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SURVEY

A Comprehensive Survey on 5G-and-Beyond Networks With UAVs: Applications, Emerging Technologies, Regulatory Aspects, Research Trends and Challenges

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ABSTRACT The rapid advancement of fifth-generation (5G)-and-beyond networks coupled with unmanned aerial vehicles (UAVs) has opened up exciting possibilities for diverse applications and cutting-edge technologies, revolutionizing the way connections, communications, and innovations unfold in the digital age. This paper presents a comprehensive survey of the deployment scenarios, applications, emerging technologies, regulatory aspects, research trends, and challenges associated with the use of UAVs in 5G-and-beyond networks. It begins with a succinct background and motivation, followed by a systematic UAV classification and a review of relevant works. The survey covers UAV deployment scenarios, including single and multiple UAV configurations. The categorization of UAV applications in 5G is presented, along with investigations into emerging technologies for enhancing UAV communications. Regulatory considerations encompassing flight guidelines, spectrum allocation, privacy, and safety are discussed. Moreover, light is shed on the latest research trends and open challenges in the field, with promising directions for future investigations identified, concluding with a summary of key findings and contributions. This survey serves as a valuable resource for researchers, practitioners, and policymakers in the UAV and communication domains. Additionally, it offers a comprehensive foundation for informed decision-making, fostering collaboration, and driving advancements in UAV and communication technologies to address the evolving needs of our interconnected world.

INDEX TERMS Drone, 5G, unmanned aerial vehicles, wireless systems.

I. INTRODUCTION

Drones, alternatively referred to as UAVs or remotely piloted aircraft systems, have garnered considerable interest in recent times owing to their capacity to potentially transform diverse industries and sectors [1]. UAVs that are equipped with wireless communication capabilities possess the capacity to gather and transmit data in real-time, execute tasks autonomously, and engage in collaborative operations with other UAVs and ground control stations. The availability

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of connected UAVs has been facilitated by the progress in wireless communication technologies and the development of next-generation wireless systems.

Traditionally, UAV applications have predominantly centered around their utilization for recreational purposes, photography, and as a pastime for enthusiasts. Nevertheless, the integration of wireless systems with UAVs has led to the feasibility of various commercial, industrial, and public sector applications. Connected UAVs are currently being employed in various sectors, including but not limited to aerial surveillance for security and law enforcement, logistics and delivery services, precision agriculture, disaster management, environmental monitoring, and infrastructure inspection.

The growing incorporation of interconnected UAVs across diverse industries has spurred significant scholarly inquiry and technological advancements aimed at tackling the communication-related obstacles and prerequisites they entail. The forthcoming wireless systems, such as 5G and subsequent generations, possess the capability to establish the essential infrastructure and capacities required for facilitating efficient and dependable communication between UAVs and ground control stations.

In particular, the utilization and management of UAVs can offer dependable and economically viable wireless communication alternatives for a diverse range of practical situations. UAVs have the capability to function as aerial base stations (ABSs), providing dependable, cost-efficient, and readily available wireless communication services to targeted regions [2]. In addition, UAVs have the capability to operate as aerial user equipment (UE), commonly referred to as cellular-connected UAVs, alongside terrestrial users such as delivery or surveillance UAVs. The utilization of UAVs in this promising domain necessitates a reconsideration of the research obstacles, with an emphasis on wireless communications and networking rather than control and navigation.

Despite the potential advantages of UAVs, several challenging parameters exist, including bandwidth limitations, high mobility, intermittent connectivity, a limited transmission spectrum, and uncertain noisy channels. The ad hoc multi-hop environment presents various challenges, including collisions and latency issues. For example, maintaining a communication range between two UAVs travelling at very high speeds in opposition to one another might be challenging.

Although there are many prospects for UAV utilization, there are a number of technical issues that must be resolved before UAVs can be used effectively for any given networking application. When utilizing UAV-BS, important factors to consider in its design encompass performance characterization, efficient three-dimensional deployment of UAVs, allocation of wireless and computational resources, optimization of flight time and trajectory, as well as network planning. In the context of the UAV-UE scenario, several key challenges arise, including handover management, channel modeling, low-latency control, 3D localization, and interference management [3].

UAVs can be classified based on various factors, including their size, range, flight characteristics, purpose, and flight capabilities. UAV classification provides a framework for categorizing UAVs into distinct groups, allowing for better understanding and analysis of their characteristics and capabilities. The classifications of UAVs are based on several factors, including [4]:

A. SIZE AND WEIGHT

UAVs are classified based on their physical dimensions and weight. This classification helps in understanding the scale and capabilities of the UAVs, as different sizes may have varying payload capacities, flight times, and operational capabilities.

B. FLIGHT CHARACTERISTICS

The classification also takes into account the flight characteristics of the UAVs, such as fixed-wing or rotary-wing design. This classification helps to differentiate between UAVs that operate more like airplanes (fixed-wing) and those that operate with rotating blades for lift and maneuverability (rotary-wing).

C. PAYLOAD CAPACITY

UAVs are categorized based on their ability to carry and support different payload types. Payloads can include cameras, sensors, communication equipment, or specialized equipment for specific applications. The payload capacity classification helps in selecting UAVs suitable for specific mission requirements.

D. FLIGHT RANGE AND ENDURANCE

UAVs can be classified based on their flight range and endurance capabilities. This classification helps to differentiate between UAVs designed for short-range or long-range missions and those with limited or extended flight times.

E. PURPOSE AND APPLICATION

The classification also considers the intended purpose and application of UAVs. This classification helps to group UAVs based on their specific use cases, such as aerial surveillance, photography, agriculture, logistics, search and rescue, or scientific research.

This paper makes a significant contribution to the literature on 5G-and-beyond networks with UAVs by offering a comprehensive survey covering various dimensions of this evolving field. The major contributions of this study are:

F. IN-DEPTH COVERAGE

A thorough examination of UAV networks in the context of 5G-and-beyond is presented, encompassing applications, technologies, regulations, research trends, and challenges. The paper serves as a one-stop reference for anyone interested in understanding the synergy between UAVs and advanced communication systems.

G. CLASSIFICATION AND DEPLOYMENT SCENARIOS

A systematic classification of UAVs based on their characteristics is provided, enabling a better understanding of their diverse roles and functionalities. Additionally, an analysis of single and multiple UAV deployment scenarios is conducted, shedding light on their respective advantages and limitations.

H. APPLICATIONS AND EMERGING TECHNOLOGIES

Through the categorization of UAV applications in 5G networks and the investigation of emerging communication technologies, insights into potential use-cases and the state-of-the-art methods for enhancing UAV communications are offered.

I. REGULATORY INSIGHTS

Addressing the regulatory aspects of UAV deployment is crucial for real-world implementations. The regulatory landscape, including pertinent guidelines and challenges related to UAV operations, is discussed in the paper.

J. RESEARCH TRENDS AND OPEN CHALLENGES

The latest research trends and open challenges in the domain are identified and discussed, paving the way for future investigations and innovations.

The structure of the paper is organized as follows. Section I, the introduction, lays the groundwork, emphasizing the significance of UAVs' impact on various industries and outlining the objectives of the survey. Section II covers related work, providing context and building upon existing research in the field. In Section III, various UAV deployment scenarios are discussed alongside examples from the literature. Section IV categorizes UAV applications based on their functionalities and characteristics, providing a comprehensive overview of the wide array of applications enabled by UAVs. Following that, Section V explores emerging technologies, investigating cutting-edge advancements that augment UAV communications in 5G-and-beyond networks. In Section VI, the critical legal and regulatory considerations related to UAV deployment are addressed. This section explores airspace regulations, privacy concerns, and other policy frameworks shaping the integration of UAVs into existing communication networks. Section VII sheds light on the ongoing research trends propelling the evolution of UAV networks. It also outlines the open challenges faced by researchers and industry professionals in achieving seamless and efficient UAV communications. Finally, Section VIII concludes by emphasizing the significance of continuous research and collaboration to address existing challenges and unlock the full potential of UAV technology. Figure 1 demonstrates the diagram of survey organization.

II. RELATED WORK

A. RECENT RELEVANT REVIEW ARTICLES

Currently, there is a proliferation of research and inquiries pertaining to networks of UAVs. Several research studies on UAVs have been conducted, focusing primarily on offering a comprehensive understanding of UAV communication models. These surveys have also explored various aspects such as applications, characteristics, challenges, and unresolved matters related to UAVs. Additionally, some surveys have proposed solutions to address specific requirements, including security concerns, medium access control protocols, quality of service (QoS), and routing protocols. Authors in [5] provided a comprehensive overview of pertinent research on machine learning (ML)-based strategies for UAV communication. These strategies aim to enhance different aspects of UAV models and functionalities, including UAV channel modeling, managing resources, positioning, and security. The study referenced in [3] presented an extensive investigation into the utilization of UAVs within wireless networks. The study thoroughly investigates the fundamental tradeoffs and significant challenges in UAV-enabled wireless networks. The objective of this study is to compile the most current and significant research findings from the limited and dispersed body of literature on wireless communications using UAVs. This paper discusses the significant opportunities and challenges associated with the deployment of UAVs as flying wireless base stations (BSs). These UAVs serve as complementary components to emerging wireless communication systems. Additionally, the paper explores the utilization of UAVs as cellular-connected UAV-UEs, which rely on existing wireless infrastructure. The emphasis is placed on various application scenarios, challenges, representative outcomes, open issues, and analytical techniques that are crucial for facilitating the practical implementation of UAVs as aerial communication platforms.

The research reported in [6] provided a comprehensive overview of the use of UAVs in cellular communications. The authors discussed the various practical aspects of UAV cellular communications, including standardization, regulation, challenges of integrating UAVs into existing cellular networks, the need for new protocols and standards, and the potential security risks associated with UAV cellular communications. In [7], the authors conducted an extensive survey of the current advancements in UAV-physical layer security (PLS), covering fundamental concepts, static and mobile deployment scenarios, air-to-ground (A2G) channels, and various UAV roles. They reviewed secrecy performance analysis and enhancement techniques for static UAV systems and scenarios involving UAV mobility.

The study conducted in [8] offered a thorough overview of the research carried out for UAV deployment and trajectory to increase the capacity of UAV wireless networks and to control them effectively, in order to promote more research on UAV wireless networks. Additionally, this paper also discussed the challenges and potential areas for future research.

In [9], the authors concentrated more on new UAV network technologies and their applications for next-generation cellular networks. The study comprehensively examined a range of developing communication technologies for UAVs, including an analysis of their respective benefits, potential applications,

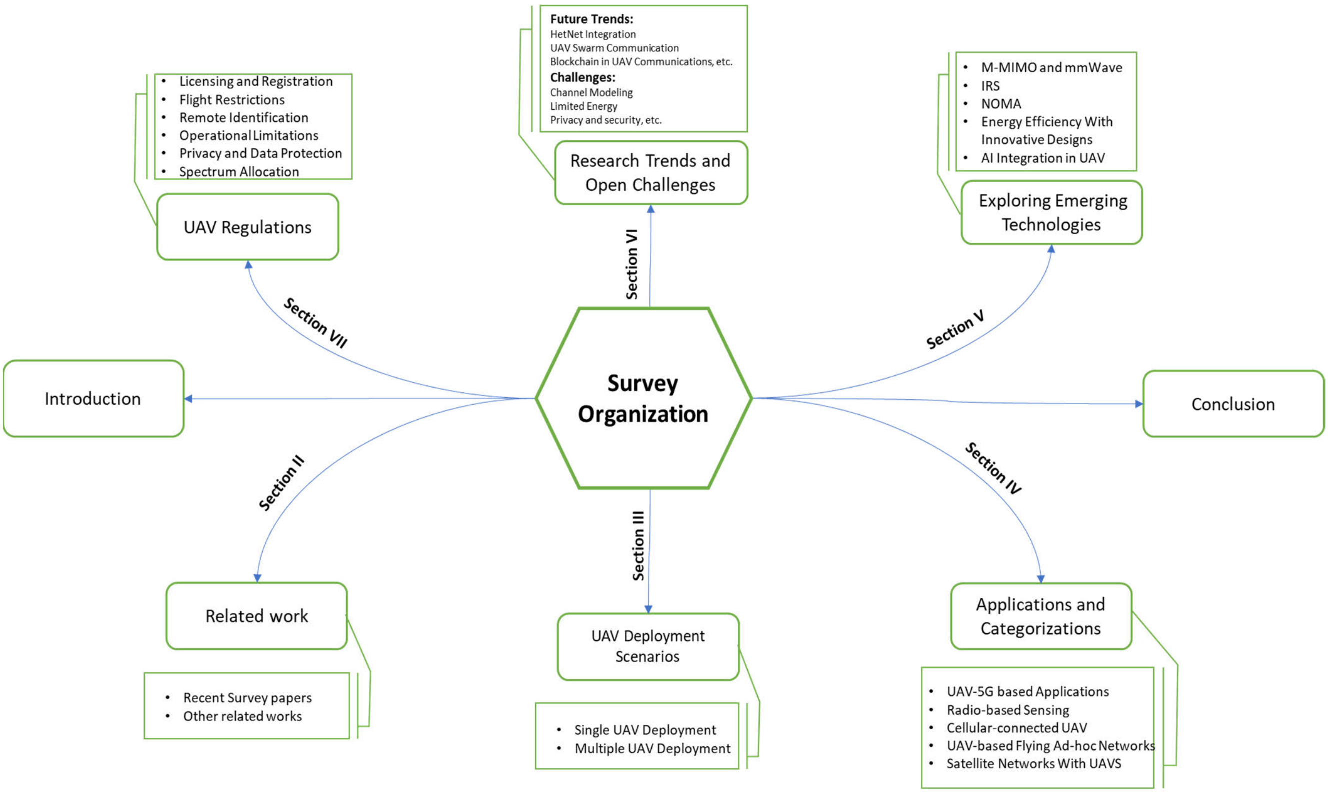

FIGURE 1. Diagram of survey organization.

technical obstacles, and future prospects. The research study encompassed an examination of communication and network technologies for UAVs, focusing on the evaluation of appropriate task modules, antennas, resource managing platforms, and network structure. Further, it encompassed a comprehensive examination of emerging technologies, considering viewpoints from both academic and industrial sectors, as supported by the latest scholarly literature. Furthermore, the paper discussed the potential advancements in UAV communication and their utilization in contemporary technologies such as the Internet of Things (IoT), 5G networks, and wireless sensor networks. The research conducted in reference [10] presented a comprehensive analysis and in-depth exploration of UAV communication protocols, networking systems, structures, and use cases. Furthermore, the paper examined UAV solutions and emphasizes significant technical challenges and unresolved research issues that necessitate further investigation and development efforts.

The survey in [11] provided an overview of related works in UAV communications and technology integration. It explored millimeter wave (mmWave) beamforming-enabled UAV communications, addressing both technical potential and challenges, as well as relevant mmWave antenna structures and channel modelling. Additionally, technologies and solutions for UAV-connected mmWave cellular networks and mmWave-UAV ad hoc networks are reviewed. The status quo on UAV communications from an industrial standpoint is overviewed in [12]. Fresh updates from the 3GPP and details on new 5G new radio (NR) features supporting aerial devices are provided. The potential and limitations of such features are dissected. The effectiveness of sub-6GHz massive multiple input multiple output (MIMO) in addressing cell selection and interference challenges is demonstrated, mmWave coverage is evaluated in different settings, and the specifics of direct device-to-device (D2D) communication in the aerial domain are examined.

Shifting the focus, in [13], the survey analyzed the impact of edge artificial intelligent (AI) on crucial UAV technical aspects and applications, spanning diverse areas such as power management, formation control, autonomous navigation, computer vision, privacy and security, and communication. It included applications like precision agriculture, delivery systems, civil infrastructure inspection, search and rescue operations, acting as aerial wireless BSs, and UAV light shows. The work in [14] explored the contemporary landscape of UAV-assisted maritime communications, drawing from both traditional optimization methods and ML techniques. It discussed various aspects, including UAV-based network architectures, component roles, and categorized UAV-aided solutions for maritime environments, addressing performance targets such as physical-layer improvements, resource management, and cloud/edge computing and caching.

With related to spectrum management for UAV operations is explored in [15], identifying suitable management schemes aligned with UAV features and spectrum requirements.

assumes coexistence with prevalent wireless technologies that occupy the spectrum. It also presented the rulings from policymakers and regulators and discussed the operation bands and radio interfaces. In other survey [16], the development of existing regulation policies and critical technologies related to the safe and efficient operation of small civil UAVs at low altitudes in urban areas is examined.

The integration of privacy and security in blockchain-assisted UAV communication is discussed in [17], outlining fundamental analyses and critical requirements for constructing privacy and security models and supporting decentralized data storage systems. The review of [18] offered a comprehensive examination of scenarios and essential technologies in UAV-assisted data collection. The system model, which includes the network framework and mathematical representation of UAV-assisted data collection for IoT, is presented. Subsequently, a thorough review of critical technologies is conducted, encompassing sensor clustering, UAV data collection modes, and coordinated path planning and resource allocation. The survey in [19] offered a comprehensive survey of UAV caching models, techniques, and applications within sixth generation (6G) networks. It covered the evolution of caching models from terrestrial to aerial domains, introduces a typical UAV caching system, and discussed recent advancements and system performance metrics in this context. Table 1 provides a concise overview of various related surveys, offering brief descriptions for each one.

B. OTHER RELEVANT WORKS ON UAV

Numerous additional research areas exist that pertain to the use of UAV communications and networking. In reference [20], the authors presented scenarios involving the deployment of both single and multiple UAVs, along with a range of use cases. These use cases involve the integration of different wireless communication techniques. Furthermore, a thorough investigation is conducted to examine the ramifications of the selected deployment techniques. The concept of swarming UAVs and its intricacies have been introduced in works [21] and [22], which provides rigorous mathematical derivations elucidating the underlying theory of the proposed approaches and algorithms. Additionally, the introduction of other concerns was observed, including collision avoidance and control latency. The utilization of channel and antenna-based methodologies holds significant importance in UAV communications. A comprehensive explanation of channel modeling in UAV communication can be found in [23]. In [24], [25], [26], and [27] various models for antenna deployment are presented, encompassing both theoretical formulations and simulation outcomes. The articles [6] and [28] discussed various strategies and methodologies for effectively managing interference in a given system or network. The concept of employing global positioning system (GPS) architecture for the purpose of system redundancy is elucidated in a notable study [29]. In [30] authors examined security concerns pertaining to the communication systems of UAVs. The literature extensively covered considerations pertaining to UAVs and structural design approaches, in addition to background and design considerations. The utilization of 5G technology in UAV applications is discussed in [31]. A comprehensive examination of UAVs with cellular connectivity can be found in [32], [33], and [34]. In addition, researchers proposed a network planning approach for UAV communication in their works in [35], [36], and [37].

III. UAV DEPLOYMENT SCENARIOS

In a wireless communication network, which consists of one or multiple UAVs, there may be different deployment scenarios. Here, deployment means the position and mobility of the UAVs in the network. Two main criteria are considered when defining these deployment scenarios, which are the purpose of usage and the performance. The purpose of use may require a specific number of UAVs or may cause any scenario which is unique for the relevant application. Besides, the other criterion is performance constraints, as in every wireless communication network. In this section, some single and multiple UAV deployment scenarios are presented with their reasonings and contributions, and the concept of swarming UAVs is explained.

