular networks, in *Proc. IEEE Wireless Microw. Technol. Conf.* (*WAMICON*), Cocoa Beach, FL, USA, 2017, pp. 1–6.

[24] M. Helmy and H. Arslan, Utilization of aerial heterogeneous cellular networks: Signal-to-interference ratio analysis, *J. Commun. Netw.*, vol. 20, no. 5, pp. 484–495, 2018.

[25] Y. Du, K. Z. Wang, K. Yang, and G. P. Zhang, Trajectory design of laser-powered multi-drone enabled

data collection system for smart cities, in *Proc. IEEE Global Commun. Conf.* (*GLOBECOM*), Waikoloa, HI, USA, 2019, pp. 1–6.

[26] *Functional Architecture for Unmanned Aerial Vehicles and Unmanned Aerial Vehicle Controllers Using IMT-2020 Networks*, Recommendation ITU-T Y.4421, Geneva, 2021.

[27] U. Senol, A. Yazar, and H. Arslan, Communications scenarios and a new mixed numerology set for flying base stations in 5G and beyond, in *Proc. IEEE Int. Black Sea Conf. Commun. Netw.* (*BlackSeaCom*), Batumi, GA, USA, 2018, pp. 91–95.

[28] M. Mozaffari, W. Saad, M. Bennis, Y. H. Nam, and M. Debbah, A tutorial on UAVs for wireless networks: Applications, challenges and open problems, *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2334–2360, 2019.

[29] X. N. Zhu, Analysis of military application of UAV swarm technology, in *Proc. 3rd International Conference On Unmanned Systems* (*ICUS*), Harbin, China, 2020, pp. 1200–1204.

[30] M. Alwateer, S. W. Loke, and A. M. Zuchowicz, Drone services: Issues in drones for location-based services from human-drone interaction to information processing, *J. Location Based Serv.*, vol. 13, no. 2, pp. 94–127, 2019.

[31] H. Shakhatreh, A. H. Sawalmeh, A. Al-Fuqaha, Z. C. Dou, E. Almaita, I. Khalil, N. S. Othman, A. Khreishah, and M. Guizani, Unmanned aerial vehicles (UAVs): A survey on civil applications and key research challenges, *IEEE Access*, vol. 7, pp. 48572–48634, 2019.

[32] V. Mazzia, L. Comba, A. Khaliq, M. Chiaberge, and P. Gay, UAV and machine learning based refinement of a satellite-driven vegetation index for precision agriculture, *Sensors*, vol. 20, no. 9, p. 2530, 2020.

[33] P. K. R. Maddikunta, S. Hakak, M. Alazab, S. Bhattacharya, T. R. Gadekallu, W. Z. Khan, and Q. V. Pham, Unmanned aerial vehicles in smart agriculture: Applications, requirements, and challenges, *IEEE Sensors J.*, vol. 21, no. 16, pp. 17608–17619, 2021.

[34] C. A. Thiels, J. M. Aho, S. P. Zietlow, and D. H. Jenkins, Use of unmanned aerial vehicles for medical product transport, *Air Med. J.*, vol. 34, no. 2, pp. 104–108, 2015.

[35] S. Sudhakar, V. Vijayakumar, C. S. Kumar, V. Priya, L. Ravi, and V. Subramaniyaswamy, Unmanned aerial vehicle (UAV) based forest fire detection and monitoring for reducing false alarms in forest-fires, *Comput. Commun.*, vol. 149, pp. 1–16, 2020.

[36] H. Zhang, L. H. Dou, B. Xin, J. Chen, M. G. Gan, and Y. L. Ding, Data collection task planning of a fixed-wing unmanned aerial vehicle in forest fire monitoring, *IEEE Access*, vol. 9, pp. 109847–109864, 2021.

[37] L. Gupta, R. Jain, and G. Vaszkun, Survey of important issues in UAV communication networks, *IEEE Commun. Surveys Tuts.*, vol. 18, no. 2, pp. 1123–1152, 2016.

