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SURVEY

Unmanned Aerial Vehicle Communications for Civil Applications: A Review

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ABSTRACT The use of drones, formally known as unmanned aerial vehicles (UAVs), has significantly increased across a variety of applications over the past few years. This is due to the rapid advancement towards the design and production of inexpensive and dependable UAVs and the growing request for the utilization of such platforms particularly in civil applications. With their intrinsic attributes such as high mobility, rapid deployment and flexible altitude, UAVs have the potential to be utilized in many wireless system applications. On the one hand, UAVs are able to operate as flying mobile terminals within wireless/cellular networks to support a variety of missions such as goods delivery, search and rescue, precision agriculture monitoring, and remote sensing. On the other hand, UAVs can be utilized as aerial base stations to increase wireless communication coverage, reliability, and the capacity of wireless systems without additional investment in wireless systems infrastructure. The aim of this article is to review the current applications of UAVs for civil and commercial purposes. The focus of this paper is on the challenges and communication requirements associated with UAV-based communication systems. This article initially classifies UAVs in terms of various parameters, some of which can impact UAVs' communication performance. It then provides an overview of aerial networking and investigates UAVs routing protocols specifically, which are considered as one of the challenges in UAV communication. This article later investigates the use of UAV networks in a variety of civil applications and considers many challenges and communication demands of these applications. Subsequently, different types of simulation platforms are investigated from a communication and networking viewpoint. Finally, it identifies areas of future research.

INDEX TERMS Unmanned aerial vehicle, UAV, communications, civil applications, wireless networks.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs), informally known as drones, have been the subject of intense research among a growing number of academic scientists and engineers in recent years [1], [2], [3], [4], [5], [6]. UAVs have historically been utilized for military applications to perform a wide range of military operations [7], [8]. However, due to significant advancements in the design and production of inexpensive and highly reliable unmanned aerial vehicles as well as the growing demand for commercial utilization of such low-cost platforms, UAVs are now being used in a vast number of civil and commercial applications [1]. In addition, UAVs' unique attributes, such as ease of use, rapid deployment to far-flung areas, high-mobility, maneuverability, and their ability to hover, make them excellent candidates for civil and commercial applications [1]. Examples of such applications include search and rescue missions [9], [10], [11], [12], precision agriculture monitoring [13], natural disaster and environmental monitoring [14], [15], delivery of goods [16], [17], [18], [19], and remote sensing [20], [21]. A single UAV or multiple UAVs can be used as communication relays or

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even aerial base stations (BSs) to provide wireless network coverage [22], [23], [24]. In geographical areas Where users are located far from one another and reliable direct communication links cannot be provided to users, UAVs can be used as communication relays to provide wireless connectivity among distant users [3], [7]. As an example, in millimeter-wave (mmWave) communications [25], [26], where short wavelengths are easily blocked by obstacles, communication relays are commonly required to bypass these obstacles [27], [28]. UAVs can also be used in Internet of things (IoT) applications [29], [30], [31], [32]. Physical objects (also called ''things'') in such applications may not be able to communicate over a long range. UAVs can then be used as dynamic gateways in IoT applications to relay wireless information [33], [34]. When drones are specifically used as flying aerial BSs, they can provide adequate support for the network connectivity in the existing terrestrial wireless networks such as broadband and cellular networks to secure transmission of data to the users [3], [35]. The main advantages of utilizing UAVs as flying BSs over conventional terrestrial BSs involve their capability to avoid obstacles, adjust and adapt their altitude, and increase the probability of establishing line-of-sight (LoS) wireless communication links with terrestrial end users [3], [7]. In fact, UAVs' intrinsic characteristics such as altitude adjustability, high mobility, and ability for rapid deployment can assist the UAV BSs to efficiently and effectively complement the existing broadband and cellular networks and provide network coverage to difficult-to-reach areas [3]. A single UAV or swarm of UAVs can be used to perform operational tasks. However, in some cases, due to limited power and capacity of a single UAV, a single UAV cannot simply complete complicated and persistent tasks; therefore, a group of UAVs is required to accomplish tasks cooperatively [36], [37], [38]. Different applications require a different number or set of UAVs to collaborate within their aerial network to perform tasks efficiently. Thus, it is important to determine the optimal number of UAVs required for a given application for efficient deployment of UAVs and effective coverage of the targeted area. Savkin *et al.* [39] proposed to use an algorithm to estimate the minimum number of drones required to be deployed in a specific surveillance and monitoring application. Mozaffari *et al.* [40] analyzed an efficient deployment of UAVs where each acts as a wireless base station that provides coverage for ground users. The group identified the 3D locations of the drones in such a way that total coverage area is maximized at the same time when the coverage lifetime of the drones is also maximized. UAVs can operate as a team and be deployed to a crowded area, such as a music festival, sporting event or other major public event, as aerial BSs to deliver cost-effective, reliable and on-demand wireless coverage [7], [24], [35], [41], or be deployed as an aerial sensor network, gathering information from large areas [42], [43]. Wireless communications and networking are vital in such a team of UAVs to ensure desired behavior of team members and coordination among multiple UAVs. However, it is very challenging to establish and maintain efficient communication links among the UAVs. Various issues exist that need to be addressed spanning from network planning, resource allocation, cell association, to deployment.

Mozzaffari *et al.* [3] investigated the key challenges and important trade-offs in UAV-enabled wireless networks. The authors mainly considered the major UAV challenges such as channel modeling, energy efficiency, three-dimensional deployment and performance analysis. The authors then discussed open problems and potential research directions relating to UAV communications. At the end, they described a variety of analytical frameworks and mathematical tools that can be used in this domain such as stochastic geometry, game theory, transport theory, machine learning and optimization theory. Furthermore, they explained how to use such tools to tackle UAV problems. Fotouhi *et al.* [5] presented a review of current developments in the UAV industry that lead to smooth integration of UAVs into cellular networks. Particularly, they reviewed some types of consumer UAVs that are currently available off-the-shelf. The authors addressed the UAVs' related communication interference issues and explained how the standardization bodies provided potential solutions for integrating aerial vehicles with the existing terrestrial BSs. They discussed the challenges and opportunities involved in assisting cellular communications with UAV-based flying relays and BSs. Moreover, the authors investigated the existing prototypes in this domain and test bed activities.

Until now, a few review papers have been written in this domain. Two of those are very relevant to this article. Hayat *et al.* [1] presented the requirements and characteristics of the UAV networks for future civil and commercial applications. The authors reviewed many research articles published over the period of 2000-2015 from a communications and networking viewpoint. They investigated the data requirements, quality of service requirements, network-relevant mission parameters, and the minimum data to be transmitted over the network for civil applications. Subsequently, they examined general networking related requirements such as safety, security, privacy, connectivity, scalability and adaptability. Finally, the group reviewed the experimental results from other projects in this field and discussed the suitability of current communication technologies for supporting reliable aerial networks. Comprehensive work presented in [1] has helped expand the body of knowledge on the topic. Further work would include more up-to-date information that further assists with identifying the current state of the technology.

Quy *et al.* [44] discussed the perspective of Vehicle Ad hoc Networks (VANET) to be implemented into smart cities. The authors presented a comprehensive perspective of the techniques to enable automobile communication networks in urban environments. Their survey specified three directions, listed as multimetric, Interne/UAV/Cloud, and Intelligent, that would be needed to enhance VANETs in the future. Another updated perspective was discussed by Zaidi *et al.* [45]. Advancing the technology into the future would require the Internet of Flying Things (IoFT). This document presented a comprehensive review IoFT definitions, characteristics, applications, cloud-computing, fog-computing, edge-computing, cellular-networks and challenges. Srivatava and Prakash [46] identified the technology for future applications as Flying Ad hoc Networks (FANET). The authors provided a comprehensive survey on UAV categorization, FANET characteristics and architecture, mobility models, routing techniques/protocols/taxonomy, simulators, and challenges. Their work is an effective guide for identifying up-to-date developments on FANETs.