A. SINGLE UAV DEPLOYMENT

Only one UAV is employed in a single UAV deployment scheme. This UAV behaves as a relay between the ground units. The ground unit can be any member of the wireless communication networks, such as a BS or a mobile user. In a single UAV deployment scenario, there are some issues highlighted by [20] to provide optimal performance for the system. These issues can be summarized as the position of the UAV in the air, the techniques that can be used for the relay operation, and some advanced arrangements that can be faced during practical applications. The possible approaches to these constraints are widely discussed in [20]. For example, when determining the optimal position of a single UAV in the air, parameters that identify the optimization problem are throughput, bit error rate, and signal-to-noise ratio (SNR).

Authors in [38] proposed a single UAV deployment for indoor emergencies by minimizing power consumption. An optimization problem involving the relationship between the dimensions of the buildings and the location of the UAVs is derived using an exhaustive algorithm and an iterative algorithm. A study conducted in [39] compared the single UAV deployment scenario to other scenarios in terms of cost. The results proved that a single UAV deployment is more cost-effective than others. This study is useful for contrasting the single UAV deployment with the following subsections in this section.

B. MULTIPLE UAV DEPLOYMENT

Contrary to a single UAV deployment scenario, there is more than one UAV for multiple UAV deployment schemes. In addition to design considerations and optimization problems in a single UAV case, other critical problems that should

TABLE 1. Summary of existing surveys.

Authors, year	Brief Description
Bithas, et al. [5], 2019	This survey offers a comprehensive overview of ML-based strategies for UAV communication, targeting improvements in UAV channel modelling, resource management, positioning, and security.
Fotouhi, et al. [6], 2019	This survey presents a comprehensive view of UAVs in cellular communications, covering practical aspects such as integration challenges, protocol development, standards, and security concerns.
Wang, et al. [7], 2022	This survey discusses UAV-PLS advancements, covering fundamental concepts, deployment scenarios, A2G channels, and UAV roles, including secrecy performance analysis and enhancements for static and mobile UAV systems.
Han [8], 2022	This survey provides an extensive overview of research on UAV deployment and trajectory for enhancing UAV wireless networks' capacity and control. It also highlights challenges and future research areas in this domain.
Sharma, et al. [9], 2020	This survey focuses on new UAV network technologies and their applications in next-generation cellular networks, covering a variety of emerging communication technologies for UAVs, analysing their advantages, potential applications, technical challenges, and future outlook.
Hentati, et al. [10], 2020	This survey thoroughly analyses UAV communication protocols, networking systems, structures, and use cases, while also highlighting important technical challenges and unresolved research areas requiring further investigation and development.
Xiao, et al. [11], 2021	This survey offers an overview of related research in UAV communications and technology integration. It delves into mmWave beamforming-enabled UAV communications, covering both technical possibilities and challenges, as well as discussing relevant mmWave antenna structures and channel modelling.
Geraci, et al. [12], 2022	This survey discusses recent 3GPP updates and 5G NR features for aerial devices, analysing their potential and limitations. It also demonstrates sub-6GHz massive MIMO's efficacy in addressing cell selection and interference, evaluates mmWave coverage in various environments, and explores aerial direct D2D communication specifics.
McEnroe, et al. [13], 2022	This survey examines the influence of edge AI on vital UAV technical aspects and applications, encompassing areas like power management, formation control, autonomous navigation, computer vision, privacy, security, and communication.
Jasim, et al. [15], 2021	This survey determines management schemes suitable for UAV features and spectrum needs, considering coexistence with existing wireless technologies in the spectrum. It also outlines policymakers' and regulators' directives and explores operation bands and radio interfaces.
Xu, et al. [16], 2020	This survey examines the development of current regulatory policies and essential technologies concerning the safe and efficient operation of small civil UAVs at low altitudes in urban environments.
Hafeez, et al. [17], 2023	This survey addresses the incorporation of privacy and security in blockchain-assisted UAV communication, highlighting the need for fundamental analyses and essential requirements to establish privacy and security models and facilitate decentralized data storage systems.
Wei, et al. [18], 2022	This review provides a comprehensive analysis of scenarios and crucial technologies for UAV-assisted data collection in IoT. It presents the system model, covering network framework and mathematical representation, and conducts a thorough review of key technologies.
Nomikos, et al. [14], 2022	This survey examines UAV-assisted maritime communications, combining traditional methods and ML techniques to enhance performance in areas like the physical layer, resource management, and cloud/edge computing.
Duong, et al. [19], 2022	This survey provides a comprehensive overview of UAV caching in 6G networks, encompassing caching model evolution from terrestrial to aerial domains, introducing a typical UAV caching system, and discussing recent advancements and performance metrics.
This Survey	It provides a comprehensive overview of deployment scenarios, applications, emerging technologies, regulatory aspects, research trends, and challenges related to the integration of UAVs in 5G-and-beyond networks. It offers a holistic examination of the subject matter.

be solved: the relative positions and the reciprocal relations of the multiple UAVs in the air. Since the medium of UAVs is three-dimensional space and each UAV may have a different connection scheme to transfer data with others, the problems require more complex approaches to find the optimal solution.

A comprehensive study that includes many different optimization approaches such as mixed-integer optimization problem, linear programming method, successive convex optimization, and penalty method is presented in [40]. In particular, the authors focused on the downlink problem, but many of the findings are relevant to different types of wireless networks in terms of optimization since they consider different approaches. Also, the effect of the increasing number of UAVs is well discussed. Authors in [41] discussed the optimization for multiple UAVs from trajectory and power issues. They placed more emphasis on theoretical formulations of the problems than on [40], and proposed a deep neural network for their models.

In multi-UAV systems, various topologies can be established, including the star, multi-star, mesh, and hierarchical mesh configurations. Each topology offers different advantages and considerations for UAV communication. Table 2 shows the summary.

TABLE 2. Summary of UAV network topologies.

Topology	Communication Characteristics	Advantages
Star	Relies on UAV-to-infrastructure communication	Simple configuration, direct communication with ground node
Multi-Star	Multiple stars connected to a ground station	Communication within stars, easy inter-star connection setup
Mesh	UAVs interconnected; packets travel through intermediate nodes	Flexibility, reliability, self-forming and reorganization features, better performance characteristics
Hierarchical Mesh	Multiple interconnected mesh networks with hierarchical connections	Hierarchical organization, inter-group communication capabilities

- **Star Topology:** In a star topology network, a ground node acts as the central point, and UAVs directly communicate with this node. This configuration relies on UAV-to-infrastructure communication, with all communication passing through the ground node. However, star topologies suffer from high latency due to longer downlink lengths compared to inter-UAV distances. The failure of the ground node can result in mission failure, as there is no inter-UAV communication. Additionally, star configurations require expensive bandwidth downlinks.
- **Multi-Star Topology:** The multi-star topology network consists of multiple stars formed by UAVs, with one node from each group connected to the ground station. Although this topology enables communication among UAVs within each star, it still relies on the central ground station for inter-star communication. Similar to the star topology, multi-star configurations face latency challenges and depend on the availability of the ground station for successful mission execution.
- **Mesh Topology:** In the mesh topology network, UAVs are interconnected, and only one UAV may connect to the control center. This configuration allows packets to travel through intermediate nodes, finding their way from any source to any destination in multiple hops. Mesh networks offer flexibility, reliability, and better performance characteristics compared to star configurations. They are particularly suitable for UAV networks as they support self-forming and reorganization features. When a node fails, the remaining nodes can reconfigure the network among themselves, ensuring continuous communication.
- **Hierarchical Mesh Topology:** The hierarchical mesh topology network involves multiple mesh networks formed by UAVs, with one node from each group connected to other groups. Additionally, a small number of UAVs may directly connect to the control center. This architecture provides hierarchical organization and inter-group communication capabilities. Similar to the mesh topology, it offers the advantages of flexibility, reliability, and self-healing capabilities.

UAV architectures can be divided into two main categories: cooperative multi-UAVs and multi-layered UAV networks as depicted in Figure 2.

C. MULTI-LAYERED UAV NETWORKS

Multi-layers UAV network architectures are based on UAVs network that cooperates with other layers such as IoT or wireless sensor network (WSN) or with cloud computing systems.

1) SWARMING UAVS

Swarming is another term used for multiple UAVs, especially in huge numbers of UAVs. The missions of a swarm of UAVs are not limited to wireless communications purposes, but also to many different scenarios as mentioned before. The swarming UAVs are presented in another subsection as it focuses on the more coordinated and robotic behavior of multiple UAVs. In addition to approaches that are similar to multiple UAV deployment scenarios, some enhanced techniques have been developed in the literature due to dealing with relatively more data. To solve the computation offloading, an architecture named fog-computing-aided swarm of drones (FCSD) (see Figure 3) is introduced in [11]. Both the latency model and reliability model of FCSD are provided to ensure powerful reliability by considering various scenarios. Another problem, which is discussed in the following sections of this paper, is energy consumption of FCSD systems concerning reliability and latency performance. For optimization problems, a Proximal Jacobi alternating direction method of multipliers is given to increase the speed of the process, and simulation results are presented for comparison in [11].

Another study [32] particularly focuses on the energy consumption problem of swarming UAVs by analyzing various properties such as idle probabilities and collisions. They have proposed a residual energy-aware online random-access scheme and show how much outperforms conventional approaches. In contrast, the study by [33] utilized collaborative computation offloading by proposing a federated learning-based method unlike [11] and stated that their methods come up with improvements of 23% in energy consumption and 15% in latency over other methods available in the literature.

Adaptive data processing and dissemination for UAV swarms is another issue that takes a wide place in literature. A holistic solution named ADDSEN for this problem is introduced in [22]. ADDSEN applies online learning technologies to achieve an adaptive balance between the rate of transmission and the rate of knowledge loss periodically (see Figure 4). This rate is used for some energy allocation and storage problems. The mentioned technique also discusses the results for both single and multiple UAV schemes. Since large-scale swarming UAV networks have numerous vehicles, clustering techniques are also applied for these scenarios. The study by [42] proposed a uniform clustering method to minimize communication latency by considering the number of cluster heads and the number of UAVs. Authors in [43] focused on clustering in swarming UAVs for IoT applications by proposing a hybrid self-organized clustering scheme. Their cluster head determination approach is based on glowworm swarm optimization, unlike the method [42] utilizes. Swarming UAVs obviously presents many open interdisciplinary problems.

2) GROUND WIRELESS SENSOR NETWORK (WSN)

The aerial sensor network is a living ecosystem that consists of dispersed data sources and UAV nodes that gather and transmit information to one another. UAVs make use of a variety of sensors to acquire environmental variables such as temperature and air pressure as they traverse their surroundings. A wide variety of UAVs can be outfitted with specialized

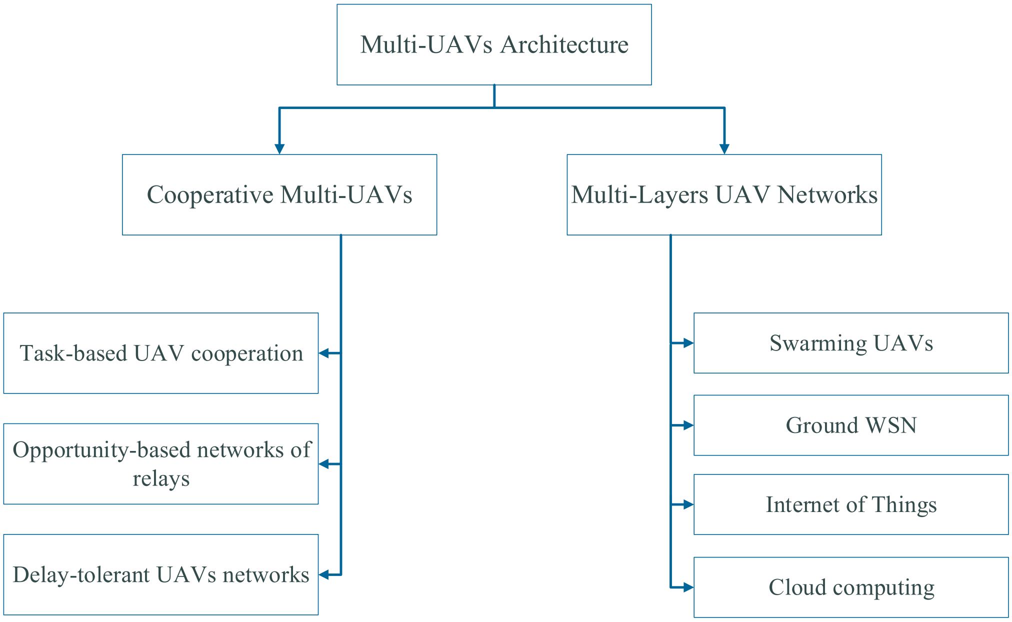

FIGURE 2. Multi-UAV architecture categorization.

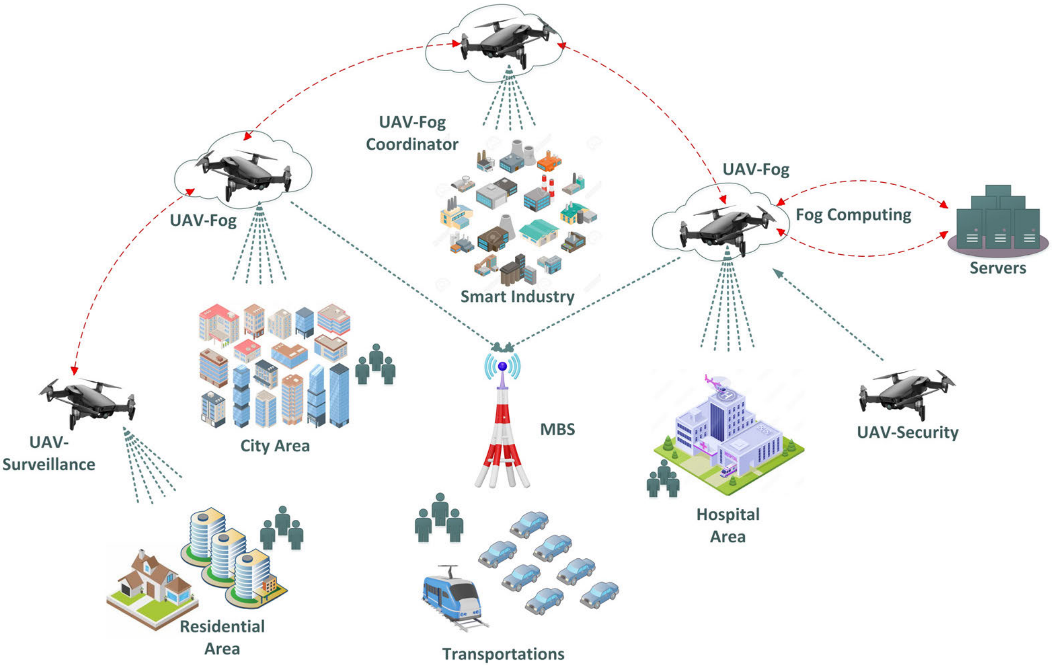

FIGURE 3. Swarming UAVs fog computing architecture.

sensors, such as infrared or high-resolution cameras, to fulfill a variety of sensing requirements. Additionally, a comprehensive sensing network calls for both aerial and ground sensors, which results in a two-layer structure: UAV layer, which incorporates the aerial sensing layer, and the ground WSN. This technique, which consists of several layers, guarantees thorough data collection and analysis for a variety of activities and applications.

Authors in [44] presented a conceptual framework that addresses the utilization of heterogeneous UAVs for ~~the purpose of~~ fire detection. The framework incorporates infrared sensors and data fusion techniques by acquiring data from computer-aided modules. The framework being proposed aims to achieve the localization of fire detection by utilizing the positional data of UAVs and the localization information of cameras. In their study, the authors presented

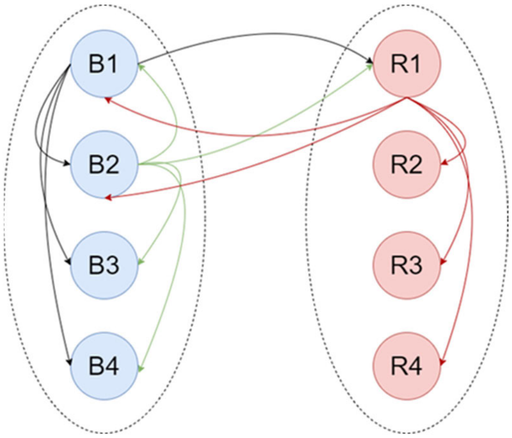

FIGURE 4. Multiple UAVs' data dissemination.

a WSN algorithm for efficient data collection. The proposed algorithm utilizes a fleet of UAVs organized into groups. This approach aims to enhance the overall performance of data collection in WSNs. The algorithm was discussed in detail in [45]. The communication architecture is exclusively dependent on ad-hoc UAVs, sensors, and the ground station. A distributed algorithm was proposed by researchers in order to effectively manage the cyclic examination of a collection of points of interest. The algorithm under consideration incorporates the various distributed data sources and potential reinforcements. The authors conducted a study in [46] that focused on opportunistic routing (OR) in WSNs assisted by UAVs. Additionally, two novel OR protocols were introduced. The first protocol is the adaptive neighbors opportunistic routing protocol, which enables a source node to distribute its traffic to neighboring nodes within its communication range. The second protocol, known as Highest Velocity Opportunistic Routing (HVOR), involves the transmission of packets from the source node to a single UAV that possesses the highest speed. Hence, the HVOR algorithm dynamically determines an optimal route and identifies the sensor node that will serve as the forwarder.

3) INTERNET OF THINGS (IOT)

UAVs have the potential to fulfill a significant role within IoT framework and can provide numerous value-added services in the realm of IoT. IoT provides the underlying infrastructure and connectivity that enables Internet of drones/UAVs UAVs (IoD) to function effectively. IoT networks, communication protocols, and cloud platforms facilitate communication between UAVs and other devices or systems. This connectivity is essential for IoD applications. The key security, privacy, and communication requirements are discussed, and a taxonomy of IoD is presented in [47] based on the most pertinent considerations.

UAVs have the capability to offer wireless access to IoT devices when terrestrial networks are unavailable, while also supporting various IoT applications like cargo transportation, video surveillance and pesticide spraying. Nevertheless, the intricate, dynamic, and heterogeneous nature of UAV-assisted IoT networks has led to a heightened interest in the utilization of AI-based techniques for the optimization, scheduling, and orchestration of such networks [48]. The structure of layers, in fact, offers services for various UAV applications, including but not limited to surveillance, search and rescue, among others. The authors carried out a study in [49] to examine the effectiveness of deploying and mobilizing UAVs for the purpose of gathering data from IoT devices located on the ground. The framework optimizes the placement and mobility of three-dimensional (3D) UAVs and facilitates dependable uplink transmissions for IoT devices by minimizing the total transmit power.

4) CLOUD COMPUTING

UAVs have limited processing and storage capacity, which precludes the performance of intense computation while in flight. The usage of cloud computing for data storage and processing can help mitigate this shortcoming. In [50], the authors provided an extensive examination of optimization techniques for radio resource management, mobile edge computing (MEC), fog, encompassing cloud and cloudlet solutions tailored for UAVs. Additionally, it delves into the mathematical modeling of objectives and constraints and offers insights into the challenges associated with the utilization of these computing paradigms. In [51], the authors introduced a cloud-based UAV management system called UAV map Planner that allows users to access UAVs via online services, plan out missions, and guarantee cooperation among UAVs. To mediate communications between UAVs and humans, a cloud-based proxy server is built. The MAVLink protocol is the foundation for the connection between the UAVs, the users, and the cloud.