[38] A. Fotouhi, H. R. Qiang, M. Ding, M. Hassan, L. G. Giordano, A. Garcia-Rodriguez, and J. H. Yuan, Survey on UAV cellular communications: Practical aspects, standardization advancements, regulation, and security challenges, *IEEE Commun. Surveys Tuts.*, vol. 21, no. 4, pp. 3417–3442, 2019.

[39] P. K. Sharma and D. I. Kim, Secure 3D mobile UAV relaying for hybrid satellite-terrestrial networks, *IEEE Trans. Wireless Commun.*, vol. 19, no. 4, pp. 2770–2784, 2020.

[40] N. N. Dao, Q. V. Pham, N. H. Tu, T. T. Thanh, V. N. Q. Bao, D. S. Lakew, and S. Cho, Survey on aerial radio access networks: Toward a comprehensive 6G access infrastructure, *IEEE Commun. Surveys Tuts.*, vol. 23, no. 2, pp. 1193–1225, 2021.

[41] Q. Q. Wu, J. Xu, Y. Zeng, D. W. K. Ng, N. Al-Dhahir, R. Schober, and A. L. Swindlehurst, A comprehensive overview on 5G-and-beyond networks with UAVs: From communications to sensing and intelligence, *IEEE J. Sel. Areas Commun.*, vol. 39, no. 10, pp. 2912–2945, 2021.

[42] G. C. Zhang, Q. Q. Wu, M. Cui, and R. Zhang, Securing UAV communications via joint trajectory and power control, *IEEE Trans. Wireless Commun.*, vol. 18, no. 2, pp. 1376–1389, 2019.

[43] M. Cui, G. C. Zhang, Q. Q. Wu, and D. W. K. Ng, Robust trajectory and transmit power design for secure UAV communications, *IEEE Trans. Veh. Technol.*, vol. 67, no. 9, pp. 9042–9046, 2018.

[44] M. T. Mamaghani and Y. Hong, Joint trajectory and power allocation design for secure artificial noise aided UAV communications, *IEEE Trans. Veh. Technol.*, vol. 70, no. 3, pp. 2850–2855, 2021.

[45] B. Yang, T. Taleb, Z. Q. Wu, and L. S. Ma, Spectrum sharing for secrecy performance enhancement in D2D-enabled UAV networks, *IEEE Netw.*, vol. 34, no. 6, pp. 156–163, 2020.

[46] S. Aggarwal, R. Chaudhary, G. S. Aujla, N. Kumar, K. K. R. Choo, and A. Y. Zomaya, Blockchain for smart communities: Applications, challenges and opportunities, *J. Netw. Comput. Appl.*, vol. 144, pp. 13–48, 2019.

[47] I. Garcia-Magarino, R. Lacuest, M. Rajarajan, and J. Lloret, Security in networks of unmanned aerial vehicles for surveillance with an agent-based approach inspired by the principles of blockchain, *Ad Hoc Netw.*, vol. 86, pp. 72–82, 2019.

[48] T. M. Fernandez-Carames, O. Blanco-Novoa, I. Froiz-

Miguez, and P. Fraga-Lamas, Towards an autonomous industry 4.0 warehouse: A UAV and blockchain-based system for inventory and traceability applications in big data-driven supply chain management, *Sensors*, vol. 19, no. 10, p. 2394, 2019.

[49] R. Gupta, A. Shukla, P. Mehta, P. Bhattachaya, and N. Kumar, VAHAK: A blockchain-based outdoor delivery scheme using UAV for healthcare 4.0 services, in *Proc. IEEE Conf. Comput. Commun. Workshops* (*INFOCOM WKSHPS*), Toronto, Canada, 2020, pp. 255–260.

[50] S. Tanwar, Q. Bhatia, P. Patel, A. Kumari, P. K. Singh, and W. C. Hong, Machine learning adoption in blockchain-based smart applications: The challenges, and a way forward, *IEEE Access*, vol. 8, pp. 474–488, 2020.

[51] Apoorva, S. Bitragunta, and S. Nitundil, Best beam selection and PHY switching policy for hybrid FSO/RF inter-satellite communication link, *IET Commun.*, vol. 14, no. 19, pp. 3350–3362, 2020.