Shakhatreh *et al.* [2] investigated the UAVs, some of the UAV challenges and their civil applications. The authors presented the existing research trends in this domain and provided further insights on potential future UAV uses. Moreover, they discussed the main challenges of UAV for civil applications including collision avoidance, as well as swarming, charging, security and networking challenges. Finally, they discussed open research challenges in this domain based on the articles they reviewed. Further updates on challenges can be explored in [45] and [46]. This article will further expand into what was identified as critical in the multiple surveyed documentation.

The main purpose of this paper is to provide a highly comprehensive guide to researchers on UAV-enabled communication technologies. This article provides a wide spectrum of organized references that combine fundamental concepts in this domain with the state-of-the-art topics. This paper also catalogs multiple overviews on specific technologies as a comprehensive starting point for new researchers. In addition, many of the cataloged references provide a comprehensive review for the subject matter experts, or provide the opportunity to explore new topics. This article reviews some of the newest technologies in this domain for utilization of drones specifically for civil applications. It is projected that drones will be used for the development of communities in the future. The civil applications of drones in particular are abundant. However, the authors attempted to summarize some of the most important applications in this domain. Some of the important contributions of this paper that make it stand out from other articles are as follows: a section with up-to-date UAV classification for use in civil applications is provided which is followed by a discussion section focusing on the impact of frequency, height, as well as size on the communication performance of the categorized UAVs. An updated section regarding the state-of-the-art uses of drones in civil applications is also provided. Some important challenges, that are associated with UAV communication including physical layer related issues, channel modeling, spectrum management and communication security, are clearly discussed. In future research directions section, an overview of a relatively new topic, quantum cryptography for enhanced UAV communication security, is also included.

This survey aims to simplify the topics and help the specialized research community by identifying niche areas in the development of communication systems involving drones. This document is organized as follows: Section II identifies the ways in which to take advantage of the UAS technologies within the realm of communications. Section III presents a thorough review of the most up-to-date classification of UAS technologies. Section IV provides a comprehensive but selective review on FANET technologies. Application scenarios are explored in Section V where relevant UAS wireless applications in industry or civilian implementations are identified. Challenges in UAV communications are discussed in Section VI. Section VII reviews simulation platforms for UAV application scenarios. Finally, Sections VIII and IX offer future research directions and conclusions, respectively, based on the reviewed literature in this document.

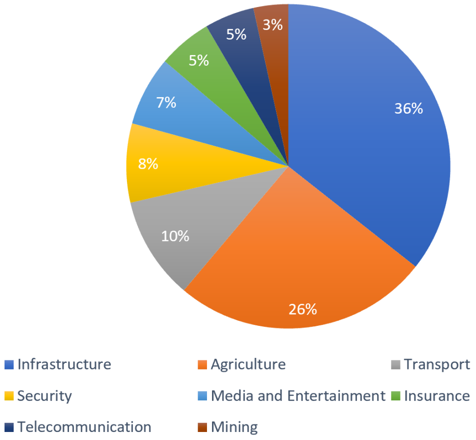


FIGURE 1. **Distribution of UAV market value by industry [48].**

II. CURRENT AND FUTURE MARKET OPPORTUNITIES

The UAV global market is very promising and offers an excellent prospect for further growth. The global market for civil applications of UAV systems is expected to be among one of the most vibrant developing sectors in the upcoming decade. The market is anticipated to expand from an almost 5 billion-dollar annual market in 2019 to about a 14.5 billion-dollar annual market by 2028. That indicates a compound annual growth rate (CAGR) of 12.5 percent in constant dollars [47]. The civil UAV market is predicted to grow to a total of 88.3 billion dollars over the next decade [47]. According to Silver *et al.* [48], the civil UAV market is divided into the following key industries: infrastructure, agriculture, transport, security, media and entertainment, insurance, telecommunication, and mining. The distribution of market value is represented by Figure 1.

By 2021, sales of consumer UAVs were expected to reach 29 million units, and sales of UAVs for commercial uses were expected to reach 805,000 units [49]. Civil governments in Europe and the United States are becoming keen to take advantage of UAV systems for various applications such as border control and maritime security. Moreover, peacekeeping operations conducted by United Nations (UN) entities can also have impact on UAV market sales [50]. Public safety deployment of UAVs for fire control and law enforcement purposes has increased over the past few years. The European maritime safety agency (EMSA) and United States Coast Guard have shown interests for broader deployment of the UAV systems. The market for UAV commercial applications is expected to increase rapidly in many sectors such as energy, transport, and insurance over the next few years. The agricultural UAV market is estimated to increase from 1.2 billion dollars in 2019 to 4.8 billion dollars by 2024. This is due to the increased pressure on the global food supply caused but an increasing world population, as well as the increase in funding for agricultural UAV development [51]. According to Silver *et al.* [48], infrastructure takes up the largest percentage of the overall market for UAV civil applications. The infrastructure sector had a 239 percent increase in adoption of UAVs in 2018 [52]. According to Mazur *et al.* [53], the estimated potential market value for drones in the infrastructure sector is 45.2 billion dollars. There are many uses for drones in infrastructure including inspection of power lines [54], [55], pipelines [56], [57], vertical structures [58], [59], damns [60], bridges [61], railways [62], and other areas. Drones can also be used for photogrammetry [63], sensing, and data collection [64]. A comprehensive analysis of the economic potential and market opportunities of drones is investigated in [65]. The number of life threatening accidents on construction sites can be reduced by 91 percent when monitored by drones, according to Mazur *et al.* [53]. The market for security drones is also expected to eventually reach 10.5 billion dollars [48]. The potential value for the telecommunications drone market is 6.3 billion dollars [48]. Drone use in the energy sector is also expected to grow to 8.4 billion dollars by 2025 [66]. According to Gammill *et al.*, drones can be used on solar farms for inspections and are 97% more efficient than manual inspections, taking only 10 minutes per MW of solar [67]. On wind farms, drones can be used to inspect a wind turbine in as little as 40 minutes for all three blades [68], [69]. UAV use in the insurance sector is also expected to grow [70]. Mazur *et al.* estimated the potential market for drones in the insurance industry to be valued at 6.8 billion dollars [53]. UAVs can be used for several applications in insurance arena including inspections, risk assessment, fraud prevention, claims adjudication, risk engineering, and natural disaster monitoring [48], [71]. One example of UAVs in the insurance industry would be the inspection of rooftops of damaged homes, as the insurance company Liberty Mutual has started adopting [72]. The market for drones in the transportation and logistics industry is estimated to be worth 11.2 billion dollars in 2022, and expected to grow to 29.06 billion dollars by 2027 [72]. Package delivery is just one application within this sector, with a market value expected to reach 6 billion dollars by 2026 [73]. There are several uses for UAVs within the mining sector, including mine planning, blast engineering, site development optimization, environmental monitoring, mapping, and stockpile management [74]. One company, AUD, was able to save 5 million USD annually by switching from hiring a plane to hiring a drone pilot for operating a drone with a camera for surveying mines prior to blasting activities [75]. The global market size for UAV commercial applications is predicted to reach 129.23 billion USD by 2025, registering a compound annually growth rate (CAGR) of 56.5 percent over the estimated period [76]. Furthermore, over 100,000 new jobs within the UAS industry are expected to be created by 2025 [77]. As the number of applications for UAV systems continues to grow and as UAV technologies continue to evolve, all of the preceding statistics show the economic importance of UAV systems for numerous sectors of industry in the near future.