D. COOPERATIVE MULTI-UAVS

The Cooperative Multi-UAVs architecture is employed in mission scenarios that entail the utilization of multiple UAVs possessing distinct communication characteristics. The architecture of Cooperative Multi-UAVs encompasses the integration of cooperative UAVs for task accomplishment, the utilization of opportunistic relaying networks, and the establishment of delay-tolerant UAV networks.

1) TASK-BASED UAVS COOPERATION

A cooperative network can be defined as a specialized graph wherein each node operates in accordance with the role assigned to another node. The task accomplishment of cooperative UAVs involves the execution of intricate tasks through coordinated operability. A cooperative UAVs network can exhibit either static or dynamic characteristics. In the context of a static network, the functionalities are predetermined or pre-established. In contrast, within the dynamic network, the behavior of nodes is uncertain, and the topology of the network may undergo changes, thereby impacting its overall performance.

The research in [52] dedicated to the development of a multi-UAV flight strategy aimed at enhancing cooperative search capabilities within a dynamic communication environment marked by uncertainty. Concretely, a novel cooperative framework tailored for a localized communication network is formulated to govern the positioning of multiple UAVs during the search operation. Moreover, local communication networks are established by considering the spatial distribution of UAVs, effectively fulfilling the demands of the search task.

2) OPPORTUNITY-BASED RELAYING NETWORKS

UAV networks exhibit a notable prevalence of link failures, necessitating the implementation of opportunistic relaying techniques. This enables an improved utilization of network parameters and resources. The impact of employing UAVs for purely opportunistic relay purposes in cooperative awareness applications within vehicular networks is examined in [53]. It is not required that UAVs alter their trajectory or speed for opportunistic relaying, ensuring minimal interference with the execution of their primary missions. In [54], the authors introduced a novel algorithm based on multi-agent DRL. It includes the design of UAV trajectories to serve mobile ground users while maintaining network connectivity, the proper allocation of frequency resources among UAVs to mitigate interference, and the selection of suitable next-hop UAVs for each data packet to minimize transmission time and reduce the probability of network congestion.

3) DELAY-TOLERANT UAVS NETWORKS

Delay-tolerant UAV networks exhibit a notable feature of limited connectivity, necessitating the adoption of a store-and-forward mechanism for the routing protocol due to the intermittent availability of links. These networks encounter comparable challenges to conventional networks.

The authors in [55] employed UAVs as delay-tolerant network relays in order to facilitate communication among the ground nodes. Every UAV remains stationary above its designated home-ground node until it receives a signal prompting it to initiate the transmission of messages to other ground nodes. The system employs a genetic algorithm to ascertain the optimal route for maximizing the efficiency of deliveries. The authors in [56] examined a network of UAVs that are capable of tolerating delays. The researchers employed a spray and wait methodology for the purpose of path selection and management. The presence of end-to-end connectivity issues, continuous link fractures, and high latency results in an increase in overheads during path selection. The suggested methodology exhibits suboptimal performance.

IV. UAV APPLICATIONS AND CATEGORIZATIONS

UAVs and terrestrial BSs (TBSs) each have unique roles in wireless communication networks. UAVs are mobile and rapidly deployable, ideal for immediate coverage or areas lacking terrestrial infrastructure. However, they face limitations like flight time and payload. In contrast, TBSs offer reliable, cost-effective, and long-term network support, covering larger areas and handling higher capacity. The choice depends on specific use cases and deployment needs. Table 3 highlights the key differences between UAV BSs and TBSs. UAVs have emerged as a groundbreaking technology with diverse applications across various domains. This section delves into the extensive range of applications and categorizations of UAV networks. By exploring the main functionalities of UAVs and their specific use cases, an in-depth understanding of the potential impact and opportunities they offer in different sectors is provided. The section categorizes UAV networks based on their applications, including surveillance and monitoring, communication relay, IoT support, and swarm intelligence.

TABLE 3. UAVs vs. TBSs.

Aspect	UAV BS	TBS
Deployment Flexibility	Rapid and flexible deployment	Fixed and time-consuming
Flight Time	Limited by battery/fuel capacity	Continuous operation
Line-of-Sight Requirements	Require clear line of sight	Less affected by obstacles
Mobility	High mobility and dynamic positioning	Stationary and fixed location
Payload Capacity	Limited due to weight constraints	Larger capacity for equipment
Reliability and Stability	Prone to disruptions and interference	More stable and reliable
Safety Concerns	Safety and airspace conflicts	Fewer safety concerns
Coverage Range	Adaptable coverage range	Fixed coverage area
Connectivity in Emergencies	Vital for emergency communications	Susceptible to infrastructure damage
Signal Interference	Potentially lower interference	Higher interference
Cost	Potentially lower deployment costs	Higher initial investment and maintenance
Capacity and Throughput	Scalable capacity and throughput	Limited scalability and throughput
Regulatory Considerations	Airspace regulations and safety compliance	Local regulations and zoning permits
Energy Efficiency	Variable energy efficiency	Stable energy consumption

A. UAV APPLICATIONS USING 5G

1) 5G-AND-BEYOND UAV BS

The incorporation of UAVs as flying BSs represents a notable progression in the domain of 5G and subsequent generations of communication networks. The utilization of ABSs presents distinct benefits, leading to transformative advancements in diverse applications and augmenting connectivity in demanding settings. This section examines the significant significance of UAVs as ABSs and investigates their various applications, highlighting their potential in influencing the future of communication.

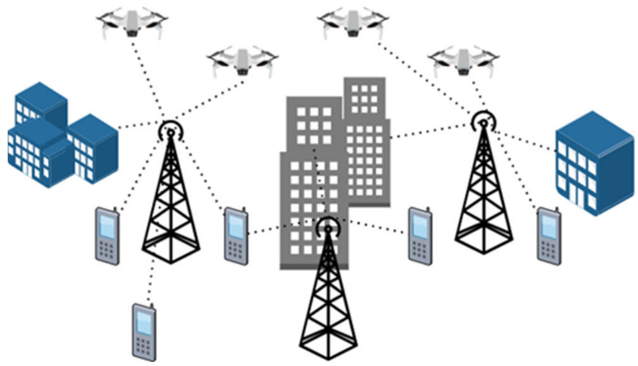

FIGURE 5. **Cellular network for 5G-and-beyond.**

2) ENHANCING BEYOND 5G'S COVERAGE AND CAPACITY

In the realm of 5G-and-beyond wireless communication networks, the escalating demand for enhanced capacity and ubiquitous coverage has propelled UAVs into the spotlight. This heightened attention stems from their remarkable qualities, which surpass the capabilities of traditional BSs and relays [57]. Consequently, the current cellular wireless networks have experienced significant strain in terms of their capacity and coverage, resulting in the birth of numerous wireless technologies aimed at addressing this issue. The mentioned technologies, including D2D communications, ultra dense tiny cell networks, and mmWave communications, have been widely recognized as the focal point of future beyond 5G wireless networks [58]. Nevertheless, although their immense advantages, these solutions possess inherent restrictions. One example of a requirement for D2D communication in cellular networks is the need for improved frequency planning and resource utilization. Figure 5 illustrates UAVs assistance that utilizes for 5G cellular network and beyond. In the realm of extremely dense small cell networks, numerous issues arise pertaining to backhaul, interference, and the comprehensive modeling of the network as a whole. In a similar vein, mmWave communication encounters limitations due to blockage and a heavy need of line-of-sight (LoS) connection in order to successfully fulfill the potential of providing high-speed, low latency communications. The aforementioned issues will be amplified in scenarios involving UAV and unmanned aerial systems (UASs). Also, UAVs equipped with high-definition cameras were being used for surveillance and monitoring purposes in various industries, including public safety, agriculture, and infrastructure inspection. These UAVs could capture and transmit high-quality video feeds in real-time, providing valuable data for decision-making. In [59], the authors constructed a simulation-level model of a 6G system, and conducted a case study to examine the application of high-definition video monitoring, utilizing the principles of UAV-swarm-based surveillance.

The integration of UAVs as flying BSs is anticipated to be an essential addition to the diverse 5G landscape. This integration holds the potential to address certain obstacles associated with current technology. The utilization of low altitude platform UAVs presents a viable and economically efficient strategy for delivering wireless connection to regions that possess inadequate cellular infrastructure.

Furthermore, the utilization of UAV BSs shows potential in situations, where deploying tiny cells only to cater to brief events, such as sports events and festivals, is not economically feasible due to the limited duration of wireless connection required for these events [60]. In contrast, high altitude platform UAVs have the potential to offer a viable and enduring resolution for addressing coverage concerns in rural settings.

Furthermore, the utilization of UAVs for mmWave communications is a promising application wherein UAVs can establish LoS communication linkages with users. Consequently, this can serve as an appealing approach to offer wireless transmission with a large capacity, capitalizing on the benefits of both UAVs and mmWave communications. Additionally, the integration of UAVs with mmWave technology, together with the potential utilization of large MIMO techniques, has the potential to establish a novel and dynamic airborne cellular network. This network can effectively deliver high-capacity wireless services, provided that it is meticulously planned and controlled.

UAVs have the capability to provide support to several terrestrial networks, including D2D and vehicle networks. For example, because of their ability to move easily and utilize LoS communication, UAVs have the capacity to expedite the distribution of information among equipment on the ground. In addition, the utilization of UAVs has the potential to enhance the dependability of wireless connections in D2D and vehicle-to-vehicle (V2V) communications by leveraging transmit diversity. Flying UAVs have the potential to assist in the dissemination of general information to ground devices, hence mitigating interference in ground networks through a reduction in the frequency of communications between equipment.

In addition, UAV BSs have the capability to employ air-to-air (A2A) connections in order to provide service to other cellular-connected UAV- UEs, thereby reducing the burden on the terrestrial network. Numerous investigations have been conducted pertaining to the utilization of UAVs in the context of 5G wireless communication technology. For instance, authors in [61] addressed radio resource slicing in 5G uplink radio access networks. The radio resource slicing problem has been investigated by using UAV cells to minimize the consumption of uplink resources. They claimed that their method improves performance in terms of network coverage, costs, and resource utilization. The study undertaken by [62] deals with the uplink issue in 5G networks from the perspective of mitigating UAVs' interference and inter-cell interference. The resource allocation scheme, so-called reverse frequency allocation, has been utilized to mitigate the aforementioned interferences. A study focusing on the placement of UAVs in 5G networks by considering factors such as latency, throughput, and data rate is introduced by [63]. Several approaches have been investigated and compared using methods such as simulated annealing and genetic algorithms and have been aimed to provide efficient data for service providers. Another study focusing on UAV placements is presented by [64]. While [63] focuses more on applications during an emergency, this study focuses on logistics applications. They propose a new algorithm that maximizes network capacity by optimizing the placement of UAVs.

3) UAVS AS PLATFORMS FOR PUBLIC SAFETY

Disasters caused by nature, including floods, hurricanes, tornadoes, and heavy snowstorms, frequently result in catastrophic outcomes. During natural catastrophes, it is common for cellular BSs and ground communications infrastructure to be susceptible to compromise. In situations of this nature, there exists a crucial requirement for the establishment of public safety communication channels between first responders and individuals in distress, with the primary objective of facilitating search and rescue endeavors. Therefore, it is imperative to implement a resilient, expeditious, and proficient emergency communication system in order to facilitate efficient communication amid public safety endeavors. In the context of public safety scenarios, the implementation of a dependable communication system is not only vital in enhancing connection, but also in potentially mitigating loss of life. Efficiently assessing disaster situations poses a formidable challenge for public safety organizations. In such scenarios, where extensive radio coverage of the affected area is paramount, UAVs emerge as the most fitting solution [65].

The utilization of UAV-based aerial networks as depicted in Figure 6 holds significant potential in facilitating rapid, adaptable, and dependable wireless communication in public safety contexts. UAVs, due to their lack of reliance on costly and restrictive infrastructure such as cables, possess the ability to effortlessly navigate and adapt their positions. This attribute enables them to promptly deliver communication services to individuals on the ground during emergency scenarios. In fact, the distinctive attributes of UAVs, including their mobility, flexible installation, and instant reconfiguration enable them to efficiently build on-demand public safety communication networks.

For example, UAVs can be utilized as mobile ABSs to provide broadband connection to regions that have experienced disruptions in their terrestrial wireless infrastructure. In addition, UAVs have the capability to maintain a continuous state of motion, enabling them to effectively traverse an entire designated region in the shortest feasible amount of time. Hence, the utilization of UAV-mounted BSs presents a viable approach to ensure rapid and pervasive connection in public safety situations.

4) MMWAVE COMMUNICATIONS WITH 3D MIMO

UAV operating in the mmWave spectrum represent an exciting frontier in wireless communication technology. However, UAV mmWave communication presents several significant challenges that need to be addressed for successful implementation and reliable operation [66], [67]. On the other hand, UAVs equipped with mmWave communication systems offer impressive data rates and low latency, making them well-suited for various high-bandwidth applications. The mmWave signals are highly directional and require a clear LoS path between the UAV and the ground station or another UAV for effective communication. Obstructions like buildings, trees, and even minor terrain variations can disrupt LoS connections, limiting the coverage area and reliability. It is challenging to obtain LoS with UAVs is accurate and can be attributed to several factors: propagation characteristics, propagation loss, mobility challenges, weather, and environmental factors. Despite these challenges, mmWave frequencies are still attractive for UAV communication in certain scenarios. They offer high bandwidths and data rates, which are essential for applications like high-definition video streaming, real-time surveillance, and UAV swarming.

FIGURE 6. UAV application in emergency situations.

In [68], the authors focused on optimizing the 3D placement and orientation of UAVs to ensure LoS coverage for users while maximizing the SNR between UAV-user pairs. In another work presented in [69], the researchers studied how LoS blockage probability affects the connectivity of UAVs in terrestrial urban deployments of mmWave NR systems and its implications for communication reliability and performance. UAVs also facilitate the utilization of mmWave communications, capitalizing on LoS links with terrestrial users and mitigating signal attenuation at elevated frequencies. The utilization of diminutive antennas on UAVs enables the implementation of sophisticated MIMO techniques, including massive MIMO, for mmWave communications. Moreover, the utilization of several UAVs might facilitate the establishment of adaptable antenna arrays in the atmosphere, hence augmenting the overall efficacy of communication systems [70]. The densely congested sub-6 GHz frequency range falls short of fulfilling the demands for ultra-high data traffic. Exploring the mmWave frequency bands emerges as a prospective avenue for UAV communications, as they allow for the deployment of sizable antenna arrays in a compact space on the UAV, enabling three-dimensional (3D) beamforming capabilities [11].

In recent times, there has been an increasing level of attention towards the concept of 3D MIMO technology, which involves the utilization of both vertical and horizontal dimensions inside terrestrial cellular networks [71]. The utilization of 3D beamforming facilitates the concurrent generation of distinct beams within 3D spatial domain, thereby mitigating inter-cell interference and facilitating the accommodation of a larger user population. UAV-based flying BSs possess the advantageous ability to effectively discern ground users situated at varying heights due to their elevated altitude. Consequently, they are highly suitable for accommodating 3D MIMO scenarios characterized by a substantial density of users.

In addition, the utilization of UAV-based wireless antenna arrays presents distinct possibilities for airborne beamforming. The array comprises individual units, each representing a single-antenna UAV. This design enables the array to have the flexibility to modify the spacing between its elements and provide effective mechanical beam-steering in any 3D direction. The flexibility and mobility exhibited by UAVs facilitate the provision of effective services to terrestrial customers in both downlink and uplink situations.

5) ENHANCING IOT CONNECTIVITY WITH UAVS

The rapid progress of wireless networking technologies has led to the emergence of a significant IoT ecosystem, encompassing a diverse range of devices. To unlock the full potential of IoT applications, including the management of smart city infrastructure, healthcare systems, transportation networks, and energy management, it becomes crucial to establish efficient wireless communication for a vast multitude of IoT devices [72]. The immense scale of IoT presents distinctive obstacles that necessitate a reconsideration of traditional wireless networks, such as cellular systems. In the context of IoT environments, certain key criteria assume vital importance, namely energy efficiency, ultra-low latency, dependability, and high-speed uplink communications. Furthermore, the deployment of IoT devices in regions with insufficient terrestrial wireless infrastructure presents significant connectivity obstacles. In [73], the authors delve into the concept of smart cities that harness innovative technologies such as the IoT and UAVs to improve the residents' quality of life. Mobile UAVs offer a potential option to effectively tackle the issues faced by IoT networks. UAVs have the capability to function as airborne BSs, effectively catering to IoT focused situations by delivering dependable and energy-efficient uplink IoT communications. Through the utilization of their aerial characteristics and elevated positioning, UAVs possess the capability to alleviate the negative impacts of shadowing and obstruction. This, in turn, enhances the communication channel between IoT devices and UAVs. Consequently, IoT devices that are constrained by battery capacity necessitate reduced transmit power in order to establish connections with UAVs, thereby prolonging their battery longevity.

Furthermore, UAVs have the capability to adaptively adjust their positions in response to the activation patterns of IoT devices. This feature enables UAVs to effectively support large-scale IoT systems, eliminating the necessity for significant development of terrestrial small cell BSs. The utilization of UAVs can greatly boost the connection and energy efficiency of IoT networks by leveraging their distinct attributes, including mobility, agility, and aerial deployment. UAVs present a viable solution for addressing the communication obstacles encountered in the IoT domain, hence enabling the successful implementation of a wide range of IoT applications.

The implementation of caching mechanisms at small base stations (SBSs) holds significant potential in improving user throughput and minimizing transmission delay. Nevertheless, static ground BSs may have difficulties in catering to mobile customers who frequently undergo handovers, as the desired content may not be accessible at the next BS. To tackle this issue, the utilization of UAVs as airborne BSs equipped with dynamic caching functionalities is suggested. This approach aims to effectively monitor user mobility patterns and facilitate the delivery of necessary content.

6) ENHANCING WIRELESS NETWORKS WITH CACHE-ENABLED UAVS

Integrating caching mechanisms within SBSs represents a promising avenue for enhancing user throughput and reducing transmission latency. Numerous caching models, initially deployed at different types of BSs and mobile devices, have been thoroughly investigated and are now being extended to aerial deployment through UAVs. This adaptation addresses the unique challenges posed by 6G networks [19].

Static ground BSs may have difficulties in catering to mobile customers who frequently undergo handovers, as the desired content may not be accessible at the next BS. In order to tackle this issue, the utilization of UAVs as airborne BSs equipped with dynamic caching functionalities is suggested. This approach aims to effectively monitor user mobility patterns and facilitate the delivery of necessary content. In [74], the authors examined the coverage performance analysis of a cellular network assisted by cache-enabled UAV-BS by developing analytical models to explore both the network's overall coverage probability and the average achievable rate of cellular users.

Cache-enabled UAVs present a viable approach to alleviate traffic congestion in wireless networks. By utilizing user-centric data such as the distribution of content requests and patterns of movement, UAVs can be strategically deployed in order to efficiently cater to the needs of users [75]. In contrast to static BSs, the utilization of UAVs in caching operations results in a reduction in complexity. This is due to the UAVs' ability to monitor and analyze user mobility patterns, hence obviating the necessity for supplementary caching at ground-based stations. The utilization of a central cloud processor involves the integration of user-centric information, which is derived from past user data, in order to effectively oversee the deployment of UAVs and ascertain the most advantageous places and mobility patterns. This minimizes the additional computational burden associated with updating the content stored in the cache. Cache-enabled UAVs employ predictive algorithms to anticipate user mobility patterns and content request information, thereby decreasing the need for regular updates of content requests across various locations. By using the caching capabilities of mobile UAVs, efficient service delivery to consumers on the ground is facilitated.