[52] J. D. Yu, X. L. Liu, Y. Gao, and X. M. Shen, 3D channel tracking for UAV-satellite communications in space-air-ground integrated networks, *IEEE J. Sel. Areas Commun.*, vol. 38, no. 12, pp. 2810–2823, 2020.

[53] J. Liu, X. Q. Du, J. H. Cui, M. Pan, and D. B. Wei, Task-oriented intelligent networking architecture for the space-air-ground-aqua integrated network, *IEEE Internet Things J.*, vol. 7, no. 6, pp. 5345–5358, 2020.

[54] N. Hosseini, H. Jamal, D. W. Matolak, J. Haque, and T. Magesacher, UAV command and control, navigation and surveillance: A review of potential 5G and satellite systems, in *Proc. IEEE Aerosp. Conf.*, Big Sky, MT, USA, 2019, pp. 1–10.

[55] P. Zhou, X. M. Fang, Y. G. Fang, R. He, Y. Long, and G. Y. Huang, Beam management and self-healing for mmwave UAV mesh networks, *IEEE Trans. Veh. Technol.*, vol. 68, no. 2, pp. 1718–1732, 2019.

[56] R. Swaminathan, S. Sharma, N. Vishwakarma, and A. S. Madhukumar, HAPS-based relaying for integrated space-air-ground networks with hybrid FSO/RF communication: A performance analysis, *IEEE Trans. Aerosp. Electron. Syst.*, vol. 57, no. 3, pp. 1581–1599, 2021.

[57] J. Kim, J. Lee, and I. Lee, Antenna tracking techniques for long range air-to-ground communication systems using a monopulse method, *IEEE Access*, vol. 8, pp. 166442–166449, 2020.

[58] Y. Shibata, N. Kanazawa, M. Konishi, K. Hoshino, Y. Ohta, and A. Nagate, System design of Gigabit HAPS mobile communications, *IEEE Access*, vol. 8, pp. 157995–158007, 2020.

[59] A. V. Savkin, H. L. Huang, and W. Ni, Securing UAV communication in the presence of stationary or mobile eavesdroppers via online 3D trajectory planning, *IEEE Wireless Commun. Lett.*, vol. 9, no. 8, pp. 1211–1215, 2020.

[60] G. J. Hu, Y. M. Cai, and Y. L. Cai, Joint optimization of position and jamming power for UAV-aided proactive eavesdropping over multiple suspicious communication links, *IEEE Wireless Commun. Lett.*, vol. 9, no. 12, pp. 2093–2097, 2020.

[61] X. S. Gan, Y. R. Wu, P. N. Li, and Q. Wang, Dynamic collision avoidance zone modeling method based on UAV emergency collision avoidance trajectory, in *Proc. IEEE Int. Conf. Artif. Intell. Inf. Syst.* (*ICAIIS*), Dalian, China, 2020, pp. 693–696.

[62] X. Yu, X. B. Zhou, and Y. M. Zhang, Collision-free trajectory generation and tracking for UAVs using markov decision process in a cluttered environment, *J. Intell. Robot. Syst.*, vol. 93, nos. 1&2, pp. 17–32, 2019.

[63] T. Baca, D. Hert, G. Loianno, M. Saska, and V. Kumar, Model predictive trajectory tracking and collision avoidance for reliable outdoor deployment of unmanned aerial vehicles, in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.* (*IROS*), Madrid, Spain, 2018, pp. 6753–6760.

[64] P. K. Sharma, D. Deepthi, and D. I. Kim, Outage probability of 3-D mobile UAV relaying for hybrid satellite-terrestrial networks, *IEEE Commun. Lett.*, vol. 24, no. 2, pp. 418–422, 2020.

[65] T. Zhang, G. L. Liu, H. J. Zhang, W. J. Kang, G. K. Karagiannidis, and A. Nallanathan, Energy-efficient resource allocation and trajectory design for UAV relaying systems, *IEEE Trans. Commun.*, vol. 68, no. 10, pp. 6483–6498, 2020.