III. UAV CLASSIFICATION

Up to now, many different versions of UAV classifications have been defined and clearly described by the scientific community. Many of the existing classifications are performed to classify the use of UAVs for military and civil applications, while a few of these classifications are specifically carried out to categorize the use of UAVs for civil and commercial applications. Watts *et al.* [78] investigated various UAV platforms including their sensor capabilities and described the advantages of each platform and their relevance to the demand of users in the scientific community. Authors in this paper categorized the UAV platforms based on a few of their specific attributes such as flight endurance, physical size, and potential capabilities. In this categorization, the authors classified UAV platforms as nano air vehicles (NAVs), micro/miniature air vehicles (MAVs), vertical take-off and landing (VTOL), low altitude short endurance (LASE), low altitude long endurance (LALE), medium altitude long endurance (MALE) and high altitude long endurance (HALE). Gupta *et al.* [79] categorized UAVs as NAVs, MAVs, mini UAVs (MUAVs), tactical UAVs (TUAVs), MALE and HALE. Korchenko and Ilyash utilized a different classification which took into account sixteen important features of the UAVs, such as flight rules, aircraft types, aircraft engine types, aircraft applications, type of control systems, take-off and landing directions, wing types and fuel systems [80]. Weibel and Hansman [81] differentiated the UAVs by mass and then categorized them into micro, mini, tactical, medium altitude and high altitude UAVs. Cavoukian [82] classified UAVs into three major types representing Micro and mini UAVs that can fly at low altitudes (below 300 m), as operating in urban canyons, inside buildings or along hallways. Tactical UAVs compared to micro and mini UAVs are heavier, ranging from 150 to 1500 kg, and can fly at higher altitudes ranging from 3000 to 8000 m. Such UAVs currently only support military applications. Strategic UAVs that belong to HALE classification can support longer flight ranges and can reach a maximum flight altitude of around 20,000 m. These types of UAVs can carry much larger payloads and more sophisticated equipment, and are also designed mainly for military applications. Australian civil aviation safety authority (CASA) classified UAVs into four groups based on their weight [83]. Micro UAVs with gross weight of 100 grams or less, small UAVs with the weight of less than 2 kg, medium UAVs with the weight of greater than 2 kg and less than 150 kg, and large UAVs with the weight of greater than 150 kg. Hassanalian and Abdelkefi [84] created a spread spectrum figure of different classes of existing UAVs, began with a UAV class that have weight of around 15,000 kg and maximum wing span of 61 m and finished with a UAV class named as smart dust (SD) [85] with a weight of around 0.005 g and minimum size of 1 mm. The authors then proposed a more comprehensive classification of all available UAVs that includes UAV, μUAV, MAV, NAV, PAV and SD [84]. SD is referred to tiny robots, consists of 100s to 1000s of miniature micro-electro-mechanical systems (MEMS) that are typically operate wirelessly within a network, and distributed over certain areas for data collection. SDs are very light nodes that can move around with winds or even remain suspended in the air for monitoring of weather conditions. SD can be used in a variety of applications such as climate control, environmental monitoring, and building safety [84], [86], [87]. Mozaffari *et al.* [3] researched the use of UAVs for wireless networks in civil applications. Based on civillian applications, he then classified UAVs into two different groups. In one classification, UAVs were categorized into LAPs and HAPs and in the other classification, UAVs were categorized based on their type into fixed-wing UAVs and rotary-wing UAVs. Shakhatreh *et al.* [2] investigated the UAV systems that are designed specifically for civil applications. The authors then provided a new UAV classification considering several specific attributes of the UAVs such as maximum altitude, payload capacity, weight, operational endurance, fuel type, and communication range. He classified UAVs based on their communication platforms into low-altitude platforms (LAPs) and high-altitude platforms (HAPs). LAPs were further subcategorized into balloon, VTOL and aircraft. HAPs were Shakhatreh201 subclassified into aircraft, balloon and airship. As mentioned before, UAVs can be used in a variety of applications ranging from military to civil and commercial applications. This article specifically investigates the use of UAV for civil and commercial applications. Each application scenario may require a specific type of UAV to achieve the stringent requirements that are imposed by the U.S. federal aviation regulations (FARs), the nature of environment, and the demanded quality of service (QoS). Thus, to be able to appropriately employ UAVs for specific applications, several key features, including payload size, flying mechanism, flying altitude, coverage range, flight time and maximum speed, must be considered thoroughly and in more detail.

A. FLYING MECHANISM

UAVs can also be classified based on their flying mechanisms into four main types [88], [89], [90] (see Figure 2. Depending on the intended application, each classification displays different advantages or limitations over one another.

1) FIXED-WING UAVs

Fixed-wing aircraft are flying machines that use a forward airspeed to generate lift using a fixed airfoil, or wings, such as an airplane [84]. Fixed-wing UAVs are mostly utilized for aerial mapping and data collection [91], [92], [93]. They are also often used for inspection of power lines [94] and pipelines [95]. Compared to rotary-wing copters, fixed-wing UAVs are intrinsically more energy efficient [96]. Although, most of the existing studies on UAV systems for wireless cellular coverage is focused on considering the rotary-wing UAVs, fixed-wing UAVs are expected to be more suitable for wireless connectivity purposes in situations where long flight times are required. This is because fixed-wing UAVs rely on a much more energy-efficient way of flight in contrast to the rotary-wing UAVs [97]. Xie and Huang [98] evaluated an UAV-enabled relaying network where a fixed-wing UAV is positioned between the base station and ground users. The authors proposed a method to optimize the radius of UAV circular trajectory along with the transmission power allocated with the purpose of maximizing energy-efficiency of the UAV relay network. Fixed-wing UAVs are also able to utilize more conventional propulsion methods such as internal combustion engines [99], [100]. This allows for the use of fuels such as gasoline to be utilized, which contains a higher energy density than batteries [99]. Among combustion engines, diesel engines have the highest effective efficiency [99]. They fly at higher speeds and can cover longer ranges [101]. For this reason, fixed-wing UAVs may be better suited for long range or high endurance purposes [102]. Unlike a single fixed-wing drone, fixed-wing UAVs can cooperatively work together as a team to cover large geographical areas and accomplish their assigned tasks much quicker. Furthermore, in terms of endurance, cooperative fixed-wing UAVs operate better compared to cooperative multi-rotor drones [103]. Elijah *et al.* investigated control and maneuvering of cooperative fixed-wing drones. The authors conclude that fixed-wing drone technology is a natural result of advancements in the hardware components that make up these drones [103].

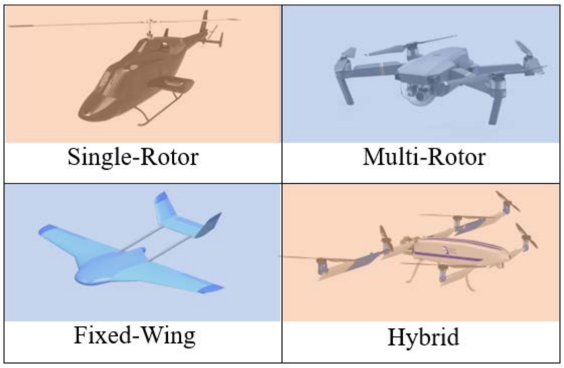


FIGURE 2. Most common UAV flying mechanisms.