B. RADIO-BASED SENSING

To fully integrate UAVs into 5G-and-beyond networks, it is crucial to ensure high-performance wireless communications and effective sensing capabilities. Currently, commercial UAVs are fitted with a range of embedded sensors, including the inertial measurement unit, accelerometers, tilt sensors, and current sensors. The sensors offer instantaneous data for ensuring the secure operation of UAVs. This includes providing estimations of the UAV's location and orientation, maintaining the desired flight route, and managing power consumption. Nevertheless, as UAVs are increasingly included into terrestrial communication networks in extensive implementations, depending simply on the sensors implanted inside the UAVs will become insufficient. In order to get the highest level of sensing performance, it is imperative to employ a synergistic approach that combines both sensing capabilities inherent inside UAVs and sensing infrastructure. This integrated strategy offers better reaction time, sensing range, coverage, dependability, precision, and efficiency.

As depicted in Figure 7, the use of radio-based sensing in UAVs may be categorized into two primary frameworks, specifically sensing conducted by UAVs and UAVs employed for sensing purposes. In the aforementioned scenario, sensing technologies are employed to facilitate the secure operation of UAVs and to monitor and manage air traffic in low-altitude airspace. In contrast, the paradigm of utilizing UAVs for sensing involves the deployment of specialized UAVs as airborne platforms to offer sensing assistance from an aerial perspective.

1) SENSING FOR UAV

Sensing for UAVs involves two typical use case scenarios: sense-and-avoid (SAA) and UAV detection, tracking, and classification. SAA is essential for safe UAV flying, especially for autonomous or semi-autonomous UAVs [76]. UAVs use sensor data to prevent collisions and obstacles without pilots. Due to radio propagation delays and ground pilot response times, SAA is necessary for real-time remote-controlled UAVs. Ground-based SAA is an alternative to on-board sensors for fast reactions in dynamic settings. UAV-enabled spraying requires sensing for constant-altitude maintenance to ensure consistent spraying even in difficult terrain [77]. Vision- or light-based sensing makes many commercial UAVs with SAA capabilities vulnerable in adverse conditions. Another notable application for UAV sensing involves the identification, monitoring, and categorization of potentially unlawful and perilous UAVs. UAVs have the potential to be utilized in a manner that compromises public safety and infringes upon individuals' privacy. The mitigation of non-cooperative or deceptive UAVs necessitates the utilization of passive radar sensing techniques that rely on the analysis of echoed or dispersed signals [78], [79]. The domain under consideration presents several challenges, one of which pertains to the limited radar cross-section exhibited by UAVs. This characteristic poses difficulties in their identification, as it becomes arduous to differentiate them from stationary clutter or other airborne entities like avian species.

Current research endeavors have been primarily directed towards the exploration of radar sensing techniques in the context of UAV networks. The exploration of methods for the detection, tracking, and interception of non-professional UAVs has been conducted in [80]. An exhaustive survey on security and privacy issues of UAV was presented in [81], with a comprehensive examination of UAV security issues conducted at four distinct levels: the software-level, the hardware-level, the sensor, and the communication-level.

2) UAV FOR SENSING

One potential and interesting approach in the field of UAV sensing is the utilization of UAVs as aerial nodes to offer wireless sensing capabilities from an aerial perspective. This approach, commonly referred to as UAV for sensing, holds significant potential. When comparing UAV-based sensing to conventional ground sensing, it becomes evident that the former offers numerous advantages. Initially, it is important to acknowledge that UAV-based sensing exhibits some advantages due to its increased height and less signal blockage. Consequently, UAV-based sensing generally offers a broader field of vision in comparison to ground sensors. Moreover, the exceptional level of control over the three-dimensional movement of UAVs enables the flexible deployment of UAV sensors in challenging and inaccessible environments, including regions that are toxic or pose significant risks. In addition, the increased maneuverability of UAVs presents a novel opportunity for enhancing sensing performance through the optimization of 3D sensor trajectories. The aforementioned feature holds significant appeal in the context of target tracking, as it allows for the dynamic adjustment of UAV placements in order to optimize target tracking capabilities. Hence, the utilization of UAV for sensing purposes exhibits a diverse array of prospective applications, including but not limited to law enforcement, precision agriculture, 3D environmental mapping, search and rescue operations, and military endeavors.

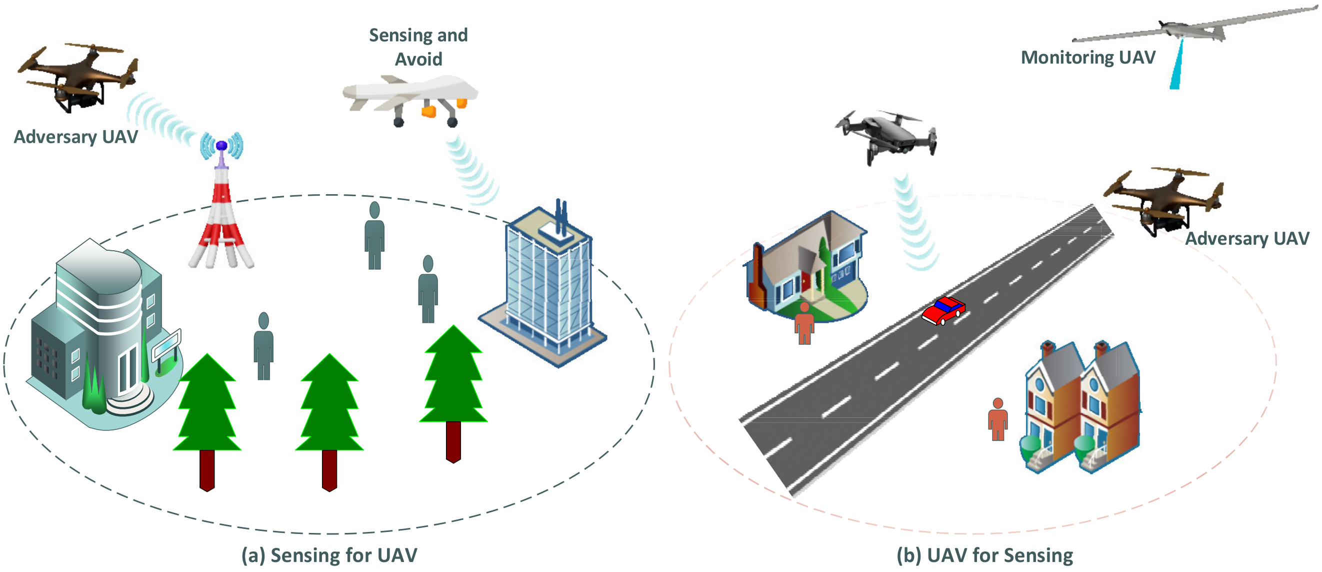

FIGURE 7. **Models of sensing in UAV networks: (a) sensing for UAV and (b) UAV for sensing.**

UAV-based sensing has gained increasing attention due to its numerous advantages. Notable applications of UAV-based sensor platforms have been outlined in [77], including experiments with an imaging radar. The use of UAVs for remote sensing in field-based crop phenotyping was surveyed in [82].

In [83], the authors explored UAV-aided air quality sensing. Furthermore, [84] introduced a dynamic and reconfigurable aerial radar network composed of UAVs to detect and track unauthorized/malicious UAVs. The study demonstrated that optimizing UAV trajectories offers additional degrees of freedom, leading to improved tracking performance compared to conventional terrestrial radar networks with fixed deployment.

C. CELLULAR-CONNECTED UAVS

The utilization of cellular-connected UAVs has emerged as a possible avenue for expanding cellular networks, as UAVs can function as both aerial UE and ABSs. The utilization of UAVs in these specific functions offers distinct possibilities for augmenting network coverage, capacity, and the availability of services. Nevertheless, additional research is necessary to address the technological obstacles associated with handover management, channel characterization, and interference reduction in order to achieve seamless integration of UAVs into the current cellular infrastructure. Ongoing research and development efforts in this particular domain have the potential to bring about a significant transformation in communication networks and effectively handle connectivity requirements across diverse situations through the utilization of cellular-connected UAVs.

Studies on the use of UAVs in cellular networks have recently gained momentum. Integration into current applications brings the problems related to the feasibility of UAVs to discussion and paves the way for new research areas. Authors in [85] pointed out flying at different altitudes and having different operating bands as one of these new feasibility problems. For examining the effects of these factors, they used experimental measurements made in the field and discussed the positive and negative aspects of UAV use in 4G and future 5G applications. They emphasized that carried out measurements show the need for further improvements in cellular-connected UAVs. The same problem was discussed for a carrier frequency of 1800 MHz and 2100 MHz, and various altitudes from 15 m to 100 m by the same authors in [86]. As a result of these trials, they also addressed the importance of other factors such as antenna tilting and 3D coverage models. A study focusses on the performance of different antenna deployments for cellular-connected UAV scenarios can be found in [87]. Another study that considers three-dimensional mobility and LoS channel properties for cellular-connected UAVs is presented by [88]. They defined the essential challenges for them and introduced the key performance indicators with analytical models by considering several performance outputs. Finally, ML solution was proposed for the optimization problem that they constituted. A network planning approach that comprises both UAV users and UAV BSs in a three-dimensional medium was introduced by [36]. They claimed that their approach reduces the average latency by 46% compared with the conventional signal-to-interference-plus-noise ratio-based cell association. The proposed approach also provides an improvement in spectral efficiency.

The present study investigates the potential utilization of UAVs as aerial UE and ABSs inside cellular networks. Specifically, the focus is on exploring the integration of cellular connectivity in UAVs, thereby enabling them to function as mobile devices and serve as communication hubs in the sky.

1) UAVS AS AERIAL USER EQUIPMENT

UAVs have recently been developed as a distinct type of aerial UE within the context of cellular networks. UAVs serve as airborne UE, functioning as communication devices with the ability to establish cellular connectivity. The introduction of this technology presents numerous benefits, including improved mobility and the capacity to utilize cellular services in geographically distant or temporarily disconnected regions. UAVs serve as airborne UE, facilitating real-time communication for diverse purposes such as aerial surveillance, disaster response, and environmental monitoring. Nonetheless, the incorporation of UAVs into cellular networks gives rise to various technical obstacles, including the need for effective management of handovers, accurate characterization of aerial channels, cyber-physical threats, energy consumption, and authentication purposes, and the potential influence of UAV mobility on the overall performance of the network. In order to tackle these complex issues, the academic community is actively engaged in the development of computational and algorithmic solutions to these issues.

The influence of the implementation of aerial UEs on the overall network efficiency was analyzed by the authors in [24]. The simulation findings indicate that the substitution of a ground user with UAV operating at an altitude of 100 meters resulted in a tenfold reduction in throughput. Additionally, the coverage was reduced from 76% to 30%.

Hence, in order to facilitate a satisfactory integration of UAVs into cellular networks, the authors in [24] developed a method that aims to achieve optimal tilting of the directional antennas in UAV UEs, thereby enabling their operation at elevated altitudes. The simulation findings indicate a significant improvement in coverage, with an increase from 23% to 89%. Additionally, the throughput has also shown a notable enhancement, rising from 3.5 b/s/Hz to 5.8 b/s/Hz. The suggested technique exhibits advantages in sparse and moderately dense cellular networks, while presenting disadvantages in highly dense cellular networks.

The ideal inter-cell interference coordination technique and air-ground performance trade-off were examined by the authors in [89]. The researchers achieved the highest possible weighted sum-rate for both the ground users and the UAV by collectively optimizing the uplink cell connections and power allocations across various resource blocks. The researchers put up a centralized strategy for coordinating inter-cell interference in order to achieve an optimal solution at the local level. Additionally, they offered a decentralized scheme wherein the cellular BSs are divided into clusters, allowing for data exchange solely between the cluster-head and the UAV.

2) UAVS AS ABS

There has been an increasing interest in the utilization of UAVs as ABSs within cellular networks in recent times. UAVs function as ABSs, operating as mobile communication nodes that can be strategically positioned to optimize network coverage and capacity. ABS technology presents a novel approach to enhancing cellular connectivity in regions with inadequate infrastructure or on occasions necessitating temporary network reinforcement. The utilization of UAVs in aerial deployment facilitates enhanced LoS circumstances, resulting in a reduction of signal blockage and shadowing effects. This, in turn, can contribute to an enhancement in communication performance. Nevertheless, it is imperative to tackle certain obstacles in order to fully capitalize on the capabilities of UAVs as ABSs. These problems encompass the efficient placement of UAVs, seamless coordination with pre-existing TBSs, power usage, and effective management of potential interference.

The authors in [90] introduced a PLS technique designed to enhance the security of wireless access provided by numerous UAV-BSs to ground UEs. The researchers examined a cohort of individuals who engage in eavesdropping activities with the intention of disrupting the transmission of data from UAV-BSs to the ground UEs. The developed technique aims to achieve maximum secrecy rate by simultaneously optimizing the transmit beamforming and the power consumption of the UAV. The difficulty of enhancing network performance and coverage in the deployment of UAV-BSs was addressed by the authors in [91]. In order to address these concerns, the researchers have developed a proposal for the deployment of UAV-BSs using a UAV-artificial bee colony method. The algorithm that has been proposed has the capability to ascertain the most suitable flying location for each UAV-BS in order to achieve the highest possible network throughput. The simulation findings demonstrate that the suggested mechanism exhibits superior performance compared to some bio-inspired algorithms in terms of enhancing network throughput and improving the coverage rate of UE.

D. UAV-BASED FLYING AD-HOC NETWORKS

The idea of flying ad-hoc networks has become increasingly significant in the context of 5G and subsequent generations of wireless communication technology. Flying ad-hoc networks (FANETs) are a notable application of UAVs, wherein numerous UAVs establish communication linkages in an ad-hoc fashion () [92], [93]. FANETs play vital roles in a wide range of applications, such as traffic monitoring, remote sensing, border surveillance, disaster management, agricultural management, wildfire management, and relay networks [94]. FANETs play a significant role in establishing dependable communication connections between far transmitters and receivers that encounter barriers or considerable spatial separation, hence enabling uninterrupted connectivity in demanding settings.

The utilization of many small UAVs in FANETs offers several advantages. In contrast to single UAV operations, the utilization of FANETs comprising several tiny UAVs has some noteworthy advantages [95].

- **Scalability:** FANETs demonstrate notable scalability, facilitating the seamless enlargement of their operating coverage through the integration of additional UAVs and the implementation of efficient dynamic routing strategies. The scalability of the network enables it to effectively serve a wider geographical area and accommodate increased communication requirements.

- **Cost Efficiency:** The cost associated with deploying and maintaining small UAVs is relatively lower as compared to larger UAVs that are equipped with intricate gear and substantial payloads. The cost-effectiveness of small UAVs enables the efficient extension and operation of networks at a reduced cost.
- **Enhanced Survivability:** One of the advantages of FANETs is the improved ability to sustain operations in challenging conditions or in the event of a UAV malfunction. In such situations, the missions can go seamlessly by employing the remaining operating UAVs. The improved ability to survive in challenging conditions guarantees the uninterrupted execution of missions and the resilience of the network, a quality that is lacking in individual UAV systems.

E. SATELLITE NETWORKS WITH UAVS

Satellite networks have been utilized for several decades to offer a range of services, encompassing Earth observation, remote sensing, and satellite communication. The conventional architecture of satellite systems, though widely used, has certain limitations in terms of cost, reconfigurability, and real-time data provision. The incorporation of UAVs into satellite networks offers a potential resolution to these obstacles. UAVs have the capability to serve as aerial platforms for the deployment and maintenance of satellite payloads. This utilization of UAVs results in reduced costs associated with satellite launches and improved reconfigurability of satellite constellations. UAVs have the potential to function as relays or data collection nodes for satellites, thereby enhancing the data gathering and distribution capabilities of satellite systems [96].

In this particular context, the authors in [97] developed an idea regarding the utilization of UAVs and satellites as a means to facilitate the integration of a substantial quantity of IoT solutions within the 5G framework. The proposed methodology utilizes satellites as intermediary nodes, UAVs as 5G-UE, and the 5G-gNB is placed on the Earth's surface. The suggested methodology enables a solution of challenges associated with terrestrial infrastructure, such as the increased concentration of IoT devices and limited coverage areas.

The study conducted by researchers [98] examined a cooperative network consisting of many antennas, UAVs, and satellites, with the aim of offering uninterrupted access to consumers. UAVs are employed as aerial relays to facilitate the transmission of signals between satellites and many ground users. This communication process is facilitated through the implementation of an amplify-and-forward protocol. The researchers derived the expression for the maximum SNR output of the suggested architecture using an opportunistic user scheduling methodology. The expression for the outage probability of the proposed design was derived based on the SNR expression. The equation for outage probability is utilized in the context of high SNR to ascertain the coding gain and diversity order of the examined design.

The authors in reference [99] have presented a safe technique for relaying UAVs in a hybrid network consisting of both terrestrial and satellite components, while considering the potential threat of an eavesdropper. Three UAV Relay Selection (URS) approaches were investigated, which were based on the Closest (CURS), Maximum (MURS), or Uniform (UURS) SNR. Subsequently, an assessment was conducted to determine the effects of different tactics on the hybrid network, specifically in relation to the risk of secrecy outage. The simulation findings indicate that the secrecy performance of MURS is superior, whereas the secrecy performance of UURS is comparatively inferior. Additionally, the CURS and UURS techniques do not improve the secrecy diversity order.

F. OTHER POTENTIAL UAV APPLICATIONS

1) SURVEILLANCE AND MONITORING

UAVs assume a paramount role in various surveillance and monitoring applications, rendering valuable contributions across diverse domains [100]. In border and coastal surveillance, UAVs provide an indispensable tool for real-time monitoring of vast and challenging terrains, bolstering border security and maritime operations. Equipped with advanced imaging and sensing technologies, UAVs offer an unmatched perspective, enabling researchers and conservationists to conduct wildlife studies, assess environmental changes, and monitor protected areas with heightened accuracy. This capability proves invaluable in preserving biodiversity and facilitating effective environmental conservation efforts.

Additionally, UAVs herald a transformative shift in infrastructure inspection and maintenance practices. By reducing the need for labor-intensive manual inspections, UAVs optimize resource utilization and operational efficiency. With their ability to capture high-resolution imagery and conduct aerial surveys, UAVs empower engineers and infrastructure managers to perform detailed assessments of structures, utilities, and assets. This enhanced data collection allows for proactive identification of potential issues, leading to timely maintenance and cost-effective asset management. The integration of UAVs in surveillance and monitoring operations epitomizes their potential to revolutionize critical sectors, bolstering safety, efficiency, and precision in safeguarding environments, structures, and resources [71].

2) COMMUNICATION RELAY

UAVs play an indispensable role as communication relays, particularly in the face of natural disasters and emergencies. When terrestrial communication infrastructure is compromised or rendered inaccessible, UAVs swiftly step in to restore critical connectivity [101]. In disaster-stricken areas, where communication lines may be disrupted, UAVs serve as lifelines, relaying essential information and facilitating timely rescue and relief efforts. These aerial relays bridge the communication gap, enabling affected communities to connect with emergency responders and access vital resources.