[66] S. A. Hoseini, J. Hassan, A. Bokani, and S. S. Kanhere, Trajectory optimization of flying energy sources using Q-learning to recharge hotspot UAVs, in *Proc. IEEE Conf. Comput. Commun. Workshops* (*INFOCOM WKSHPS*), Toronto, Canada, 2020, pp. 683–688.

[67] Y. J. Jin, H. L. Zhang, S. H. Zhang, Z. Han, and L. Y. Song, Sense-store-send: Trajectory optimization for a buffer-aided Internet of UAVs, *IEEE Commun. Lett.*, vol. 24, no. 12, pp. 2888–2892, 2020.

[68] M. Alzenad and H. Yanikomeroglu, Coverage and rate analysis for unmanned aerial vehicle base stations with LoS/NLoS propagation, in *Proc. IEEE Globecom Workshops* (*GC Wkshps*), Abu Dhabi, the United Arab Emirates, 2018, pp. 1–7.

[69] W. D. Mei and R. Zhang, UAV-sensing-assisted cellular interference coordination: A cognitive radio approach,

IEEE Wireless Commun. Lett., vol. 9, no. 6, pp. 799–803, 2020.

[70] M. Hua, Y. Wang, M. Lin, C. G. Li, Y. M. Huang, and L. X. Yang, Joint CoMP transmission for UAV-aided cognitive satellite terrestrial networks, *IEEE Access*, vol. 7, pp. 14959–14968, 2019.

[71] Y. W. Huang, W. D. Mei, J. Xu, L. Qiu, and R. Zhang, Cognitive UAV communication via joint maneuver and power control, *IEEE Trans. Commun.*, vol. 67, no. 11, pp. 7872–7888, 2019.

[72] A. V. Savkin and H. L. Huang, Deployment of unmanned aerial vehicle base stations for optimal quality of coverage, *IEEE Wireless Commun. Lett.*, vol. 8, no. 1, pp. 321–324, 2019.

[73] S. Arabi, E. Sabir, H. Elbiaze, and M. Sadik, Data gathering and energy transfer dilemma in UAV-assisted flying access network for IoT, *Sensors*, vol. 18, no. 5, p. 1519, 2018.

[74] W. Q. Huang, D. M. Kim, W. R. Ding, and P. Popovski, Joint optimization of altitude and transmission direction in UAV-based two-way communication, *IEEE Wireless Commun. Lett.*, vol. 8, no. 4, pp. 984–987, 2019.

[75] W. D. Mei, Q. Q. Wu, and R. Zhang, Cellular-connected UAV: Uplink association, power control and interference coordination, *IEEE Trans. Wireless Commun.*, vol. 18, no. 11, pp. 5380–5393, 2019.

[76] C. Caillouet and N. Mitton, Optimization and communication in UAV networks, *Sensors*, vol. 20, no. 18, p. 5036, 2020.

[77] S. Aggarwal, N. Kumar, and S. Tanwar, Blockchain-envisioned UAV communication using 6G networks: Open issues, use cases, and future directions, *IEEE Internet Things J.*, vol. 8, no. 7, pp. 5416–5441, 2021.

[78] R. Shrestha, R. Bajracharya, and S. Kim, 6G enabled unmanned aerial vehicle traffic management: A perspective, *IEEE Access*, vol. 9, pp. 91119–91136, 2021.

[79] F. Noor, M. A. Khan, A. Al-Zahrani, I. Ullah, and K. A. Al-Dhlan, A review on communications perspective of flying ad-hoc networks: Key enabling wireless technologies, applications, challenges and open research topics, *Drones*, vol. 4, no. 4, p. 65, 2020.

[80] I. J. Jensen, D. F. Selvaraj, and P. Ranganathan, Blockchain technology for networked swarms of unmanned aerial vehicles (UAVs), in *Proc. IEEE 20th Int. Symp. World Wireless*, *Mobile Multimedia Netw.* (*WoWMoM*), Washington, DC, USA, 2019, pp. 1–7.