2) MULTI-ROTOR UAVs

Unlike fixed-wing aircraft, multi-rotor UAVs generally do not utilize wings to generate lift. Instead, these UAVs use several vertically-oriented motors/propellers (typically 3-8) to provide downward thrust to generate lift and keep the UAV airborne [104], [105]. Kotarski *et al.* provided a complete mathematical model for designing a multi-rotor UAV [106]. The authors presented a modular design approach for the development of an educational engineering platform. Due to the lack of aerodynamic structures that are necessary for flight with fixed-wing aircrafts, the size of the multi-rotor UAVs can be much smaller than that of fixed-wing aircraft in order to carry payloads of the same size and weight [107]. Another advantage of multi-rotor UAVs is that they can be launched virtually anywhere, as they are able to conduct vertical takeoff and landing (VTOL) [105]. Multi-rotor UAVs are capable of hovering and holding their position [105], whereas fixed-wing aircraft must constantly remain in motion [103], enabling greater maneuverability to multi-rotor UAVs. However, multi-rotor UAVs also have several shortcomings such as having limited speed and endurance, and since they rely solely on downward thrust to remain airborne, they are only able to maintain an average flying time of between 20 and 30 minutes [108]. Moreover, battery weight and energy storage constraints also affect the flight time of multi-rotor UAVs [109]. Biczyski *et al.* created a set of tools to aid in the design of customized solutions that can be specially tailored for a specific application [109]. The athours also proposed a technique for measuring the multi-rotor propulsion system via the selection of motors and propellers. The proposed method can provide data for the selection of the Electronic Speed Controller (ESC) and battery. Furthermore, the authors provide a method of comparing several configurations via estimation of flight time by modelling battery discharge at a constant power requirement [109]. The rapid development of multi-rotor drones has enabled a considerable number of applications in various commercial sectors. For instance, multi-rotor UAVs can be used to deliver light packages as shown in [110], [111], and [112]. Stolaroff *et al.* investigated the energy use and greenhouse gas emissions of multi-rotor drones for commercial package delivery [113]. The authors found the current practical range of multi-rotor UAVs to be about 4 km with existing battery technology. They also showed that UAV-based delivery systems could reduce greenhouse gas emissions and energy use in the freight sector. A number of applications of multi-rotor UAVs in construction management is also investigated in by Adepoju [89] and Li *et al.* [114]. Yang *et al.* also investigated the use of multi-rotor UAVs for wireless transmission of high definition (HD) videos in aerial photography [115]. Multi-rotor drones can also be used for autonomous monitoring, analysis, and countering of airborne particles [116], [117]. However, in order to be able to equip drones with light-weight sensors, low-cost, off-the-shelf Particulate Matter (PM) sensors must initially be compared with the standard costly reference instruments and then be calibrated [118], [119].

3) SINGLE ROTOR UAVs

Single rotor drones (also known as mono-copters) are very similar to helicopters in terms of design and structure [84], [120]. In fact, single rotor drones consist of two rotors; one rotor is located on top and the other one is positioned at the tail. The larger rotor on the top is used for lift while the smaller one at the tail is used for control [121]. Compared to multi-rotor systems, Single rotor drones have higher endurance with longer flights and can carry heavier payloads to perform a variety of tasks [122], and they are often powered by gas engines [123]. Much like the multi-rotor UAVs, single rotor drones are also suitable for aerial photography [124] in addition to spraying agricultural crops [121], [125]. Although the use of single rotor drones for agricultural plant protection has been greatly appreciated, various shortcomings still exist in this field. For instance, one of the disadvantages of using single rotor drones in agricultural plant protection is studied by Wen *et al.* [126]. The authors showed that the rotor flow field of a single rotor UAV can cause drift of the droplets, resulting in waste and secondary disaster. They proved that digital simulation can be useful to overcome this problem. Generally, single rotor UAVs can come with higher operational risks as the rotating blades positioned on the top often pose risks to human being and nature [88], [125]. Therefore, trained professionals are needed to fly them [122].

4) HYBRID FIXED-WING/MULTI-ROTOR UAVs

Hybrid fixed-wing/multi-rotor UAVs combine the aspects of a multi-rotor and a fixed-wing aircraft [127], [128], [129]. These aircraft utilize both an airfoil and downward thrust to combine the VTOL capabilities of a multi-rotor with the higher efficiency of a fixed-wing aircraft. Because of this, a hybrid aircraft is able to take off and land virtually anywhere and then fly long distances or for long periods of time [108], [130]. This allows for a much more versatile system, as no runways or catapults are needed while maintaining higher range and flight time capabilities [130]. Saeed *et al.* provided a comprehensive overview on the latest technological advances in small hybrid UAVs [127]. Ducard and Allenspach reviewed the designs and flight control techniques of hybrid UAVs [131]. Ke *et al.* provided a novel design and implementation details of a hybrid UAV with model-based flight capabilities [132]. Zhou *et al.* presented more details on performance evaluation of hybrid VTOL UAVs in their review [133].

B. FLYING ALTITUDE

UAVs can also be classified into two groups based on their flying altitudes; low-altitude platforms (LAPs) and high-altitude platforms (HAPs). LAPs are designed to fly at low altitudes, as their name implies. Typically LAPs can fly at altitudes of around tens of meters up to about a few kilometers [3], [134]. LAPs are relatively inexpensive and can move around with greater maneuverability [6], [135]. Federal aviation administration (FAA), a governmental body that prescribes rules related to aviation activities in the United States (US), provides specific regulations regarding the LAPs. FAA has limited flying operation of LAPs to not higher than a maximum allowable altitude of around 120 m. Furthermore, Unlike HAPs, LAPs can be deployed more rapidly which makes them a proper solution for time-sensitive applications such as search and rescue (SAR) missions. LAPs can easily be replaced or recharged if required and are able to gather information from ground sensors. Low-altitude UAV networks can be used to provide wireless network coverage in urban environments [136]. Galkin *et al.* presented a scenario in which a network of UAVs operating at a specific altitude above the ground could deliver wireless services to end users within their coverage areas [136]. On the other hand, UAVs that fly at high altitudes, typically above 20 km, are able to operate in the upper layer of the atmosphere and are usually quasi-stationary [137]. In such high-altitude environments, the performance of coverage relies highly on line-of-sight (LoS) propagation attributes and is also somewhat dependent on the angle of elevation [138]. Although, propagation delays and atmospheric effects can cause certain challenges associated with channel modeling for UAV communications, high-altitude platforms can increase the UAVs' coverage and also to provide communication skeleton for aerial heterogeneous networks [138]. In addition, HAPs are designed such that they can operate with longer endurance (e.g. up to several months) in missions [137]. Moreover, HAPs are usually used for providing a broader range of network wireless coverage for greater geographic areas [7], [137]. However, HAP systems are relatively expensive and require much longer deployment time compared to LAPs.