Beyond disaster scenarios, UAVs extend communication services to remote and underserved regions, overcoming geographical barriers that hinder conventional connectivity. In remote and challenging terrains, where establishing and maintaining terrestrial communication networks is impractical, UAVs serve as the much-needed link, empowering communities with access to information, education, and essential services. This role is particularly significant in remote rural areas and isolated communities, where connectivity fosters socio-economic development and empowers individuals with knowledge and resources [102].

Moreover, UAVs prove instrumental in industrial settings where communication infrastructure may be limited or non-existent. In remote industrial operations such as mining, oil and gas exploration, or infrastructure development, UAVs act as communication relays, enabling real-time data transfer and coordination among workers and management. This enhances operational efficiency, safety, and remote monitoring capabilities, optimizing industrial processes and minimizing downtime. In emergency response scenarios, such as search and rescue missions or medical aid delivery, UAVs serve as vital communication relays, facilitating seamless coordination between on-ground teams and command centers.

3) INTERNET OF THINGS (IOT) SUPPORT

UAVs play a crucial function in facilitating the IoT by offering a wide array of applications. UAVs serve as data collection nodes, functioning as aerial sensors to acquire significant data from distant and demanding locations, catering to a range of IoT applications. In the field of precision agriculture, UAVs that are equipped with specialized sensors play a crucial role in assisting farmers with the monitoring of crops, analysis of soil conditions, and optimization of agricultural techniques [48]. These technological advancements aim to improve productivity and optimize resource management in the agricultural sector. Moreover, UAVs that are equipped with environmental sensors play a significant role in the implementation of smart city applications. These UAVs are capable of monitoring various environmental parameters such as air quality and noise levels [103]. The data collected by these sensors is crucial for urban planning and the efficient management of cities. The capabilities of UAVs that support the IoT demonstrate their considerable capacity to transform data collection and improve decision-making in several fields.

4) SWARM INTELLIGENCE

The concept of swarm intelligence has revolutionized the capabilities of UAV networks, propelling them towards unprecedented levels of efficiency, adaptability, and collaborative potential. Within the realm of UAV swarms, several key aspects stand out, showcasing their transformative impact on various applications, ~~thus~~ including [104]:

- **Collaborative Sensing and Mapping:** UAV swarms demonstrate exceptional prowess in data collection and mapping tasks. By working together cohesively, these swarms enable collaborative sensing, efficiently covering vast areas and generating accurate 3D maps. This capability finds valuable application in diverse fields, including land surveying, environmental monitoring, and disaster assessment. Case studies exemplify the swarms' efficiency in mapping and monitoring large-scale environments, revealing their potential in expediting data acquisition and enhancing situational awareness in critical scenarios as in [105].
- **Distributed Task Execution:** A defining strength of UAV swarms lies in their ability to efficiently distribute tasks among individual UAVs. In search and rescue operations, disaster response, and emergency medical support, the coordination and resource allocation of UAV swarms lead to heightened efficiency and rapid response times. By dividing complex tasks into smaller sub-tasks, UAV swarms leverage their collective intelligence, accomplishing missions that would be arduous or impractical for a single UAV [106].
- **Adaptive and Resilient Networks:** Swarm intelligence empowers UAV networks with a remarkable degree of adaptability and resilience. In dynamic and unpredictable environments, such as disaster-stricken areas or regions with limited communication infrastructure, UAV swarms demonstrate their capacity to swiftly reroute communication paths, ensuring the establishment of robust and reliable communication links. This adaptability enables UAV swarms to maintain seamless connectivity in the face of challenges, further enhancing their suitability for critical operations. Case studies exemplify the effectiveness of UAV swarm networks in maintaining communication under challenging conditions, solidifying their position as a reliable communication backbone in adverse scenarios as in [107].

The integration of swarm intelligence in UAV networks has unlocked new frontiers of efficiency and cooperation. UAV swarms exemplify a synergy of collective intelligence, enabling collaborative data sensing, agile task execution, and adaptive networking. Their capacity to tackle complex challenges, provide comprehensive coverage, and respond rapidly to dynamic situations positions UAV swarms as a formidable force across a wide spectrum of applications. As research and development in swarm intelligence advance, UAV networks are poised to redefine the boundaries of aerial capabilities, opening up new possibilities in fields ranging from disaster response and environmental monitoring to infrastructure maintenance and beyond.

V. EXPLORING EMERGING TECHNOLOGIES

UAVs have emerged as versatile platforms with vast potential in the field of wireless communication. Over the years, significant advancements in communication technologies have been leveraged to enhance UAV capabilities, enabling them to play critical roles in various applications. In this section, the recent technological breakthroughs that have revolutionized UAV communications are explored. These advancements focus on supporting enhanced mobile broadband (eMBB) services and enabling seamless communication for massive machine-type communication (mMTC). Specific topics such as massive MIMO (M-MIMO) and mmWave technologies, intelligent reflecting surfaces (IRS), non-orthogonal multiple access (NOMA), energy harvesting, energy-efficient designs, and the integration of artificial intelligence (AI) will be delved into. Through an in-depth analysis of these cutting-edge technologies, the aim is to understand their implications, benefits, and challenges for UAV communications. This knowledge will equip with the tools needed to develop efficient and robust communication systems for UAVs, leading toward a future where UAVs are seamlessly integrated into daily life, industries are transformed, and wireless communication is revolutionized.

A. M-MIMO AND mmWave

M-MIMO is a crucial technology in the current 5G standard, showing promise for supporting cellular-connected UAV communications [108], [109]. Large arrays at ground-based BSs enable fine-grained 3D beamforming, reducing interference between high-altitude UAVs and low-altitude terrestrial users, resulting in higher network throughput. However, accurate channel state information at ground BSs is essential for effective M-MIMO beamforming, presenting challenges with cellular-connected UAVs. UAVs introduce complexities to the M-MIMO system. Their strong LoS channels cause severe pilot contamination across ground BSs, not resolved by conventional decontamination techniques for terrestrial users. Efficient beam tracking is challenging due to UAVs' high mobility in 3D space, leading to excessive pilot overhead [110]. The application of hybrid beamforming-based M-MIMO in practical scenarios can facilitate the coordination of UAV groups or swarms. However, this approach introduces additional challenges related to pilot contamination and beam tracking [111]. Leveraging LoS-dominant air-ground channels, it offers more degrees of freedom for macro diversity. However, challenges remain, including efficient power control, low-complexity fronthaul/backhaul provisioning, and network scalability for UAV swarms [112].

Further, an alternative approach to support rate-demanding eMBB services in 3D space involves utilizing the abundant spectrum available in the mmWave bands [91]. Although mmWave communications have inherent limitations like signal attenuation and vulnerability to blockage, UAV mobility can mitigate these challenges. UAVs, whether acting as aerial platforms or users, can adjust their trajectories intelligently to reduce propagation loss by moving towards ground nodes and bypass obstacles to increase LoS paths. However, like M-MIMO, mmWave communication requires a large number of antennas, and the high UAV mobility and shorter wavelength signals lead to fast channel variations. As a result, effective dynamic beam training and tracking techniques become crucial. Existing works propose the use of movement prediction filters, like Kalman filters, to track time-varying UAV-ground channels [113]. Future research should also address low-complexity spectrum management [114] and high-speed, reliable backhaul design as important topics in this domain.

B. INTELLIGENT REFLECTING SURFACE (IRS)

Although M-MIMO and mmWave communications provide potential benefits, their actual application is hindered by difficulties such as high complexity, hardware expense, and higher energy consumption [115]. IRS have recently emerged as a viable and economically efficient approach to improve received power and mitigate A2G interference in three-dimensional space [116]. IRS is composed of passive reflecting elements, each possessing a configurable reflection coefficient. This characteristic allows for intelligent coordination of reflections, facilitating the reconfiguration of the wireless channel. The integration of desired signals and interference cancellation in a coherent manner leads to a substantial increase in communication throughput, without the need for additional active BSs or. relays. In addition, it should be noted that IRSs possess practical advantages such as their lightweight nature, which enables convenient deployment on walls or high-speed moving vehicles, hence facilitating a wide range of applications [117]. IRS serves as a revolutionary technology that effectively converts the radio environment into an intelligent one, hence yielding significant advantages for various industries such as transportation, manufacturing, and smart cities. The use of IRS has garnered attention as a prospective technology for the development of 6G networks.

Extensive research has been conducted on IRS in several system configurations, as seen by studies referenced in sources [118], [119]. The device has the capability to be installed on land in order to facilitate communications for UAVs (see Figure 8), or it can be affixed to UAVs for communications on the ground, as depicted in Figure 9 [120]. Table 4 presents a comprehensive overview and comparative analysis of prior research efforts pertaining to the domains of IRS and UAV.

C. NON-ORTHOGONAL MULTIPLE ACCESS (NOMA)

NOMA has garnered significant attention for its application in supporting machine-type devices (MTD). NOMA allows multiple devices to share the same time-frequency resources simultaneously using power domain multiplexing. This technology is particularly beneficial for the massive connectivity requirements of the IoT and machine-type communications (mMTC), as it efficiently manages resources, increases capacity, and lowers latency. UAVs can leverage NOMA to connect and manage a large number of machine-type devices

TABLE 4. Comparison of current studies on IRS and UAV.

IRS Use Case	No. of IRS	Design Objective	Approach	Ref.
Terrestrial IRS	Single	Maximizing the rate	successive convex approximation (SCA)	[123]
	Single	Power reduction	successive convex approximation, and Lagrange duality	[124]
	Multiple	Achieve maximum weighted rate	Reinforcement Learning	[125]
	Multiple	Enhance received power	successive convex approximation	[126]
	Multiple	Minimizing BER	Penalty based algorithm	[127]
UAV-IRS	Single	Maximum SNR with the lowest possible	Two-step method	[122]
	Single	Maximizing the rate	Reinforcement learning	[128]
	Single	Optimizing energy efficiency security	SCA	[129]
	Single	Maximizing energy efficiency	Fractional programming	[130]

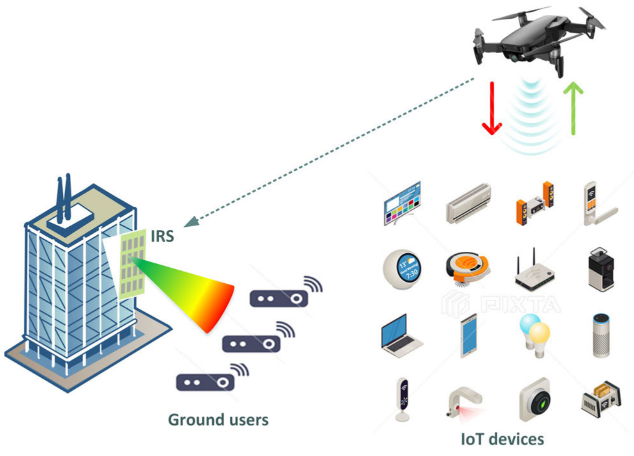

FIGURE 8. IRS optimized UAV communications.

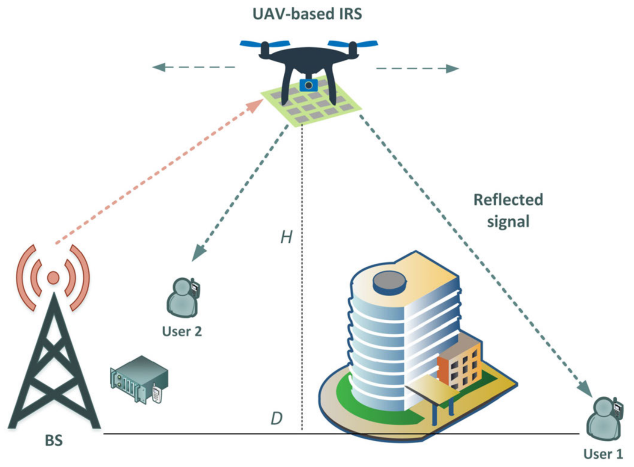

FIGURE 9. Improving terrestrial communications using UAV-IRS.

efficiently, making it ideal for applications such as remote sensing, environmental monitoring, and automated surveillance [129]. NOMA employs the utilization of superposition coding at the transmitters and successive interference cancellation at the receivers in order to attain effective access and partially alleviate co-channel interference. Research has demonstrated that NOMA has notable efficacy in scenarios when consumers encounter significantly disparate channel circumstances [130].

1) ADVANCING CELLULAR-CONNECTED UAVS WITH NOMA

NOMA confers pragmatic merits within cellular networks hosting both coexisting UAV and ground users. It facilitates the reutilization of resource blocks by UAVs, concurrently accommodating a greater number of aerial users, particularly in densely populated scenarios, in contrast to the non-scalable orthogonal multiple access (OMA). The inclusion of LoS links engenders A2G communications of heightened reliability, surpassing that of non-LoS terrestrial channels. The robust LoS air-ground pathways also empower UAVs to be concurrently visible to multiple ground BSs, thereby attaining an elevated macro-diversity advantage for user affiliation. Nevertheless, the deployment of NOMA within such air-ground contexts presents its own set of challenges. Uplink transmissions from UAVs have the potential to notably impair signals from ground users across several ground BSs, thereby constraining the performance gain of NOMA over OMA, particularly in scenarios marked by unfavorable channel conditions emanating from individual BSs. A resolution to this conundrum materialized in the form of a decode-and-forward (DF)-oriented collaborative NOMA strategy, which harnessed interference cancellation mechanisms among neighboring BSs interconnected by backhaul links [131]. This particular strategy attains amplified data rates compared to OMA and non-collaborative methodologies, a distinction that becomes more pronounced during congested ground traffic circumstances. Further refinements were introduced through a quantize-and-forward-oriented cooperative interference cancellation schema [132], wherein proximate BSs quantize received UAV signals sans decoding them.

In the downlink phase, UAV receivers confront robust co-channel interference stemming from multiple ground BSs. The conventional methods of interference alleviation utilized in the uplink are inapplicable due to the transformation of UAVs' roles from sources of interference to recipients. An applicable strategy is cooperative beamforming, where non-serving BSs collaborate in transmission to enhance the received power at UAVs and surmount co-channel interference. Nevertheless, its efficacy wanes with the escalation of ground user density, thereby circumscribing the pool of available BSs for cooperative beamforming endeavors. To surmount this predicament, a novel cooperative beamforming schema integrating interference transmission and cancellation (ITC) was introduced in [133]. This schema involves the forwarding of signals from terrestrial users who share the same resource block as the UAV to the BSs catering to the UAV. Subsequently, these signals, alongside the UAV's signals, are dispatched through cooperative beamforming. This results in the augmentation of desired signal potency at the UAV's receiver, concurrently quelling terrestrial interference sans exerting any influence on existing transmissions. While the centralized implementation of this approach involves extensive backhaul transmissions among different BSs, a distributed algorithm based on the concept of divide-and-conquer was conducted in [133]. The distributed design requires only local information exchange among BSs, reducing implementation complexity and signaling overhead. Research results show that the distributed design significantly improves UAV performance compared to conventional schemes without ITC, particularly in high-density terrestrial user scenarios [133]. However, supporting massive UAVs or UAV swarms remains a challenging problem that requires further exploration [134].

2) NOMA WITH UAV

UAVs, operating as BSs, can efficiently exploit the varying channel conditions of different ground devices in order to maximize the potential performance advantages offered by NOMA. In a previous study, researchers in [135] examined the utilization of UAVs for NOMA transmissions involving two stationary ground users. The capacity region was determined by simultaneously optimizing the trajectory of the UAV and the allocation of transmit power/rate over time, taking into account practical limitations such as the maximum speed and transmit power of UAVs. The findings indicate that NOMA exhibits superior performance compared to OMA, which includes time division multiple access (TDMA) and frequency division multiple access (FDMA). Additionally, the capacity advantage of NOMA over OMA diminishes as the maximum speed and/or flight duration of UAVs increase. The comparison between two-user NOMA and OMA for UAV-assisted communication was expanded to include other design objectives, such as sum-rate [136] and outage probability. The study examined a Rician air-ground channel conducted in [137], where a UAV followed a circular trajectory at a constant speed. The goal was to reduce the probability of outages, and criteria for the superiority of NOMA over TDMA were established using channel and UAV trajectory parameters.

In the context of a multi-user environment, it is imperative to establish appropriate user pairing and allocate bandwidth effectively in order to fully exploit the capabilities of NOMA. Reference [138], the UAV paired with one user in close proximity (cell-centered) and one user at a greater distance (cell-edge). Subsequently, the problem of multi-user rate max-min optimization was formulated by simultaneously optimizing the allocation of bandwidth, power, UAV height, and antenna beamwidth. In subsequent literature, the application of NOMA was further expanded to encompass networks with multiple antennas and numerous UAVs. For instance, the study conducted in [139] focused on the downlink transmission from a multi-antenna UAV to many clusters of ground users. The researchers generated analytical formulas for both the outage probability and the ergodic rate. The exploration of several UAVs in a large-scale cellular network was further expanded upon in [140]. In the study [141], the utilization of the user angle was employed as a means of feedback information for mmWave NOMA communications. In circumstances involving multi-antenna transmission, angle information has been demonstrated to possess great potential in enhancing the separation NOMA users in the power domain, as compared to the typical limited feedback system that relies solely on distances of users. The study conducted in [142] focused on the resource allocation problem inside a multi-UAV aided IoT NOMA uplink transmission system. The objective was to optimize the channel assignment, uplink transmit power, and flying heights of UAVs in order to maximize the system capacity.

D. ENERGY EFFICIENCY WITH INNOVATIVE DESIGNS

Energy harvesting and energy-efficient designs play a vital role in supporting machine-type devices onboard UAVs. Machine-type devices, which are often resource-constrained and battery-powered, require efficient energy management for extended operation. UAVs can integrate energy harvesting techniques, such as solar cells or kinetic energy harvesting, to recharge or supplement the power of connected devices. Additionally, employing energy-efficient communication protocols and hardware design minimizes power consumption, prolonging the battery life of machine-type devices. These advancements enable UAVs to effectively manage energy resources and ensure the sustained operation of connected devices for prolonged missions.

UAVs offer a promising solution to overcome these constraints. In the initial study [143], focused on examining a novel UAV-enabled wireless power transfer system, in which a UAV-mounted energy transmitter is utilized to wirelessly charge distributed energy receivers situated on the ground. Specifically, we delve into a fundamental scenario involving two users and explore how the UAV can best utilize its mobility through trajectory planning to maximize the energy transferred to both energy receivers within a defined charging timeframe. In [144], the authors introduced a novel wireless power transfer system, facilitated by an UAV equipped with a mobile energy transmitter. The system involves dispatching the UAV to provide wireless energy to a group of energy receivers situated at predetermined ground locations. The research examines the optimal utilization of UAV mobility through trajectory planning to maximize the energy delivered to all energy receivers (ERs) within a finite charging duration.

An UAV-enabled wireless power transfer network is investigated in [145], in which a UAV operates at a consistent altitude in the sky to deliver wireless energy to a linearly arranged set of ground nodes. The primary aim is to enhance the minimum received energy for all ground nodes by optimizing the UAV's one-dimensional path while adhering to the maximum UAV flying speed limitation.

To illustrate, the pursuit of system energy amplification was explored in [146], while [147] delved into the maximization of max-min throughput. Broadening the scope, [148] extended the optimization endeavors to encompass a two-user interference channel housing two UAVs. Venturing into advanced methodologies, [149] introduced multi-agent deep reinforcement learning as a means to grapple with the overarching max-min optimization quandary inherent in multi-UAV-enabled WPCNs. More recently, the concept of UAV-empowered simultaneous wireless information and power transfer (SWIPT) has been introduced, wherein the UAV undertakes the role of an aerial BS for the dual transmission of information and energy to terrestrial recipients [150], [151]. The sphere of optimization inquiries has embraced factors such as UAV trajectory, transmission power, and the power splitting ratios of users. These considerations are geared towards the maximization of achievable rates within the confines of energy harvesting constraints. Furthermore, within the purview of IoT applications pertinent to emergency communications, [151] furnishes an encompassing overview of UAV-facilitated SWIPT.