[81] A. S. Khan, G. J. Chen, Y. Rahulamathavan, G. Zheng, B. Assadhan, and S. Lambotharan, Trusted UAV network coverage using blockchain, machine learning, and auction mechanisms, *IEEE Access*, vol. 8, pp. 118219–118234, 2020.

[82] M. Keshavarz, M. Gharib, F. Afghah, and J. D. Ashdown, UASTrustChain: A decentralized blockchain-based trust monitoring framework for autonomous unmanned aerial systems, *IEEE Access*, vol. 8, pp. 226074–226088, 2020.

[83] C. P. Ge, X. S. Ma, and Z. Liu, A semi-autonomous distributed blockchain-based framework for UAVs system, *J. Syst. Archit.*, vol. 107, p. 101728, 2020.

[84] V. Hassija, V. Chamola, D. N. G. Krishna, and M. Guizani, A distributed framework for energy trading between UAVs and charging stations for critical applications, *IEEE Trans. Veh. Technol.*, vol. 69, no. 5, pp. 5391–5402, 2020.

[85] I. Cermakova and J. Komarkova, Modelling a process of UAV data collection and processing, in *Proc. IEEE Int. Conf. Inf. Soc.* (*i-Society*), Dublin, Ireland, 2016, pp. 161–164.

[86] X. B. Xu, H. Zhao, H. P. Yao, and S. G. Wang, A blockchain-enabled energy-efficient data collection system for UAV-assisted IoT, *IEEE Internet Things J.*, vol. 8, no. 4, pp. 2431–2443, 2021.

[87] A. Islam and S. Y. Shin, BUS: A blockchain-enabled data acquisition scheme with the assistance of UAV swarm in Internet of Things, *IEEE Access*, vol. 7, pp. 103231–103249, 2019.

[88] Z. G. Ding, Y. W. Liu, J. Choi, Q. Sun, M. Elkashlan, C. L. I, and H. V. Poor, Application of non-orthogonal multiple access in LTE and 5G networks, *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 185–191, 2017.

[89] W. C. Chen, S. J. Zhao, R. Q. Zhang, Y. Chen, and L. Q. Yang, UAV-assisted data collection with nonorthogonal multiple access, *IEEE Internet Things J.*, vol. 8, no. 1, pp. 501–511, 2021.

[90] J. W. Zhao, Y. Wang, Z. X. Fei, X. Wang, and Z. Y. Miao, NOMA-aided UAV data collection system: Trajectory optimization and communication design, *IEEE Access*, vol. 8, pp. 155843–155858, 2020.

[91] X. D. Mu, Y. W. Liu, L. Guo, J. R. Lin, and Z. G. Ding, Energy-constrained UAV data collection systems: NOMA and OMA, *IEEE Trans. Veh. Technol.*, vol. 70, no. 7, pp. 6898–6912, 2021.

[92] W. D. Ye, W. J. Wu, F. Shan, M. Yang, and J. Z. Luo, Energy-efficient trajectory planning and speed scheduling for UAV-assisted data collection, in *Proc. 2020 16th International Conference on Mobility, Sensing and Networking* (*MSN*), Tokyo, Japan, 2020, pp. 190–197.

[93] S. Z. Yang, Y. S. Deng, X. X. Tang, Y. Ding, and J. M.

Zhou, Energy efficiency optimization for UAV-assisted backscatter communications, *IEEE Commun. Lett.*, vol. 23, no. 11, pp. 2041–2045, 2019.

[94] S. Fu, Y. J. Tang, Y. Wu, N. Zhang, H. X. Gu, C. Chen, and M. Liu, Energy-efficient UAV-enabled data collection via wireless charging: A reinforcement learning approach, *IEEE Internet Things J.*, vol. 8, no. 12, pp. 10209–10219, 2021.

[95] S. Kaul, R. Yates, and M. Gruteser, Real-time status: How often should one update? in *Proc. IEEE INFOCOM*, Orlando, FL, USA, 2012, pp. 2731–2735.