C. WEIGHT/PAYLOAD CAPACITY/SIZE

UAVs can also be categorized by weight, payload capacity, and size. The National Aeronautics and Space Administration (NASA) classifies UAVs into three categories based on weight; Category I encompasses UAVs 55 lb and less, Category II ranges from 55-330 lbs, and Category III encompasses UAVs greater than 330 lbs [139]. The U.S. Department of Defense (DoD) categorizes UAVs into 5 groups: groups 1-5 are represented in size as small, medium, large, larger, and largest, respectively, and with gross takeoff weights in lbs of 0-20, 21-55, <1320, >1320, and >1320, respectively [140]. The DoD also factors airspeed and normal operating altitude into these groups. The article also categorized UAVs into the following size categories: Very small (<50cm), Small (50cm – 2m), Medium (5-10m), and Large UAVs. Payload is defined as the maximum amount of weight that a UAV can carry including additional sensors, cameras or packages for delivery [5]. Many UAVs make use of predetermined payload sizes in order to carry their required items. As an example, for oil and gas pipeline monitoring, predetermined but various payload sizes can be used. Gomez and Green proposed three different scenarios for monitoring oil and gas pipelines using small UAV systems [141]. In scenario 1, where UAV systems are used for proximity survey/visual identification of pipe damage, payload capacities of less than 7 kg are used. In scenario 2, where UAV systems are employed for short distance survey/visual identification of leaks, payload capacities of less than 25 kg are used, and in scenario 3, where UAV systems are used for long distance survey/automatic sensing of soil properties, payload capacities of about 200 kg are used [141]. In some applications such as agricultural spraying and package delivery, a predetermined payload capacity cannot be used, since weight of the carried package can dynamically be changed during the mission. The dynamic change in the weight of the payload can influence on stability and controllability of the UAV [142]. The weight of payloads is varied from tens of grams up to hundreds of kilograms. Some applications use smaller payload capacities to accomplish their missions. For instance, Koparan *et al.* developed an unmanned aerial vehicle-assisted water quality measurement system (UAMS) with a payload capacity of 750 g for in situ surface water quality measurement [143]. Other applications use higher payload capacities to achieve their tasks. For instance, in China more than 60% of UAV-based agricultural spraying systems use payloads with the capacity of less than 15 kg. A UAV sprayer which includes a larger payload size can spray a farm more efficiently compared to a UAV sprayer with a smaller payload. Thus, with increasing size of farms, the demand for higher payload capacities also increases [144]. Weight and payload can significantly affect a UAV's energy consumption. Other factors contributing to energy consumption include flying mechanism, distance, altitude and speed [145]. As energy consumption is one of the most important factors in almost all unmanned aerial vehicles, it should be carefully considered when using a UAV for civil applications. A review of energy consumption models and their relations to the UAV routing mechanisms is investigated by Thibbotuwawa *et al.* [146].

D. COMMUNICATION RANGE/COVERAGE RANGE

Coverage range plays an important role when choosing a UAV for a particular application. The authors of [147] defined 5 different categories with corresponding ranges: Nano (<1km), Micro and Mini (<10km), Close Range (10-30 km), and Short Range (30-70km). The authors state that there are UAVs over the Short Range category, but they are rarely used for civil applications. According to [123], UAVs can be classified as: Very low cost close-range (5km), Close-range (50km), Short-range (150km), Mid-range (650km), and Endurance (300km) UAVs. In terms of operation, UAVs are classified mostly into two categories. A UAV can operate autonomously or be remotely controlled by a pilot. A remotely piloted UAV is required to establish a reliable unidirectional/bidirectional communication link between itself and its pilot. Due to the nature of the remote presence of human(s) in UAV systems, communication range also plays an important role to support pilot-UAV communication link. Communication protocol must be selected such that it can support a variety of missions with different communication range requirements. The communication range is defined as the maximum distance from which an UAV can remotely be controlled. Communication range is varied from tens of meters for small UAVs to hundreds of kilometers for larger UAVs [5]. However, the communication range of most UAVs that are specifically designed to be used in civil and commercial applications is relatively limited. Many commonly used wireless communication protocols are restricted by short communication ranges and are easily blocked by obstacles. Use of communication relays can be beneficial to solve limitations associated with communication ranges [148]. In addition, the pilot-UAV communication range is highly depended on several factors such as types of antenna, operation frequencies and the nature of environments that an UAV is flying.

E. FLIGHT TIME

The flight time, or endurance, of a UAV can be an important consideration for UAV civil applications. The amount of fuel, whether gas or electric, fuel consumption rate, environmental conditions, flying mechanism, and design of the UAV will largely determine the flight time of a UAV [149]. UAVs can be classified based on endurance into the following categories: Miniature-UAVs (less than 2 hours), Close Range (2-4 hours), Short-Range (3-6 hours), Medium-Range (6-10 hours), and Medium Altitude Long Endurance (MALE), High-Altitude Long Endurance (HALE), Stratospheric Over (24-48 hours) [150]. While there are several categories of UAVs with flight times over two hours, many commercially available drones would fit into the first category of miniature UAVs, as shown by [151]. The article reviewed several aspects of many commercially available UAVs, including flight time, and all of the drones reviewed had flight times of thirty minutes or less. For some applications, these flight times are viable options. For example, [152] used a UAV capable of flying just 8 minutes and was able to use the drone for below-canopy tree surveys. The authors utilized the UAV to survey a 20 m × 20 m patch of trees and was able to detect 73% of trees greater than 200 mm diameter-at-breast-height using a mounted LiDAR unit and their own post-processing software. Erdenebat and Waldman [153] were able to use photogrammetry with a commercially available drone (called DJI Matrice 600). In this work, they were able to measure the deformation of a concrete bridge under various loads with a flight time between 18 and 40 minutes (0-5.5 kg). Some applications, however, require higher flight times. The authors of [102] developed a fixed wing UAV capable of flying up to 3 hours or 180km for the purposes of surveying calving glaciers in Greenland. The UAV was capable of producing accurately geo-referenced and high special resolution ortho-images and digital elevation models, surveying up to four tidewater glaciers in a single flight, and performing repeat mapping surveys of six calving glacier termini in 2017 and 2018. UAVs with a longer flight duration were found in [154] to be more effective when used in hover-fly-hover (HFH) scenarios whereas UAVs with a shorter flight duration were found to be more useful when hovering in a fixed position. [155] explored the minimization of flight times when using UAVs to collect data from wireless sensor networks. The authors observed that the optimal flight speed is proportional to the distances between sensors and energy of the sensors, and inversely proportional to data upload requirements.

F. MAXIMUM SPEED

Maximum speed may be another important factor in UAV civil applications. The classifications in [140] factor airspeed into the categorizations of UAVs, with group 1 (small UAVs) having airspeed up to 100 knots, groups 2-3 (medium to large) with airspeeds up to 250 knots, and groups 4 and 5 which can have any airspeed. From a civil standpoint, there are federal limitations to airspeed, however. The Federal Aviation Administration (FAA) states that a drone operator with a Part 107 license may only fly up to 87 knots [156]. *Wu et al. [154]* investigated the use of a UAV-enabled two-use broadcast channel, where a UAV is used to send information to two users in different geographic locations. The authors considered two cases with large/low flight duration/speed, where the UAV's maximum speed and transmit power were the primary constraints, and attempted to optimize the UAV's trajectory and transmit power allocations over time with a fixed flight duration. In the first case, a hover-fly-hover trajectory with time division multiple access based orthogonal multiuser transmission is able to achieve the desired capacity. However in the second case, it is better for the UAV to remain in a fixed location in closer proximity to the user with higher achievable rate and superposition coding based non-orthogonal transmission is required with interference cancellation at the receiver of the closer user.