E. ARTIFICIAL INTELLIGENCE INTEGRATION IN UAV

The integration of AI in UAV communication systems has shown remarkable potential for enhancing efficiency and intelligence. AI techniques, such as ML and deep reinforcement learning, can be leveraged to optimize UAV trajectory planning, resource allocation, and signal processing. These approaches enable UAVs to dynamically adjust communication parameters for optimal network performance and sensing services. Enormous recent surveys papers have been published that mainly focused on AI/ML.

Several surveys discussed UAV communications with ML e.g., [152], [153], and [154]. The survey in [155] explored the training of ML models across a collection of geographically dispersed clusters of resource-limited devices using swarms of UAV. In [156], the survey offered a current and extensive overview of ML techniques applied in UAV operations and communications while identifying areas of potential expansion and research voids. A few general surveys discussed ML techniques for UAV trajectory in terms of optimization [157], planning [158].

In UAV-aided communication scenarios, AI-driven beamforming and power control can optimize flight paths in real-time based on wind patterns, detect and avoid obstacles, manage battery usage, while intelligent spectrum management can mitigate interference and improve overall system performance. Additionally, AI-based algorithms can enhance UAV sensing capabilities for applications such as target tracking, environmental monitoring, and disaster response. The synergy of AI and UAV technologies opens up new horizons for advanced communication and sensing services.

The integration of AI is a pivotal element in the development of forthcoming cellular networks, playing a significant role in the achievement of network intelligence [159]. The integration of AI technology has given rise to two significant paradigms in the field of wireless communications: AI-empowered wireless communications [160] and edge intelligence [161]. AI and ML techniques are utilized in the former to optimize wireless systems and improve communication performance. This departure from conventional model-driven approaches emphasized the use of data-driven mathematical techniques. In the aforementioned framework, the integration of AI and MEC capabilities occurs within BSs and access points located at the network edge [162]. This integration facilitates the deployment of intelligent applications that demand significant communication and computation resources, including autonomous driving and industrial automation [161]. Edge intelligence provides a reduction in end-to-end latency and a decrease in traffic loads to the core network when compared to traditional cloud and on-device intelligence methods.

In addition to the aforementioned paradigms, AI is poised to play a crucial role in the realm of 5G and future UAV communication networks, offering two pivotal features. AI and ML emerge as viable computational tools to address intricate challenges in highly dynamic UAV-enabled 3D networks. These methodologies present a promising alternative to conventional model-driven optimization approaches, particularly in scenarios where obtaining precise network state information proves challenging. A notable problem that benefits from these techniques is the joint optimization of UAV trajectory and communication design. The integration of UAVs into edge intelligence not only enables the development of innovative applications, such as UAV virtual reality and UAV swarms, but also introduces novel complexities in efficiently managing computationally demanding and time-sensitive AI tasks from an aerial perspective. This situation necessitates the collaborative development of mobility and trajectory control for UAVs, alongside the allocation of communication and compute resources. However, this task presents significant challenges due to the dual roles that UAVs can assume, acting as either aerial users or aerial edge servers, or even adopting both roles simultaneously. The concurrent management of these functionalities requires careful consideration and effective resource allocation strategies to ensure seamless integration and optimal performance within UAV communication networks. In this subsection, the examination begins with ML techniques utilized for the design of UAV trajectories and communications. Subsequently, the design of computation offloading for UAVs integrated with MEC is delved into. Lastly, the concept of distributed edge ML involving UAVs is presented.

1) OPTIMIZING UAV TRAJECTORY USING ML

The optimization of both UAV movements and communication utilization of resources is of utmost importance in order to achieve optimal performance in 5G and future UAV communication networks. Conventional offline methodologies that rely on model-driven optimization presuppose complete or partial knowledge of network state information. However, these approaches may not be well-suited for dynamic environments characterized by fluctuating traffic demands, user mobility, and complicated channel propagation caused by UAVs. In order to solve this, academics are now adopting ML techniques and data-driven methodologies.

ML can be categorized into three main types: supervised learning, unsupervised learning, and reinforcement learning (RL). RL holds considerable promise in the realm of designing coordinated movement and communication strategies for UAVs. RL facilitates the swift adaptation of UAV communication networks to dynamic environments by improving various aspects such as UAV actions (e.g., deployment, trajectory, and resource allocations) and reward functions (e.g., communication rate). Two study areas have used RL to optimize UAV operations in the literature: cellular-connected UAVs [163] and UAV-assisted communication networks [164], where UAVs act as BSs and users, respectively.

In [165], the authors proposed a deep reinforcement learning (DRL) approach for optimizing the trajectories of UAVs in the context of ultra-dense small cell networks. The premise involves UAVs equipped with sensing radios to acquire distance data pertaining to the UE and other UAVs within the network, which is subsequently employed to adjust the trajectories of the UAVs. However, the complex path planning challenge for each UAV remains a persistent issue. An optimal operational strategy is introduced in [166] by utilizing multi-agent RL to address these challenges. Multiple parameters, including the quantity of deployed UAVs, initial charging capacity, and charging completion capacity, define a multi-UAV system. In [167], the authors presented a multi-agent deep Q-network scheme, where the UAVs operate as agents, independently performing actions based on their observations while sharing a common reward. Additionally, a multi-agent meta-RL algorithm is introduced for rapid adaptation to new tasks to address tasks with limited prior experience.

The authors in [168] introduced utilization of an UAV-enabled relaying system in emergency communications based on RL methods. The primary objective is to maximize the aggregate data transmission from the users to the BS, achieved through the optimization of user communication scheduling, user association, power allocation, and UAV trajectory.

The localization of ground users through the utilization of UAVs as aerial anchors is investigated in [169]. It introduced an innovative localization framework that incorporates FL and RL. This framework involves multiple UAVs learning trajectories within diverse environmental settings, resulting in faster convergence of the RL model and reduced localization errors.

The researcher in [170] presented beamforming control and trajectory design algorithm based on as multi-pass deep Q-network. In this algorithm, the UAV serves as an agent responsible for periodically observing the state of the UAV multicast network and taking actions to adapt to the dynamic environment.

A novel DRL technique named pointer network-A* designed in [171] to efficiently learn a UAV trajectory policy that minimizes energy consumption. The parameters of pointer network-A* are trained using small-scale cluster problem instances, aiming for quicker training through an unsupervised approach with the actor-critic algorithm. In [41], the authors presented a new scheme for joint trajectory and communication scheduling in wireless caching networks, involving multiple UAVs. To simplify the solution on each UAV, a model-specific deep neural network (DNN) is introduced to learn the optimal control solution in real-time. The DNN is designed in accordance with the structural properties of the value function and stationary distribution, based on the analysis of the homotopy perturbation method.

2) COMPUTATION OFFLOADING FOR UAV-ENABLED EDGE INTELLIGENCE

Edge intelligence applications that involve the integration of UAVs and AI rely on the generation and processing of vast volumes of data at distributed edge devices. These devices encompass not only UAVs but also conventional smart sensors and smartphones. The seamless execution of sophisticated AI training and inference algorithms is essential to derive meaningful insights and enable intelligent decision-making processes. However, the implementation of these AI tasks is often computationally demanding and data-intensive, surpassing the computational capacities of the local wireless devices themselves. To address this challenge, computation task offloading emerges as an appealing solution. It allows UAV edge servers to offload their resource-intensive AI tasks to MEC servers equipped with high computation capabilities. Once offloaded, the MEC servers process the tasks and transmit the computation results back to the UAV edge servers for further analysis or action. This approach optimizes the utilization of computational resources and ensures efficient AI execution while minimizing the computational burden on the UAVs [172].

Figure 10(a) illustrates a typical scenario where a UAV serves as either an aerial user or an edge device within cellular networks. In such cases, the UAV may possess computation tasks that can be efficiently executed through offloading to ground-based BSs. This strategy enables effective collaboration between UAVs and BSs to handle sophisticated AI tasks, enhancing the overall network performance. Moreover, UAVs have the potential to carry MEC servers themselves, extending their support to on-ground devices' AI implementations. Figure 10(b) demonstrates how UAVs can aid widely distributed devices on the ground during computationally intensive AI tasks, particularly in urgent situations, such as emergency response scenarios. The UAV's mobility and proximity to the devices enable rapid deployment of computational resources and seamless offloading of AI tasks, contributing to timely and intelligent decision-making processes. Under both scenarios, the joint design of UAV trajectory, communication, and computation becomes paramount. The proper coordination of these aspects ensures efficient and effective task offloading, enabling edge intelligence applications to function seamlessly in real-world environments. In this line of research, AI tasks are typically modeled as general computation tasks with specific data and computation requirements, facilitating the integration of AI capabilities within UAV-enabled communication networks and MEC environments. This integration promises to unlock novel opportunities for improving network intelligence, enhancing communication performance, and enabling intelligent applications with extensive communication and computation requirements.

3) UAV-DRIVEN FEDERATED EDGE LEARNING

Aside from the process of diverting computations to a central MEC server, edge devices such as UAVs have the potential to participate in cooperative AI tasks, capitalizing on their locally dispersed data and computational proficiencies. This methodology, recognized as distributed edge learning, encompasses the concept of federated edge learning, which confers benefits in terms of data security and privacy [161]. Within the realm of federated edge learning, an assemblage of edge devices, encompassing UAVs, collaboratively employ their dispersed data to facilitate the training of shared AI models without necessitating data exchange. The edge server in this context can take the form of a terrestrial-based BS in instances involving cellular-connected UAVs, or another UAV within UAV swarms, as portrayed in Figure 11(a) and Figure 11(b). The iterative execution of federated edge learning encompasses UAVs revising their local AI models during each iteration and subsequently consolidating these updates at the edge server to refine global AI models. This undertaking demands recurrent interchange of AI model parameters between UAVs and the edge server, thereby necessitating meticulous optimization of multiple UAV trajectories, communication strategies, and computation scheduling over temporal intervals, attributing to the 3D mobility of the UAVs. Despite the escalating interest in federated edge learning within the realms of wireless communications and ML communities, research pertaining to the integration of UAVs in edge learning is still in its nascent stages. Several studies have investigated the potential of federated learning applications within UAV wireless communication networks [173]. The allocation of wireless resources to ensure the efficiency of UAV-enabled federated edge learning was the subject of examination in [174]. Moreover, inquiries have delved into the realm of federated learning for UAV swarms as documented in [175]. Furthermore, proposals have been put forth wherein UAVs undertake the role of edge servers in the context of federated learning, as presented in [176], including considerations for support within the Internet of vehicles framework as explored in [177]. Nonetheless, a comprehensive exploration into the fundamental performance thresholds of federated learning when integrated with mobile UAV nodes remains largely uncharted.

In [178], the authors introduced a federated learning framework for UAV swarms, incorporating MEC where model aggregation is shifted to edge servers. In this framework, the overall federated learning cost is characterized as a weighted combination of the total delay incurred by UAV swarms to complete the federated learning task and the energy consumption of the system. To facilitate dynamic and intelligent UAV services, a centralized dynamic service algorithm called deep deterministic policy gradient based centralized has been introduced in [179], relying on deep reinforcement learning. Nonetheless, considering the training complexities associated with the centralized approach, a more favourable distributed learning algorithm, federated learning-based federated, has been proposed, which integrates federated learning methods.

A cognitive network of UAVs has been introduced in [180], with the primary objective of providing dependable edge computing services to IoT devices within a specified area. To minimize latency for IoT devices, a partial federated learning model has been devised and implemented on UAVs. A critical challenge arises from handling the non-independent and non-identically distributed nature of heterogeneous data while ensuring learning convergence. To effectively tackle this issue, a novel and high-performance federated learning scheme, referred to as the hierarchical federated learning algorithm, is introduced in [181] for the edge-assisted UAV network. This approach leverages edge servers positioned in BSs as intermediate aggregators, incorporating commonly shared data to address the challenge effectively.

The effectiveness of global federated learning models may be hampered by the significant heterogeneity of local data, potentially hindering the training process, and undermining the performance of local agents. To overcome these challenges, a novel approach is introduced in [182], referred to as personalized federated DRL (PF-DRL), designed for multi-UAV trajectory optimization. PF-DRL seeks to create personalized models for each agent, effectively addressing data scarcity concerns and alleviating the adverse effects of data heterogeneity.

F. SYMBIOTIC RADIO COMMUNICATION AND SENSING

Active radio technology, depending on the design of transmitters that consist of highly power-consuming elements such as oscillators, up-converters, and other components, has a

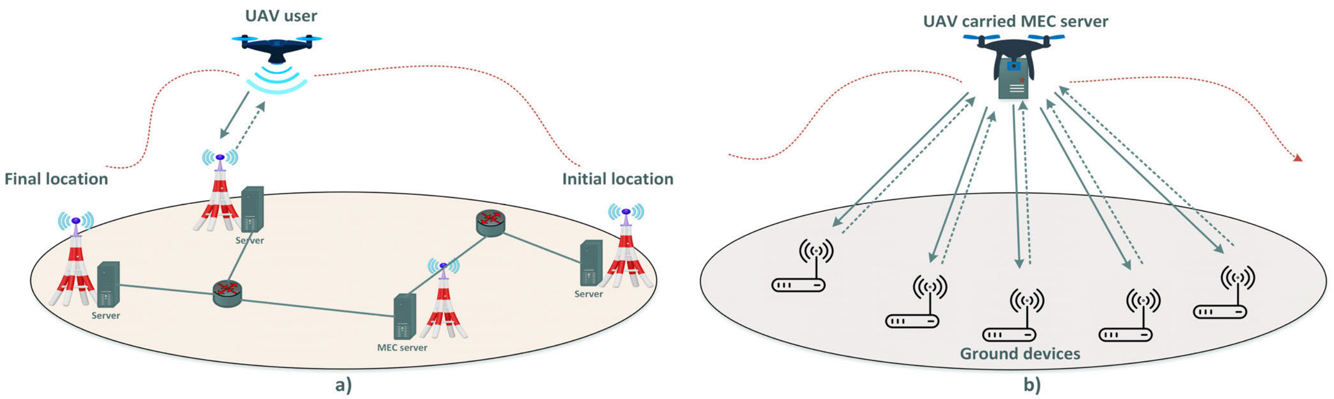

FIGURE 10. Computation offloading utilizing UAVs: (a) UAV Connected to cellular network; (b) UAV-Enhanced MEC System.

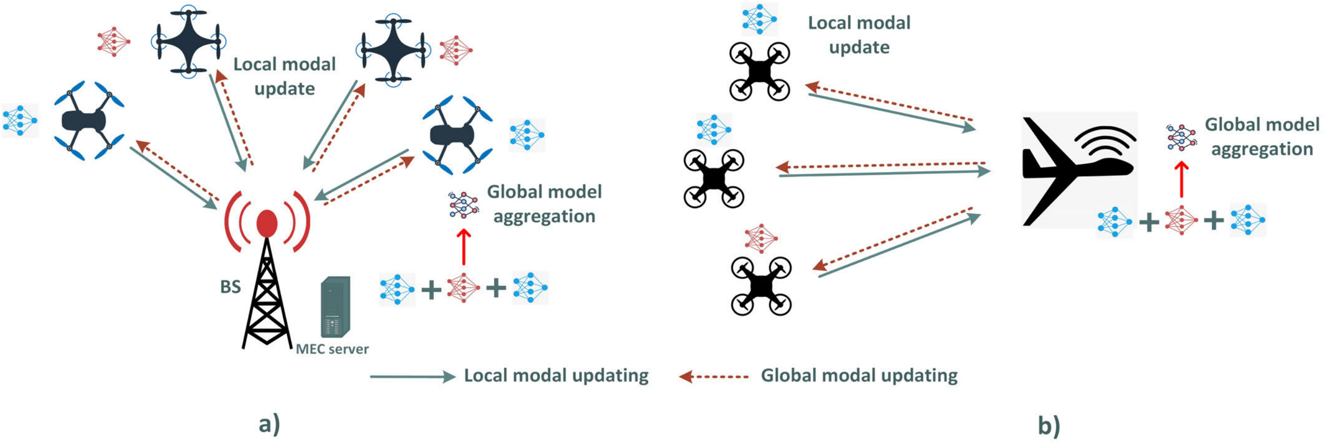

FIGURE 11. Federated edge learning utilizing UAVs: (a) Coordination with ground BSs; (b) UAV Peers.

negative impact on the newly developed services in the next wireless networks by shortening battery life, especially for those devices that have a limited battery or are difficult to recharge and replace, such as IoT devices and UAVs that need to utilize the available battery efficiently [183].

Backscattering radio technology is a recent approach to designing transmitters with zero active components, leading to the elimination of the consumed power by means of active transmission. One more efficient technology is called ambient backscatter communication (AmBC), which uses ambient radio frequency (RF) signals such as cellular signals, Wi-Fi signals, or any form of RF transmission that coexists to serve a primary user. The transmitter in AmBC embeds its message in the ambient RF signal by varying the reflection coefficients through varying the load impedance at the backscatter transmitter. Then an intelligent receiver can detect changes in the reflection coefficients to decode the message transmitted by the AmBC transmitter.

Recently, a new technology known as symbiotic radio (SR), which benefits from both CR and AmBC to overcome their drawbacks effectively. SR overcomes CR by having two spectrum sharing systems, primary and secondary, which helps in providing mutually beneficial spectrum sharing. On the other hand, SR overcomes AmBC by enhancing more reliable backscattering through joint decoding [184]. Therefore, the utilization of SR technology has considerable potential as a viable approach to facilitate collaborative resource allocation across radio systems via symbiotic associations [183].

Knowing that, UAVs will play a major role in the next generation of wireless networks with a wide range of applications, as discussed in Section IV [185]. With limited battery life, UAVs need efficient energy management to ensure sustainability and long battery life [89]. To address this challenge, UAVs can leverage SR to reduce the need for active transmitters. Utilizing SR in 5G-and-beyond will significantly reduce the power consumption of UAVs, enabling long-term and sustainable applications in the future [184].

Figure 12 shows that not only SR can be used for communication but also for sensing UAVs. In this figure, a scenario includes air-to-air and air-to-ground symbiotic communication and sensing (SCAS), in which a communication signal

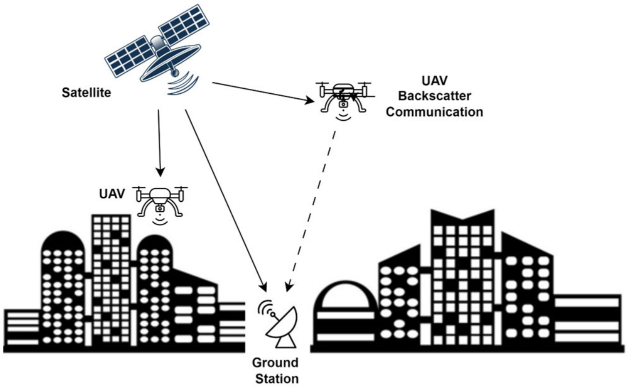

FIGURE 12. Air-to-Air and Air-to-Ground SCAS.

is transmitted from a satellite to an UAV and a ground station. The UAV utilizes backscatter technology to transmit its data via backscattering communication. Upon receiving the backscattered signal, the base station performs SCAS to determine the location of the UAV as well as retrieve the accompanying data [183].