[96] S. H. Zhang, H. L. Zhang, Z. Han, H. V. Poor, and L. Y. Song, Age of information in a cellular Internet of UAVs: Sensing and communication trade-off design, *IEEE Trans. Wireless Commun.*, vol. 19, no. 10, pp. 6578–6592, 2020.

[97] J. Liu, P. Tong, X. J. Wang, B. Bai, and H. Y. Dai, UAV-aided data collection for information freshness in wireless sensor networks, *IEEE Trans. Wireless Commun.*, vol. 20, no. 4, pp. 2368–2382, 2021.

[98] M. A. Abd-Elmagid and H. S. Dhillon, Average peak age-of-information minimization in UAV-assisted IoT networks, *IEEE Trans. Veh. Technol.*, vol. 68, no. 2, pp. 2003–2008, 2019.

[99] G. Ahani, D. Yuan, and Y. X. Zhao, Age-optimal UAV scheduling for data collection with battery recharging, *IEEE Commun. Lett.*, vol. 25, no. 4, pp. 1254–1258, 2021.

[100] J. F. Qiu, D. Grace, G. R. Ding, J. N. Yao, and Q. H. Wu, Blockchain-based secure spectrum trading for unmanned-aerial-vehicle-assisted cellular networks: An operator's perspective, *IEEE Internet Things J.*, vol. 7, no. 1, pp. 451–466, 2020.

[101] B. D. Shang, V. Marojevic, Y. Yi, A. S. Abdalla, and L. J. Liu, Spectrum sharing for UAV communications: Spatial spectrum sensing and open issues, *IEEE Veh. Technol. Mag.*, vol. 15, no. 2, pp. 104–112, 2020.

[102] B. D. Shang, L. J. Liu, R. M. Rao, V. Marojevic, and J. H. Reed, 3D spectrum sharing for hybrid D2D and UAV networks, *IEEE Trans. Commun.*, vol. 68, no. 9, pp. 5375–5389, 2020.

[103] F. Shen, G. R. Ding, Z. Wang, and Q. H. Wu, UAV-based 3D spectrum sensing in spectrum-heterogeneous networks, *IEEE Trans. Veh. Technol.*, vol. 68, no. 6, pp. 5711–5722, 2019.

[104] W. B. Xu, S. Wang, S. Yan, and J. H. He, An efficient wideband spectrum sensing algorithm for unmanned aerial vehicle communication networks, *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1768–1780, 2019.

[105] Y. P. Li, R. Q. Zhang, J. H. Zhang, and L. Q. Yang, Cooperative jamming via spectrum sharing for secure UAV communications, *IEEE Wireless Commun. Lett.*, vol. 9, no. 3, pp. 326–330, 2020.

[106] N. Tang, H. Y. Tang, B. Q. Li, and X. B. Yuan, Cognitive NOMA for UAV-enabled secure communications: Joint 3D trajectory design and power allocation, *IEEE Access*, vol. 8, pp. 159965–159978, 2020.

[107] A. Islam and S. Y. Shin, BUAV: A blockchain based secure UAV-assisted data acquisition scheme in Internet of Things, *J. Commun. Netw.*, vol. 21, no. 5, pp. 491–502, 2019.

[108] Z. Y. Guan, H. Z. Lyu, D. W. Li, Y. M. Hei, and T. C. Wang, Blockchain: A distributed solution to UAV-enabled mobile edge computing, *IET Commun.*, vol. 14, no. 15, pp. 2420–2426, 2020.

[109] V. Sharma, I. You, D. N. K. Jayakody, D. G. Reina, and K. K. R. Choo, Neural-blockchain-based ultrareliable caching for edge-enabled UAV networks, *IEEE Trans. Ind. Informat.*, vol. 15, no. 10, pp. 5723–5736, 2019.

[110] B. Q. Wang, J. F. Xie, S. W. Li, Y. Wan, Y. X. Gu, S. L. Fu, and K. J. Lu, Computing in the air: An open airborne computing platform, *IET Commun.*, vol. 14, no. 15, pp. 2410–2419, 2020.