G. DISCUSSION: FREQUENCY, ALTITUDE AND SIZE EFFECTS ON COMMUNICATION PERFORMANCE

Since there is a lack of universal regulation for the frequency utilization, a difficult issue in air-to-ground channel modeling that needs to be addressed is the diversity of suitable frequencies for UAV communication systems [157]. With reference to channel modeling, taking the operating frequency into account contributes to the creation of a more complete model, improving the generality of the model and enabling its application in a variety of situations with diverse operating frequencies [157]. Latest research on air-to-ground channel modeling methods mostly concentrates on low-frequency bands, including those of IEEE 802.11a/g/n (2.4 GHz, 5.8 GHz), or L-band (1-2 GHz), or C-band (4 GHz), which the International Telecommunication Union (ITU) recommends for drone communications [157], [158]. For instance, Asadpour *et al.* [159] showed through testing that the 802.11n communication protocol works poorly in circumstances involving high levels of mobility and aerial work. Asadpour *et al.* demonstrated that as soon as drones take to the air, network throughput between them drops below the theoretical maximum. Schneckenburger *et al.* investigated the properties of the L-band air-to-ground radio channel for positioning applications, and then reported their findings in [160]. Authors in [161] measured the performance of air-to-ground channels over sea at the C-band with low airborne altitudes (0.37-1.83 km). They showed that the likelihood of appearance of multi-path components increases as the airborne altitude decreases. Authors in [162] presented a comprehensive survey regarding air-to-ground propagation channel modeling. Space-air-ground integrated network (SAGIN) is an integration of satellite systems, aerial networks, and terrestrial communications [163]. Aerial networks located at the middle layer of the SAGIN uses drones for information acquisition, transmission, and processing. Drones that operate in this layer must establish communication links with ground terminals in addition to communicating with satellites which mostly operate in the C, K and Ku-bands [163]. Existing cellular networks mostly operate in the sub-6 GHz [157]. However, it is likely that future applications in SAGIN use beyond-6 GHz bands. Considering this, authors in [157] investigated multi-frequency (sub-6 GHz and beyond-6 GHz bands such as 1 GHz, 4 GHz, 12 GHz, and 24 GHz) air-to-ground propagation channels for low-altitude UAV vertical flights. In this research, important large-scale and small-scale channel parameters, such as shadowing, path loss and autocorrelation as well as small-scale fading features were greatly modeled and analyzed.

The effect of the UAV's altitude on the propagation channel is another key issue in air-to-ground channel modeling. The height of the drone considerably affects the signal transmission, according to several research studies performed on the physical layer of the open systems interconnection (OSI) model [164], [165], [166], [167]. For example, the authors in [166] measured air-to-ground channels over cellular networks, where the UAV altitude varied from 1.5 m to 120 m. The findings in [166] indicate that when the altitude increases, the path loss exponent (PLE) reduces from 3.7 to 2.0, which implies that the scattering environment slowly becomes minimal with the height. Authors in [168] also investigated the impact of UAV altitude in various aerial channel environments. The battery life of UAV is significantly influenced by drone size, drone weight, and environmental factors [169]. Smaller UAVs can only fly for a short period of time whereas larger UAVs may travel for hours. Battery life is also greatly influenced by wireless communication; wireless communication uses a large amount of energy when compared to data computing and information sensing [170], [171]. Therefore, significant energy savings can be achieved by lowering the energy used for data exchange. Zeng *et al.* [172] proposed a method to minimize the energy consumption of wireless communication for rotary-wing UAVs. Zeng *et al.* in this research, initially developed an analytical model for the propulsion energy expenditure of the rotary-wing drones; then offered a method for reducing energy that simultaneously optimizes the trajectory of the UAV, the distribution of communication time among the various ground nodes, and the overall mission completion time; and ultimately proposed a strategy for the energy-saving issue in which the drone also communicates while flying.

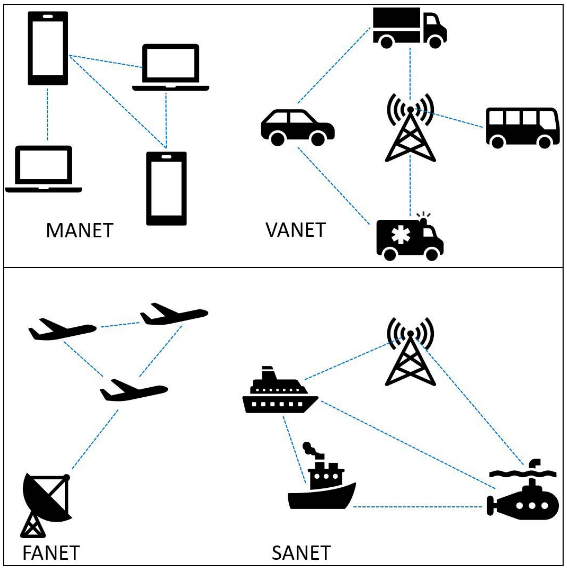


FIGURE 3. Types of Ad-hoc networks [178].

IV. AERIAL NETWORKING

In a multi-UAV system, it is possible for UAVs to work together within a network; this is known as a flying ad hoc network, or FANET [173]. FANETs are often seen as a subset of vehicle ad hoc networks (VANETs), which are a subset of mobile ad hoc networks, or MANETs [174]. MANETs usually are comprised of devices such as cellular phones, laptop computers, and other mobile devices [175]. VANETs are comprised of vehicles and road-side infrastructure that can communicate with each other within a network [176], [177]. The work of Albu-Salih [178] illustrated this definition in a simple way. The difference between MANET, VANET, FANET and SANET can be seen in Figure 3. Al-Absi *et al.* [179] further expanded the classification of ad hoc networks by adding a maritime domain into the unmanned systems network types with the ship ad hoc networks (SANETs). Detailed comparisons of different types of ad hoc networks are provided in [179] and [180].

A. MULTI-UAV SYSTEMS

While most UAV systems today are comprised of only a single UAV, there are advantages to having systems containing multiple UAVs. For instance, when comparing the use of a single UAV to multiple UAVs for agricultural applications in [181], the authors found, under several considerations including an autonomously controlled system compared to a remotely controlled system, setup time, flight time, battery consumption, coverage ratio, inaccuracy of land, and etc., that a multi-UAV system significantly outperforms a single UAV system.

The authors of [182] proposed an algorithm to offer dynamic repositioning of an aerial base station UAV in order to improve spectral efficiency between aerial base station and user equipment (UE). In their work, the authors utilized a single drone and was able to increase the spectral efficiency by 10.5-15% as opposed to a static UAV. When applying this concept to a network of several UAVs [183], the authors were able to achieve almost 100% gain in spectral efficiency. In another paper [184], the authors compared the use of multiple UAVs with adaptive trajectories to that of a single UAV with a fixed trajectory. The authors were able to demonstrate that the performance of several UAVs is higher than a single UAV in terms of coverage rates and event detection rates. The authors in [185] outlined several advantages including lower cost, increased mission survivability, increased scalability, and shorter mission duration. In a UAV network, should one UAV fail, the operation may still be successful as the other UAVs can continue the mission, leading to a higher survivability [186]. Cheng *et al.* [187] provided a model for evaluating the resilience of a UAV swarm for joint reconnaissance missions, as well as other applications. Simulations in [187] indicated that their model could provide more realistic and objective resilience evaluations compared to other existing studies. The authors stated that their work could be used to assist in designing an optimal UAV swarm.