VI. UAV REGULATIONS

The widespread deployment and operation of UAV-based communication systems face substantial challenges and limitations due to regulatory issues. Governments and regulatory entities across the globe are currently engaged in the formulation of regulations aimed at guaranteeing the safe, secure, and responsible utilization of UAVs [186], [187]. The regulatory factors and considerations that influence UAV operations encompass the following:

A. LICENSING AND REGISTRATION

In many regulatory frameworks, operators of UAVs are mandated to acquire licenses or certifications for both commercial and recreational purposes. However, some countries like Vietnam does not mandate the possession of a pilot license for UAV operations, distinguishing its regulations from those of notable jurisdictions like the United Kingdom, the United States, Singapore, and Australia [188]. The acquisition of these licenses may entail the completion of knowledge assessments, the attainment of pilot certifications, or the acquisition of specific authorizations, which are contingent upon the weight and functionalities of the UAV. Furthermore, it may be necessary to register UAVs with the relevant governing bodies in order to establish a system of responsibility and the ability to track their movements.

B. FLIGHT RESTRICTIONS AND AIRSPACE REGULATIONS

UAVs are required to adhere to airspace regulations in order to uphold safety standards and mitigate the risk of potential disruptions to manned aircraft operations. Restricted airspace zones, no-fly zones, and altitude limitations are established by authorities in order to mitigate the potential for collisions and uphold the integrity of manned aviation operations [16], [187]. Adherence to these regulations is of utmost importance, in order to mitigate the risk of unauthorized access to restricted zones and ensure the preservation of a secure distance between aircraft.

C. REMOTE IDENTIFICATION AND TRACKING

Remote identification technology for UAVs is an emerging capability enabling ground-based observers to identify UAVs in airspace while gathering relevant information about the UAV and its operator [189]. The overarching concept and standardized framework for remote identification of UAS primarily pertain to the electronic identification of airborne unmanned aircraft. These standards establish the baseline performance criteria for direct remote identification [190]. Additionally, 3GPP has initiated various endeavors to cater to the connectivity requirements of UAS using mobile networks, including the 5G system. The comprehensive requisites for remote identification of UAS are outlined in [191]. In order to augment accountability and streamline identification processes, it may be necessary for regulations to mandate the inclusion of remote identification and tracking capabilities in UAVs. This capability allows authorities to ascertain the identity of the operator and monitor the UAV throughout its duration of flight. Remote identification systems commonly employ the transmission of distinct identifiers, such as serial numbers or digital signatures, to ground control stations or authorized receivers.

D. OPERATIONAL LIMITATIONS AND RESTRICTIONS

Regulatory measures have the potential to impose operational constraints on UAVs, encompassing limitations on factors such as flight altitude, proximity to airports, and traversing specific regions such as densely populated areas, vulnerable facilities, or essential infrastructure. The aforementioned limitations are implemented with the objective of safeguarding the well-being of the general public, ensuring the preservation of personal privacy, and maintaining the overall security of the system. Airspace restriction represents a prevalent regulatory approach applied across numerous countries and regions concerning UAV operations [16]. Particularly in nations with stringent UAV regulations, such as the United States and China, UAV operators must seek airspace authorization before conducting flights. In this process, assuming the UAV is registered under the operator's real name and the pilot holds the necessary certification, the pilot submits both the flight plan and airspace authorization request to the relevant airspace management authority.

E. PRIVACY AND DATA PROTECTION

The emergence of privacy issues pertaining to UAV operations has prompted the establishment of regulatory measures aimed at preserving individual privacy and ensuring the security of personal data [192]. Recent developments in security and privacy concerns impact the IoD network, along with contemporary techniques for mitigating IoD attacks [193].

Regulations have the potential to impose restrictions on the capturing and processing of personal data without obtaining consent, as well as to impose limitations on the utilization of surveillance equipment in specific situations. Ensuring adherence to privacy regulations frequently entails the acquisition of explicit consent, the anonymization of collected data, and the implementation of secure data handling protocols.

F. SPECTRUM ALLOCATION

UAV communication systems heavily rely on the allocation of wireless spectrum to enable the seamless transmission of data and control signals. Regulatory authorities hold a pivotal role in this spectrum allocation process, ensuring the provision of suitable frequency bands for UAV communication. Their primary objective is to safeguard uninterrupted UAV operations by effectively managing potential interference issues. The overarching goal of these spectrum allocation regulations is to strike a delicate balance between the escalating demand for spectrum resources and the specific requirements of UAV communication systems.

The operation of UAVs introduces numerous complexities in the realm of radio spectrum management, with a focus on ensuring operational safety, efficient spectrum utilization, and harmonious coexistence with pre-existing wireless networks. Conventional spectrum allocation methodologies prove inadequate when applied to UAV networks, primarily due to the dynamic nature of UAV operations. This dynamicity necessitates adaptive spectrum strategies and robust mechanisms to ensure the continuous and reliable delivery of services [15]. For UAS operation, radio spectrum usage encompasses a range of critical functions, including communication, navigation and surveillance electronic conspicuity, command and control, detect and avoid, as well as the relay of payload data [194].

G. OPERATIONAL PROCEDURES AND SAFETY STANDARDS

Regulations have the potential to delineate operational procedures, safety standards, and maintenance requirements pertaining to UAVs. The primary objective of these regulations is to establish measures that guarantee the secure functioning of UAVs and minimize the potential hazards arising from malfunctions, collisions, or incidents. The standardization in [195] outlines specific prerequisites for ensuring the quality and safety of UAS design and production, encompassing unmanned aircraft, remote pilot stations, datalinks, payloads, and associated support equipment. The work in [196] examined New Zealand's regulatory framework for aviation safety concerning unmanned aircraft, considering the viewpoint of unmanned aircraft operators. Generally, any documents provided by an organization may encompass a range of essential components, such as pre-flight check protocols, records of maintenance activities, emergency response protocols, and the necessary training prerequisites for operators.

H. BEYOND VISUAL LINE OF SIGHT (BVLOS) OPERATIONS

Regulations frequently impose limitations on BVLOS operations, referring to the operation of UAVs beyond the operator's direct visual range. BVLOS operations necessitate the utilization of sophisticated technologies, seamless integration into existing airspace systems, and the implementation of comprehensive safety protocols. In BVLOS operations, the UAV is permitted to function beyond the LoS, adhering to a predetermined flight path and relying on instrumentation-based flight data, including onboard cameras and detect-and-avoid technologies [197].

Regulatory bodies are currently engaged in active exploration and development of regulations aimed at facilitating and overseeing BVLOS operations. These regulations are being formulated with the intention of addressing various concerns pertaining to safety, collision avoidance, and the establishment of effective command and control mechanisms.

I. INTEGRATION WITH AIR TRAFFIC MANAGEMENT SYSTEMS

The integration of UAVs into established air traffic management systems assumes paramount importance as the frequency of UAV operations continues to rise. A shared comprehension of the essential functions and structural aspects of UAS traffic management is presented in [198], offering a comprehensive explanation of the system layer within the UAS traffic management framework. Additionally, in [199], a framework for ensuring adherence to regulatory guidelines, encompassing safety, security, privacy, and various organizational prerequisites, is presented for entities offering UAS traffic management services. In order to ensure the safe integration of UAVs and to prevent conflicts with manned aircraft in controlled airspace, regulations may necessitate the adherence of UAVs to designated protocols, communication standards, and coordination procedures. The future perspective of 6G-enabled UAV traffic management ecosystems in highly congested urban airspace, emphasizing non-terrestrial aspects, encompassing aerial and satellite communication [200].

J. SECURITY AND COUNTER-UAV MEASURES

Regulations have the capacity to effectively mitigate security concerns that arise from the operations of UAVs, encompassing issues such as unauthorized access, potential threats, and the implementation of counter-UAV measures.

These regulations encompass a wide range of operational guidelines, safety measures, and legal frameworks aimed at promoting responsible UAV use while addressing potential security threats posed by UAVs [201]. Government entities have the ability to establish regulations regarding the utilization of specific UAV technologies, deploy counter-UAV systems in areas of high sensitivity, and develop procedures for reporting and addressing security incidents. A methodology for assessing attack and countermeasure techniques in of commercial UAVs is outlined in [202]. In [203] delineates prerequisites for the operational procedures of unmanned aircraft, which, when combined with existing and forthcoming standards on UAS, constitute a comprehensive safety and quality standard for unmanned aircrafts. Additionally, it applies universally to all commercial UAS, regardless of their size, classification, purpose, or location, and represents the global benchmark for the secure operation of commercial UAS.

Regulations pertaining to UAVs exhibit variability across different countries and geographical regions, with distinctions made based on factors such as urban or rural settings. Regulations governing UAVs operations in the United States are promulgated by the federal aviation authority (FAA) and the national aeronautics and space administration (NASA). NASA is currently engaged in a collaborative effort with the federal communications commission (FCC) and the FAA to undertake the development of UAV control frameworks. FCC is presently engaged in an investigation to determine the necessity of establishing a new spectrum policy specifically tailored to regulate UAV operations.

VII. RESEARCH TRENDS AND OPEN CHALLENGES

A. RESEARCH TRENDS

The integration of UAVs into 5G-and-beyond networks has emerged as a promising paradigm to revolutionize wireless communications, enabling a wide array of innovative applications and services. As the deployment of UAVs becomes more prevalent, researchers and industry stakeholders are actively exploring novel approaches to harness the full potential of these aerial platforms in synergy with advanced communication technologies. This section delves into the latest trends shaping UAV-enabled communication systems, encompassing heterogeneous network integration, UAV swarm communication, security and privacy, ML and AI for UAVs, green UAV communication, and spectrum management.

1) HETEROGENEOUS NETWORK INTEGRATION

The integration of UAVs into terrestrial heterogeneous networks (HetNets) is currently a topic that has been capturing significant attention in the research community. This integration aims to enable UAVs to interact seamlessly with various types of networks, such as 5G, 6G, Wi-Fi, and satellite networks. By integrating UAVs into HetNets, the scope of applications for UAV communication and networking expands significantly.

One of the key benefits of heterogeneous network integration is the enhanced coverage and connectivity that UAVs can provide. As UAVs can operate at varying altitudes and positions, they can extend the reach of terrestrial networks to remote or difficult-to-access areas. Additionally, UAVs can act as aerial relays to facilitate communication in areas with limited ground infrastructure. The flexibility of UAVs to switch between different networks based on factors like network availability, demand, and application requirements offers numerous advantages. For instance, during emergencies or events with high data traffic, UAVs can be deployed as temporary network boosters to offload traffic from congested TBSs. Moreover, UAVs can be utilized to bridge communication gaps in disaster-stricken regions, enabling critical communication and coordination.

Research in this area is focused on addressing various challenges, such as efficient handover mechanisms, developing intelligent network selection algorithms [204], cross-layer design approaches, and seamless integration of UAVs into existing HetNets. By effectively addressing these challenges, the integration of UAVs into HetNets promises to revolutionize the way wireless communication is approached in 5G-and-beyond networks [205].

2) UAV SWARM COMMUNICATION

The concept of UAV swarms, where multiple UAVs operate in coordinated groups, is an exciting area of research with promising applications. UAV swarms have garnered considerable interest in fields like surveillance, delivery services, and emergency response scenarios. These swarms offer significant advantages over individual UAVs, such as increased reliability, enhanced coverage, and improved scalability.

In UAV swarm communication, research is focused on developing efficient communication protocols and algorithms to facilitate seamless and reliable inter-UAV communication. This entails addressing challenges related to swarm coordination, dynamic formation and dissolution of swarm members, and information exchange among UAVs. To achieve effective swarm communication, researchers are exploring communication strategies that ensure synchronized actions and cooperation among UAVs in swarm scenarios.

One of the key areas of interest is establishing robust communication links between UAVs within the swarm while minimizing interference and latency. By optimizing communication paths and dynamically adapting communication strategies based on swarm dynamics, researchers aim to enhance the performance and resilience of UAV swarm communication [206].

3) SECURITY AND PRIVACY

As UAVs become increasingly integrated into daily life, ensuring secure and private communication is of paramount importance. UAV communication networks handle sensitive data and perform critical tasks, making them potential targets for cyberattacks and privacy breaches.

To address these concerns, ongoing research focuses on cryptographic techniques, trust-based protocols, and privacy-preserving mechanisms designed specifically for UAV communication networks. Encryption and secure key exchange protocols ensure that transmitted data remains confidential and protected from unauthorized access. Trust-based protocols establish a system of trust between UAVs and ground stations, enabling secure communication and preventing unauthorized access to the network. Additionally, privacy-preserving mechanisms aim to protect user identities and sensitive information, ensuring that UAV operations remain anonymous and secure.

Moreover, secure and robust communication protocols are essential to safeguard against potential jamming, spoofing, and eavesdropping attacks. By incorporating advanced security measures into UAV communication networks, researchers aim to establish reliable and resilient systems that can withstand potential security threats. The challenge lies in striking a balance between security measures and the performance and efficiency of UAV communication. Researchers are actively working to develop lightweight and scalable security solutions that do not compromise the real-time communication demands of UAV applications. Meanwhile, they also focused on addressing the unique security challenges posed by UAVs, such as aerial attacks and privacy invasion [6].

4) AI TECHNIQUES FOR UAVS

In the upcoming decade, the utilization of AI methods in UAV communication systems is set to expand significantly. Researchers will exploit artificial neural networks, deep learning (DL), and ML algorithms to enhance the optimization of UAV communication networks, as these methodologies have demonstrated notable advantages across various applications. The research community still needs to further explore the development of an acceptable AI technique for the UAV communication system, which is a multi-dimensional network that is more sophisticated than current terrestrial communication networks. Meanwhile, AI has shown great potential in addressing complex challenges faced by UAVs, such as path planning, resource allocation, and interference management.

One of the primary applications of ML in UAV communication is predictive modeling for optimal path planning [207]. By analyzing historical data, environmental conditions, and user requirements, ML algorithms can predict the most efficient and safe routes for UAVs. These predictive models enable UAVs to autonomously plan their trajectories to optimize communication coverage and reduce flight time. In addition to path planning, ML techniques are also utilized for dynamic resource allocation. By continuously monitoring network conditions and demand patterns, ML algorithms can optimize resource allocation, ensuring efficient utilization of available bandwidth and power resources. Furthermore, AI-driven interference management is a key focus area to enhance the reliability and performance of UAV communication networks. AI algorithms can intelligently analyze interference patterns and adapt communication parameters in real-time to mitigate interference and improve overall network efficiency.

The successful implementation of AI in UAV communication and networking requires the availability of high-quality training data and the development of robust learning models. Moreover, the integration of AI techniques into UAV communication systems must be complemented by stringent security and privacy measures to safeguard sensitive data and prevent potential malicious attacks.

5) BLOCKCHAIN IN UAV COMMUNICATIONS

Blockchain is an important ongoing research trend driving the evolution of 5G-and-beyond networks with UAVs. As a distributed ledger technology, Blockchain offers secure and transparent transactions, enabling trust and accountability in UAV communication and data management. It provides a decentralized and tamper-resistant platform for sharing UAV-generated data among multiple stakeholders, ensuring data integrity and authenticity in collaborative UAV missions. Moreover, Blockchain enables the creation and management of decentralized digital identities for UAVs, enhancing security through decentralized access management. Smart contracts, programmable self-executing contracts on the Blockchain, automate various aspects of UAV missions and enable autonomous decision-making among UAVs. Blockchain's support for cryptocurrency and microtransactions facilitates secure and real-time transactions among UAVs, promoting resource exchange and service collaboration without traditional intermediaries [17]. Additionally, Blockchain-based consensus mechanisms can be applied to UAV traffic management, enabling decentralized coordination and conflict resolution among multiple UAVs in congested airspace, thereby improving overall traffic efficiency and safety. Furthermore, Blockchain ensures data integrity and traceability, making recorded data tamper-proof and auditable, vital for applications like UAV-based critical infrastructure inspections.

While the integration of Blockchain in UAV communications offers numerous benefits, there are challenges to address, including scalability, energy efficiency, and regulatory considerations. Researchers are actively exploring innovative approaches to optimize Blockchain solutions for UAV communications, unlocking their full potential in 5G-and-beyond UAV networks.

6) SPECTRUM MANAGEMENT

Efficient spectrum management stands as a paramount research trend in the context of 5G-and-beyond networks with UAVs. With the increasing proliferation of UAVs in diverse applications, ranging from aerial surveillance and monitoring to disaster response and communications, effective spectrum allocation and utilization become imperative for ensuring seamless and reliable UAV communication [208]. Spectrum sharing techniques lie at the core of spectrum management research. These techniques are designed to enable UAVs to efficiently share spectrum resources with existing communication systems, fostering coexistence without causing harmful interference. The development of intelligent spectrum sharing mechanisms ensures that UAVs can dynamically access available spectrum bands based on real-time requirements, optimizing communication performance while efficiently utilizing the available resources. Dynamic spectrum access is a key focus within the spectrum management domain. By implementing dynamic access mechanisms, UAVs can opportunistically utilize underutilized spectrum bands, leveraging temporal and spatial variations in spectrum availability. Dynamic spectrum access empowers UAVs to adapt swiftly to changing environmental conditions and communication demands, resulting in enhanced communication reliability and throughput [209]. For instance, cognitive radio techniques are being explored to enable UAVs to dynamically access and utilize underutilized spectrum bands. Cognitive UAV communication enhances spectral efficiency by opportunistically accessing available frequency bands while avoiding interference with primary users [210].

Interference management represents a critical aspect of spectrum management for UAVs. As UAVs often operate in highly congested and dynamic environments, interference from neighboring communication systems can significantly impact communication performance. Research efforts concentrate on devising innovative interference mitigation techniques that allow UAVs to coexist harmoniously with other wireless networks. Advanced interference avoidance algorithms, intelligent beamforming strategies, and cooperative spectrum sensing mechanisms are among the key solutions being explored to mitigate unwanted interference. By effectively managing spectrum resources and addressing interference challenges, the spectrum management research trend seeks to optimize spectral efficiency for UAV communication. This optimization not only ensures the reliability and quality of UAV communication links but also enhances the overall performance and capacity of UAV networks.

B. OPEN CHALLENGES

Every system containing complex elements brings different challenges to be solved. Since connected UAV schemes form a complex system with elements of the transmission medium, the complexity is greater than conventional networks. Also, there are many different approaches to creating a wireless network with UAVs as presented up to this point. In order to analyze these approaches correctly, a correct relationship must be established between UAVs and conventional wireless communication networks. In this way, difficulties can be identified more easily. These difficulties will also determine future research trends. This section discusses the main challenges in wireless communication with connected UAVs and research on these issues. These challenges are presented under the following subsections: collision avoidance, control latency, limited energy, privacy problems, mobility management, channel modeling, UAV antenna configurations, interference management, GPS architecture for system redundancy, and cyber-physical security.