[111] G. Faraci, C. Grasso, and G. Schembra, Design of a 5G network slice extension with MEC UAVs managed with reinforcement learning, *IEEE J. Sel. Areas Commun.*, vol. 38, no. 10, pp. 2356–2371, 2020.

[112] ITU, Studies on frequency-related matters, including possible additional allocations, for the possible introduction of new non-safety aeronautical mobile applications, presented at World Radiocommunication Conference, document Resolution 430, 2019.

[113] N. H. Motlagh, T. Taleb, and O. Arouk, Low-altitude unmanned aerial vehicles-based Internet of Things services: Comprehensive survey and future perspectives, *IEEE Internet Things J.*, vol. 3, no. 6, pp. 899–922, 2016.

[114] O. Anicho, P. B. Charlesworth, G. S. Baicher, and A. Nagar, Situation awareness and routing challenges in unmanned HAPS/UAV based communications networks, in *Proc. 2020 International conference on unmanned aircraft systems* (*ICUAS*), Athens, Greece, 2020, pp. 1175–1182.

[115] Z. H. Wang, J. Z. Li, H. Q. Chen, and T. F. Qin, A novel divergence measure-based routing algorithm in large-scale satellite networks, *IET Commun.*, vol. 15, no. 5, pp. 708–722, 2021.

[116] M. Q. Vu, T. V. Pham, N. T. Dang, and A. T. Pham,

Outage performance of HAP-UAV FSO links with Gaussian beam and UAV hovering, in *Proc. 2020 IEEE 92nd Vehicular Technology Conference* (*VTC2020-Fall*), Victoria, Canada, 2020, pp. 1–5.

[117] E. H. S. Cardoso, J. P. L. De Araujo, S. V. De Carvalho, N. Vijaykumar, and C. R. L. Frances, Novel multilayered cellular automata for flying cells positioning on 5G cellular self-organising networks, *IEEE Access*, vol. 8, pp. 227076–227099, 2020.

[118] H. C. Wang, G. C. Ren, J. Chen, G. R. Ding, and Y. J. Yang, Unmanned aerial vehicle-aided communications: Joint transmit power and trajectory optimization, *IEEE Wireless Commun. Lett.*, vol. 7, no. 4, pp. 522–525, 2018.

[119] Y. J. Qin, M. A. Kishk, and M. S. Alouini, Performance evaluation of UAV-enabled cellular networks with battery-limited drones, *IEEE Commun. Lett.*, vol. 24, no. 12, pp. 2664–2668, 2020.

[120] H. V. Abeywickrama, B. A. Jayawickrama, Y. He, and E. Dutkiewicz, Comprehensive energy consumption model for unmanned aerial vehicles, based on empirical studies of battery performance, *IEEE Access*, vol. 6, pp. 58383–58394, 2018.

Zhonghao Wang received the BEng degree in communication engineering from Tianjin University, Tianjin, China in 2017. He is currently a master student in computer science and technology at the School of Computer and Electronic Information, Guangxi University, Nanning, China. His research interests include satellite communication, Unmanned Aerial Vehicle (UAV) communication, Space-Air-Ground Integrated Network (SAGIN), UAV sensing, and blockchain.

Fulai Zhang received the BEng degree in electronic science and technology from Guangxi University, Guangxi, China in 2018. He is currently a master student in computer science and technology at the School of Computer and Electronic Information, Guangxi University, Nanning, China. His research interests include satellite communication, SAGIN, spectrum sensing, spectrum management, and machine learning.

Qiqi Yu received the BEng degree in communication engineering from Hainan University, Haikou, China in 2018. She is currently a master student in computer science and technology at the School of Computer and Electronic Information, Guangxi University, Nanning, China. Her research interests include satellite communication, UAV communication, SAGIN, spectrum sharing, and machine learning.

Tuanfa Qin received the PhD degree from Nanjing University, China in 1997. He is presently a professor at the School of Computer and Electronic Information, Guangxi University, Nanning, China. He is also a senior member of China Institute of Electronics, and a senior member of China Communications Institute. His research interests include multimedia communications, satellite communication, SAGIN, blockchain, and network coding.