Multiple UAVs used in a network can also allow for the system to be more easily scalable as shown in [186] and [188]. Sampdro *et al.* [189] proposed a scalable mission planning architecture consisting of a global mission planner (GMP) and agent mission planner (AMP). The GMP monitored and assigned high-level missions through the AMP, which monitored and provided specific tasks of the mission to individual UAVs within the network. Using simulations and indoor test flights, the architecture demonstrated robustness and flexibility in several scenarios. Finally, Chriki *et al.* [173] and Manathara *et al.* [190] indicated that with a higher number of UAVs, missions could be completed more efficiently. Sathyana *et al.* [191] compared several approaches for solving the traveling salesman problem (TSP), where the objective was to reach several targets once while determining the shortest/optimal route, and applied these to the swarming of UAVs. The study determined a 2-opt approach to yield the best performance for the TSP, and when applied to a multiple travelling salesman problem, where each UAV within a group of UAVs was assigned to a subset of the targets, the results were much better and the computational time was drastically reduced.

Wei *et al.* [192] provided an operation-time simulation framework for mission planning and swarm configuration of UAV networks. To solve the problem of real-time mission planning within a UAV network, Zhang *et al.* [193] proposed a new algorithm for dynamic task generation, as well as an asynchronous task allocation mechanism which reduced the computational complexity of the algorithm and increased the communication speeds between several heterogeneous UAVs.

While there are several advantages of using multiple UAVs within a network, there are also some challenges introduced. The primary challenge is the communication protocol as indicated in [185]. There are three primary types of radio communication within FANETs: UAV to UAV, UAV to ground control station (GCS), and UAV to satellite (SATCOM) according to [173] and [194]. UAV to UAV communications can be either direct or indirect. In other words, a UAV system can directly communicate with another UAV system or can relay its message through other UAVs. This allows the UAV network to be more efficient both in data rate as well as communication range [173].

UAV to GCS communications allow the UAV network to communicate to ground infrastructure for information relaying and connecting to the global network. For instance, Chriki *et al.* [173] proposed a centralized data-oriented communication architecture for swarm of UAVs for crowd monitoring applications. The GCS was used to manage bandwidth usage within the local swarm, acting as the central coordinator. Two classes of urgent messages were created: important result and critical state. Using these classes along with other relevant information, the GCS could then authorize data transmission of UAVs within the network, and thus optimizing bandwidth usage efficiency. The third major method of communications, SATCOM, can be useful in areas such as over oceans or mountains where ground stations may not be present, however the cost is very high according to [194]. Skinnemoen *et al.* [195] investigated the use of UAVs for obtaining live images for a variety of applications including search and rescue, safety and security, border patrol, police operations, and disaster management. In many use cases, terrestrial networks were insufficient for providing live imagery, so satellite communication was required either in the UAV itself or relayed through ground. As doing so generally incurs high cost, is slow, and requires higher capacity than is available, the authors presented a new concept for obtaining live imagery from UAVs while combating these obstacles.

UAV to satellite communications also presents the challenge of unstable beam tracking due to UAV navigation. Zhao *et al.* [196] proposed a new approach for blind beam tracking for Ka-band UAV-satellite communications. Using a hybrid large scale antenna array, the UAV first mechanically adjusted the position of the antenna in the relative orientation of the target satellite using beam stabilization and dynamic isolation, derived from data fusion of low-cost sensors. The precision was then fine-tuned electrically by adjusting the weight of the antennas, and an array structure based simultaneous perturbation algorithm was created.

B. CLASSIFICATION: Ad-hoc NETWORKS, MANET, VANET, FANET, AND SANET

FANET nodes have higher mobility and thus they can travel faster compared with MANET nodes and sometimes VANET nodes according to [197]. Authors in [197] explained that the speed of MANETs are generally limited to the speed of human being (about 6 km/hr). While VANET nodes can travel faster (usually up to 100 km/hr), their speeds are still generally restricted to maximum speed limit in roads. Due to the high mobility of FANET, topology changes are more frequent so the mobility of a FANET becomes an important

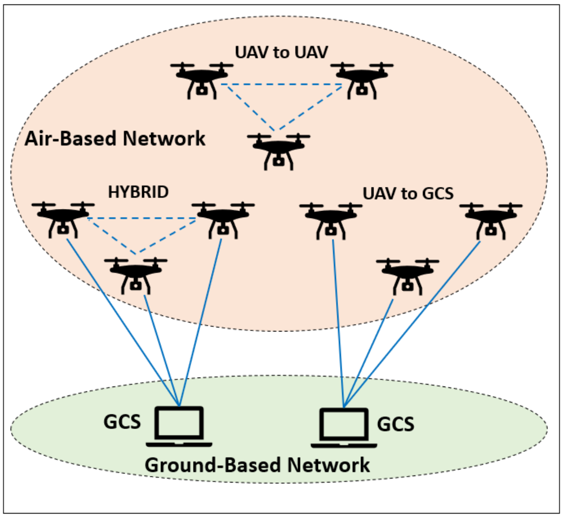


FIGURE 4. Types of FANET communications [45].

design consideration according to [198], which outlined four different mobility models for FANETs: Random Waypoint Mobility Model, Gauss Markov Mobility Model, Semi Random Circular Movement Model, and Mission Plan Based Model.

As FANET network topology is constantly changing due to the high mobility of UAV platforms, routing protocols become an important challenge within the UAV network as indicated in [186] and [199]. Table 1 offers a com+ + +prehensive comparison between critical parameters among MANET, VANET, FANET and SANET. The table information was extracted from [179] and [200].

C. FANET COMMUNICATION ARCHITECTURE

There are several types of FANET architectures. Such architectures can be summarized as UAV to UAV, UAV to Ground Control Station (GCS) and Hybrid [45]. Figure 4 illustrates these types of FANET architectures.

Srivastava *et al.* in [46] expand the definition of FANET architectures by adding more possibilities into the existing architectures, which provides a more complete FANET architecture by combining UAVs and GCSs in the form of radio towers, satellite dishes and relay satellites. Another type of FANET configuration can be defined as UAV to infrastructure/ground station. As mentioned previously, UAVs can be used as aerial base stations to overcome the limitations of the current cellular communications infrastructure. Khan *et al.* [201] explained that non-orthogonal multiple access (NOMA) can be used in 5G communications to boost the spectrum efficiency. NOMA can serve both ground equipment as well as aerial equipment simultaneously due to asymmetric channel conditions. Communications links to aerial users are generally stronger than that of ground users, allowing base stations to first decode signals received from UAVs while treating ground user signals as noise, then subtract the decoded signals from the UAVs in order to decode the weaker signals received from ground users [201].

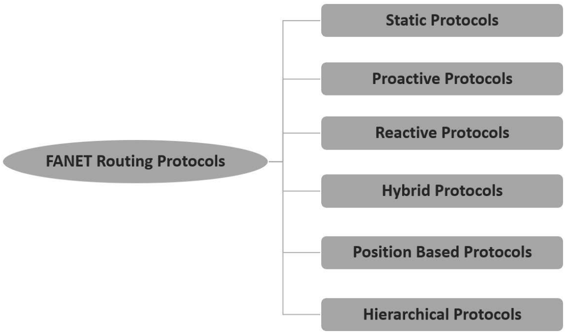


FIGURE 5. FANET routing protocols [201].

D. FANET GENERAL ROUTING TECHNIQUES AND PROTOCOLS

Routing protocols can be categorized into six primary categories: Static Routing Protocols, Proactive Routing Protocols, Reactive Routing Protocols, Hybrid Routing Protocols, Geographic/Position Based Routing Protocols, and Hierarchical Routing Protocols according to [201] and [202]. Figure 5 illustrates routing protocols of FANET.