1) COLLISION AVOIDANCE

In multiple UAV scenarios, collision avoidance is also another consideration for the system designs. This issue does not cover only collision between different UAVs but also collision between UAVs and other obstacles in the environment. A comprehensive review paper that focused on comparison and analysis of different collision avoidance algorithms available in the literature is provided by authors in [211]. Several research papers representing different approaches to this issue are described in this subsection. One of the interesting scenarios for collision avoidance algorithms is studied by [212]. They adapted an algorithm that considers some channel restrictions, position data, and video parameters for first person view UAV applications. They claimed that their algorithms made the probability of collision 58.63% better than previous studies in this matter. A recent study that solves the avoidance problem by reinforcement learning is presented in [213]. The study provided collision avoidance without any previous data about other UAVs' trajectories in the network. They solved the optimization problems for their given approach and proposed that the results are promising compared to other studies. Authors in [214] provided a collision avoidance approach that considers the quality of coverage for the UAVs in surveillance missions. They developed a new coverage model by proving its convergence and providing its simulation results.

2) CONTROL LATENCY

Control latency is one of the crucial topics in connected UAVs. Control latency which is provided by varying cellular systems using UAVs will be better thanks to technologies such as 5G. Advantages of 5G for improving control latency and additional benefits over 4G are discussed in [20]. Results are presented according to the 20 MHz carrier bandwidth and 2.6 GHz carrier frequency using LTE-Advance Network. Besides; 50 m, 100 m and 300 m are selected as different altitudes for UAVs. Results related to these altitudes are illustrated for varying latency data samples. Details about control latency and a more comprehensive literature review can be found in [20].

3) LIMITED ENERGY

In a network which consists of UAVs, energy is one of the most significant challenges which limits performance. Since UAVs have limited energy, all scenarios related to UAVs must be designed by considering energy issues. It requires much different research that must be done, such as battery design and charging optimization. In [215], a cloud-based UAV navigation system is explained to obtain a more efficient battery charging scenario for networks which use UAVs as relays. Since lack of coordination between UAVs during battery charging may cause a blockage on the network, they propose a solution by using globally coordinated routes [215]. In another research, an auction-based multiple UAV charging plan is proposed to increase the performance of procurement of energy on time [216]. Also, problem of how to place the charging station for UAVs is discussed in [217]. They propose a deployment solution for placement of UAVs and this system recursively changes the configuration of charging stations with respect to usage data. All the provided articles show that charging optimization is quite popular in the literature. It is not mentioned in this paper, but there are many articles related to battery design, and it is another crucial branch of this issue that requires much further research.

4) PRIVACY PROBLEMS

As with every wireless communication system, privacy is one of the key aspects. UAVs were not designed to consider security problems originally. Thus, when they are used in communication networks, privacy issues should be taken into consideration. Security challenges in connected UAVs are sorted in detail in [218]. It highlights that UAV networks are quite different than classical wireless networks. Less power requirement and carrying of less information are sorted as examples for differences between classical networks than UAV networks [218]. Requirements of privacy and security for wireless UAV networks and their architecture are studied in [219]. They also propose prospective approaches for problems such as flexibility, protection, and leakage. Their solutions cover location protection and privacy protection. More detail related to these solutions can be found in [219].

5) MOBILITY MANAGEMENT

To fully take advantage of UAV installation, further visual LoS processes is of critical significance as UAVs act as air users, which maintain connection with the TBSs for direction and control objectives in the downlink [220]. Typically, BS antennas sidelobes may serve UAVs while flying in the sky which deliver lower antenna gains [26], [220]. This will create significant challenges to the mobility management of cellular-connected UAVs in terms of reference signal received power (RSRP). The highest RSRP will be maintained when the distance is far between TBSs and UAV. Figure 13 illustrates the cellular-connected UAV when it is flying over a rural area. This scenario of irregular signal coverage of TBSs will lead to reduced mobility performance such as radio link failure, handover failure, in addition to useless handovers, named ping-pong events [221]. Regardless of that, due to the loss of direction and control of signal, the UAV may hit a civil aircraft or even collide into a populated zone which might cause dangerous events. Therefore, functional mobility management to deliver authoritative connections between UAVs and TBSs is of critical significance. In [221] and [222] provided more details on the mobility management, particularly handover procedures, for connected UAVs within forthcoming mobile networks, encompassing technologies such as 5G, 6G networks.

6) CHANNEL MODELING

One of the main issues in UAV communication is channel modelling. Similar to other wireless communication applications, determining aspects of wireless communication channels in connected UAVs is critical to be able to design an optimal system in order to provide reliability. Unlike other commonly known fading channels, there are more parameters that characterize UAV communication channels. For example, since a UAV may act as a component during connection, it shows some Rician fading channel characteristics. However, LoS components can disappear in certain time slots. Then, it can be said that channel turns into a Rayleigh fading channel. These examples can be increased. To model UAV communication, different approaches and formulations are presented in the literature. These approaches and formulations include parameters such as path loss exponents, shadowing effects, etc. In addition to these parameters, there are some different channel definitions for A2G and A2A. A detailed review of these differences is presented in [3]. There are other possible methods for characterizing UAV channels. One of them is obtaining empirical results. Due to the complexity of theoretical derivations in UAV communications, empirical results are more supportive than other classical wireless communication studies for determining the future directions of channel modelling. In practical channel modelling studies, there are many different setups and considerations. As an example, a very effective method is proposed in [23].

In [223], the authors investigated continuous phase modulated signal transmission in UAV communication networks with doubly-selective channels. It proposed a two-stage receiver design that includes a linear time-varying equalizer and a recursive symbol recovery process from pseudo-symbols in the Laurent representation.

A2A channel modeling describes the wireless communication channels between UAVs when they are in flight. Several works have been done in A2A channel modeling such as [224], [225], and [226]. The researchers in [224] employed the ray tracing method to conduct path gain analyses based on the distance between two UAVs in distinct scenarios. The study explores various antenna types employed in A2A communication channels when one UAV functions as a transmitter and the other as a receiver, assuming a LoS connection between them. In [225], a 3D geometry-based stochastic channel model is introduced to account for unique A2A channel characteristics, including arbitrary 3D mobility and time-domain non-stationarity. They focused on deriving and examining critical channel attributes such as the root mean square delay spread, space-time correlation function, stationary interval and Doppler power spectrum density, as per the theoretical framework. The authors in [226] presented the measurement of an A2A channel at a frequency of 1420 MHz within an urban environment. This study analysed the delay and power characteristics of multipath components using the gathered measurement data. Additionally, the study calibrated a ray-tracing simulator to extend its applicability to various UAV scenarios.A2G channel modeling in UAV communication describes the wireless communication channel characteristics between a UAV and a ground station or terrestrial device. In the researchers in [227] measured A2G signals from UAVs and developed a channel model incorporating a

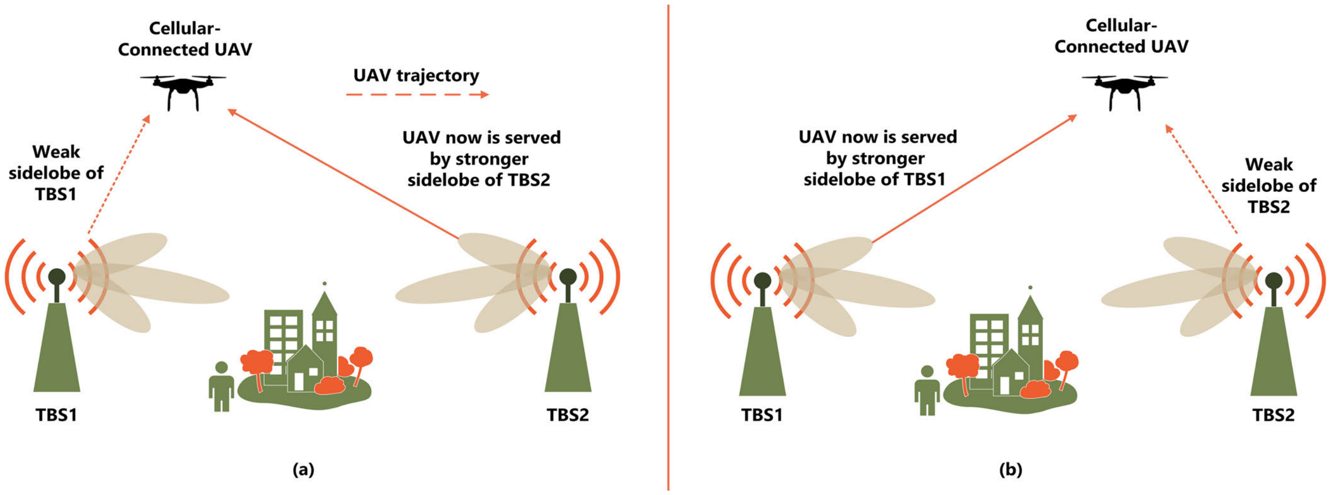

FIGURE 13. HO scenario of a cellular-connected UAV moving towards horizontal direction. (a) UAV is associated with TBS2 due to its higher side-lobe gain than TBS1. (b) After moving forward, the UAV is now associated with TBS1 due to its higher sidelobe gain.

two-ray ground-reflection effect for the UAV communication system. This channel modelling approach offers a suitable path loss model for assessing the quality of service in A2G wireless communication. Several channel measurement campaigns were conducted within the airport vicinity, covering the UHF and L-band frequencies (approximately 433 MHz and 1.518 GHz) [228]. In cases where there was a clear LoS, distance-dependent path loss models were developed for both frequency bands. In [229], the authors investigated A2G channel modeling and transmission performance in a cellular-connected M-MIMO UAV swarm system. They introduced a correlated A2G channel model that considers factors like non-isotropic scattering, LoS propagation, and mobile scatterers. Additionally, a novel analytical expression for uplink signal-to-interference-and-noise ratio is derived, accounting for channel aging and strong LoS effects. A 3-D elliptic-cylinder MIMO channel model for UAV communication in A2G scenarios is proposed in [230]. This study focused on the mobility and altitude of UAV transmitters in the elevation plane, utilizing the newly proposed UAV-MIMO channel model as a basis. The authors in [231] performed cluster-based characterization and modeling of A2G channels. This study represented the first of its kind to focus on the clustering and tracking of multipath components within dynamic A2G channels

7) UAV ANTENNA CONFIGURATIONS

Like in all wireless communication applications, there are many antennas configuration approaches for UAV communications. In addition to previous antenna knowledge for wireless communications, some issues have to be taken into consideration for UAV communication. For example, noise which is caused by the UAV itself changes previous approaches. Moreover, the specific characteristics of aerial communications can be counted as another example. According to [24], optimal tilting of the UAV antenna enhanced the throughput from 3.5 to 5.8 b/s/Hz and the coverage from 23% to 89%. And they also declare that their configuration increases performance of microcells limits and network density performance. In [25], a new reconfigurable microstrip antenna including adjustable conical beams is proposed for UAV communications. That antenna covers a bandwidth from 2.39 to 2.49 GHz which is also so suitable for 2.4 GHz applications. Beamforming is another hot topic in antenna designs and performance of beamforming with down-tilted antennas for UAV communications applications is presented in [26].

8) INTERFERENCE MANAGEMENT

Interference is one of the inevitable problems with wireless communications systems, and it requires specific solutions to handle it. Some possible solutions for interference problems mentioned by standardization institutions for UAV communications users are surveyed in [6]. As a novel approach, [28] it proposes an interference-aware path planning structure for a UAV communication network. Their main contribution is for solving the tradeoff problem between minimizing both the interference caused on the ground network along its route and maximizing the energy efficiency. They propose a deep reinforcement method based on the echo state network (ESN). In their system, each UAV utilizes the ESN to identify the optimal transmission power, path, and cell association vector at varying positions along its route. Also, the proposed method is supported by simulation results. The interference management problem in UAV communications contains many possible approaches in itself thanks to ML techniques for further studies.

9) GPS ARCHITECTURE FOR SYSTEM REDUNDANCY

There are many applications for determining the position of UAVs exactly about Real Time Kinematic GPS (RTK-GPS). Nevertheless, these applications are found to be instable for

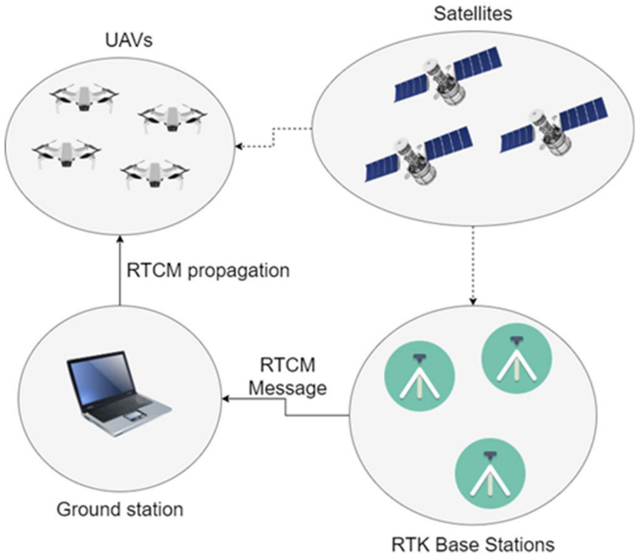

FIGURE 14. Radio technical commission maritime services propagation system design.

networks and cause some errors in services. Thus, GPS architecture is another problem that has to be solved for better systems. An effective architecture for improving system performance is proposed in [29] by parallelizing or switching the GPS data resources. They also discuss how to allocate messages through the UAV network. Evaluation on empirical testbeds and validation results are also available. Figure 14 shows an example propagation system model.

10) CYBER-PHYSICAL SECURITY

It is unarguable that security is so critical to any communication system. It can be considered as a more crucial problem for UAV communication applications as UAVs require remote control by nature. When UAVs become an inevitable part of cellular systems, security becomes more important for providing coherence in networks. There is a comprehensive background about security in UAV communication are introduced in [6]. Cyber-attacks on UAV systems are increasing day by day. Thus, techniques should be developed continuously. Examples of these threats can be counted as jamming, hijacking, eavesdropping, denial of service, and spoofing. In addition to cyber-attacks, there may also be physical attacks. These attacks are detailed in [6]. As a specific example, a homomorphic cryptography system is proposed in [30] to provide the security of controllers. They also proposed a linearly homomorphic authenticated encryption (LinHAE) architecture to make real-time operations safer for autonomous flight.

A comprehensive overview of PLS within the context of UAV systems is provided in [224], with an examination of various communication channels, including ground-to-ground, ground-to-air, A2G, and A2A [232]. PLS metrics, such as secrecy outage probability, average secrecy capacity, and the probability of strictly positive secrecy capacity, are studied in UAV-to-ground communications, considering the presence of shadowing, as discussed in [233]. Also, an overview of the improvement of the PLS of UAV networks by the IRS is presented in [234]. Various use cases of PLS for enhancing UAV communications by the IRS are examined, and recent advancements in this field are briefly summarized. Nonetheless, a significant limitation of IRS lies in its confinement of communication to the reflective dimension, thereby rendering it inaccessible to users positioned behind the IRS surface. In [235], the authors proposed the utilization of intelligent omni-surfaces as an alternative to IRS, alongside the deployment of UAVs, to attain secure communication within an IoT communication system.

An emergent self-Awareness module is suggested to be incorporated into the physical layer of cognitive UAV radios for the enhancement of PLS, particularly in the context of countering jamming attacks. Self-Awareness is founded on the acquisition of a hierarchical representation of the radio environment through the utilization of a proposed hierarchical dynamic Bayesian network. DL-empowered punctured low density parity check codes are introduced in [236] for the purpose of ensuring secure and dependable data transmission for UAVs over the additive white gaussian noise channel, independent of the computational capabilities and channel state information (CSI) of the Eavesdropper. Similarly, the authors in [237] conducted the analysis of PLS for a dual-hop wireless network based on UAV, taking into account imperfect CSI and the influence of mobility effects.

The PLS of UAV-based communication is enhanced through the implementation of NOMA techniques. In [238], the authors examined the secrecy performance of a full-duplex relay NOMA system utilizing UAVs over the Nakagami-m fading channel. The insertion of an artificial noise component into the transmit signal of the full-duplex aerial relay station, with power allocation based on the NOMA protocol, is suggested for the purpose of ensuring secure communication for users. Besides, the secrecy outage probability in the context of in terrestrial networks aided by UAVs is investigated in [239], utilizing cooperative user selection. In this system, the user is chosen from those directly connected to the UAV. With a particular emphasis on achieving optimal resource allocation, the research in [240] delved into optimizing PLS for UAV communication by employing NOMA. It studied the feasibility of pairing users with trustworthiness disparities and the influence of optimal power allocation coefficients.

VIII. CONCLUSION

In this paper, a comprehensive survey of the deployment scenarios, applications, emerging technologies, regulatory aspects, research trends, and challenges associated with the use of UAVs in 5G-and-beyond networks has been presented. The paper begins with a brief background on UAVs and 5G networks, followed by a systematic classification of UAVs and a review of relevant works. Various UAV deployment scenarios, including single and multiple UAV configurations, are then discussed. UAV applications in 5G are categorized, and emerging technologies for enhancing UAV communications are investigated. Additionally, regulatory considerations, such as flight guidelines, spectrum allocation, privacy, and safety, are addressed in the context of deploying UAVs in 5G networks. The latest research trends and open challenges in the field are highlighted, and promising directions for future investigations are identified. This survey is intended to serve as a valuable resource for researchers, practitioners, and policymakers in the UAV and communication domains, providing a comprehensive overview of the state-of-the-art in UAV-enabled 5G networks and outlining the key challenges and research directions essential for realizing the full potential of this technology. The hope is that this survey will inspire further research in this exciting area and accelerate the development of UAV-enabled 5G networks.

ABBREVIATIONS LIST

Term	**Description**
3GPP	3rd generation partnership project
5G	fifth generation
6G	sixth generation
A2A	air-to-air
A2G	air-to-ground
ABS	aerial base stations
AI	artificial intelligence
AmBC	ambient backscattering communications
BS	base stations
BVLOS	beyond visual line of sight
CSI	channel state information
CURS	closest UAV Relay Selection
D2D	device-to-device
DL	deep learning
DNN	deep neural network
DRL	deep reinforcement learning
eMBB	enhanced mobile broadband
ESN	echo state network
FAA	federal aviation authority
FANETs	flying ad-hoc networks
FCC	federal communications commission
FCSD	Fog computing-aided swarm of drones
FDMA	frequency division multiple access
HetNets	heterogeneous networks
HVOR	highest velocity opportunistic routing
IoD	Internet of drones
IoT	Internet of things
IRS	intelligent reflecting surfaces
ITC	interference transmission and cancellation
LoS	line-of-sight
LTE	long term evolution
MEC	mobile edge computing
MIMO	multiple input multiple output
ML	machine learning
M-MIMO	massive multiple input multiple output
mMTC	massive machine-type communication
mmWave	millimeter wave
MURS	maximum UAV relay selection
NASA	national aeronautics and space administration
NOMA	non-orthogonal multiple access
NR	new radio
OMA	orthogonal multiple access
OR	opportunistic routing
PLS	physical layer security
QoS	quality of service
RL	reinforcement learning
RSRP	reference signal received power
RF	radio frequency
SAA	sense-and-avoid
SBSs	small base stations
SNR	signal-to-noise ratio
SWIPT	simultaneous wireless information and power transfer
SR	symbiotic radio
SCAS	symbiotic communication and sensing
TBSs	terrestrial base stations
TDMA	time division multiple access
UASs	unmanned aerial systems
UAV	unmanned aerial vehicles
UE	user equipment
URS	UAV relay selection
V2V	vehicle-to-vehicle
WPCNs	Wireless powered communication networks

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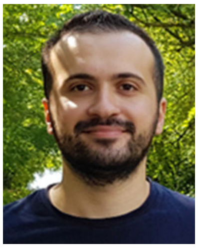

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