Generally, in FANETs, appropriate selection of routing protocols is a challenging task as network topology is constantly changing due to the high mobility of UAV platforms [203]. There are five main requirements for designing proper routing protocols in FANETs: high adaptability, scalability, high residual energy, low latency, and high bandwidth as indicated in [204] and [203]. First, there must be a high amount of adaptability due to the frequent changes in network topology and low node density [205]. Adaptability is important as link disconnections will be frequent, reliable routes must be identified quickly and routing tables must be frequently updated [206], [207]. Hong *et al.* [207] proposed a routing scheme that was able to adapt to rapid changes in the network topology and as a result it could improve the performance of the network. The results were verified using several simulations and mobility models. Second, routing must be sufficiently scalable to accommodate the various applications of UAV networks ranging from small scale operations with few nodes to large scale operations with high node density [207]. Scalability is important as the coverage range of a single UAV is limited, but a network of several UAVs can easily expand the operational scalability, and adapt to many different applications [194]. Oubbati *et al.* [194] outlined and compared the scalability properties as well as operational features of several existing routing protocols. Third, routes must be established with high residual energy in order to reduce potential link disconnections resulting from node failure, as UAVs are primarily battery powered [208]. The authors of [206] and [209] developed a scheme to explore routing paths while considering energy consumption, link breakage prediction, and connectivity degree of the

TABLE 1. Comparison of four types of Ad-hoc networks [179], [200].

Point of Comparison	MANET	VANET	FANET	SANET
Node Mobility	Low	High	Very high	Medium
Mobility Model	Random	Regular	Regular for predetermined paths, but special mobility models for autonomous multi-UAV systems	Random
Line of Sight	Not available for all cases	Available in some cases	Available in most cases	Available in some cases
Node Density	Low	High	Very low	High
Number of Nodes	High	High	Low	Low
Topology Update	Not often	Often	Often	Not Often
Topology Change	Slow	Fast	Very Fast	Medium
Radio Propagation Model	Typical, close to ground	Typical, close to ground	Typical, high above ground	Typical, close to ground
Power Consumption and Network Lifetime	Energy efficient protocols, low power consumption	Not needed, high power consumption	Energy efficiency for mini UAVs, but not needed for small UAVs, high power consumption	High power consumption
Computational Power	Limited	High	High	High
Localization	GPS	GPS, AGPS, DGPS	GPS, AGPS, DGPS, IMU	GPS, DGPS
Security	High data confidentiality, integrity and reliability	High data confidentiality, integrity and reliability	High data confidentiality, integrity and reliability	High data confidentiality, integrity and reliability
Routing Protocol	Proactive: DSDV, OLSR, CGSR; Reactive: DSR, AODV, TORA	Proactive: DSDV, OLSR, FSR; Reactive: DSR, AODV, TORA	Proactive: DSDV, OLSR, DOLSR; Reactive: DSR, AODV, TSODR	Proactive: DSDV, OLSR; Reactive: DSR, AODV, TORA
Simulator	OMNET++, NS-2, NS-3, GloMoSim, OPNET, QualNet	OMNET++, NS-2, NS-3, GloMoSim, OPNET, QualNet, SIMITS, MATLAB	OMNET++, NS-2, NS-3, GloMoSim, OPNET, QualNet, MATLAB	OMNET++, NS-2, NS-3, GloMoSim, OPNET, QualNet, MATLAB

discovered paths. Using several simulations, the authors showed that the scheme minimized the number of path failures and packet losses, increasing the lifetime of the network. Authors in [199] proposed a new methodology for saving wasted energy by 25% in FANET routing by suppressing unnecessary hello messages that are traditionally used for establishing and maintaining routes. Fourth, routing must be low latency in order to accommodate high mobility constraints and for time-sensitive applications such as collision avoidance within a UAV swarm [4]. The authors in [210] developed a routing protocol with a focus on efficiency in terms of latency, energy, and reliability. The protocol was topology aware and utilized a multi-objective optimized link state routing protocol, and also utilized a new method for selecting relay nodes, The proposed protocol took into consideration the traffic loads on both the communication channel and on each UAV node, as well as link stability and energy constraints. The system was simulated in various scenarios, and indicated higher efficiency when compared to the original optimized link state routing protocol. Finally, FANET routing protocol must have high bandwidth to accommodate data collected from the UAV network and be able to send them to the infrastructure for data processing [211].

1) STATIC ROUTING PROTOCOLS

Static routing protocols use a routing table that is constant for the duration of the UAVs' mission. A routing table is a file that is stored in a device which holds information for packet forwarding, listing routes to certain network destinations [212]. Static routing can be manually configured or injected, and are generally used when dynamic routing is not preferred, or for reaching a stub network [201]. Due to the nature of the static routing protocol, the applicability of this protocol is limited [213]. Static routing protocols may be useful in situations where the network topology will remain constant throughout the mission [214]. One example of where a static routing protocol is useful is Load Carry and Deliver (LCAD), which was one of the first routing models for FANET [212]. LCAD utilizes a store-carry-and-forward technique, and can be useful for applications that are not time sensitive, such as data collection from fixed sensors or tracking. Authors in [215] showed another example of using static routing protocol, called multi-level hierarchical routing (MLHR). Using this system, a cluster head within a cluster of UAVs disseminates data traffic to the other UAVs.

2) PROACTIVE ROUTING PROTOCOLS

In a proactive routing protocol, each node maintains a table that is periodically updated and contains routing information to all nodes [216]. With this protocol, the destination path can be immediately accessed, eliminating the delay that a node may experience when packets are needed to be sent [217]. However, this method also increases the bandwidth usage and takes up network resources creating paths that may or may not be used. Authors in [218] conducted an experiment comparing three different routing protocols for FANET: Ad-hoc On-demand Distance Vector (AODV), Destination-Sequenced Distance Vector (DSDV), and Optimized Link State Routing Protocol (OLSR). The study found OLSR, a proactive routing protocol, to outperform the other two in terms of average throughput, packet delivery ratio, and end to end delay.

3) REACTIVE ROUTING PROTOCOLS

Reactive routing calculates routes on demand when the need arises. This reduces the overhead of building and maintaining routes that are unused by each node, however there will be increased latency for sending data packets as the node must wait until a route is acquired. Reactive protocols are suboptimal for bandwidth utilization as the network will be flooded as the route to the destination is being determined [219]. However for highly dynamic networks with frequent network topology changes, reactive protocols can be scaled more easily. There are two primary methods for reactive routing: source routing and point-to-point routing. With source routing, the data packet will contain the complete address from source to destination. This eliminates the need for intermediate nodes to maintain routing information and the packet is simply forwarded to the next node until it reaches its destination [220]. In point-to-point routing, the packet only contains the destination address and the next hop address. In this system, each intermediate node will need to utilize its own routing table to determine which node to forward the packet to in order to get it closer to its intended destination [221].

4) HYBRID ROUTING PROTOCOLS

Hybrid routing protocols use a combination of both reactive and proactive routing protocols. The most common form of a hybrid routing protocol is a zone routing protocol, or ZRP [222]. In zone routing protocol, zones are defined for each node and is expressed in number of hops, known as the radius of the zone. Zones of neighboring nodes overlap with the node in question. In order to change the number of nodes in a zone, transmission power is regulated to increase or decrease the number of nodes within the routing zone. In ZRP, a node will first check to see if the destination is within its zone. If so, the packet will be routed using a proactive routing protocol. If the destination is outside of the local zone, reactive routing will be used [223].

5) GEOGRAPHIC/POSITION BASED ROUTING PROTOCOLS

Geographic routing protocols (GRPs) also fall under the hybrid routing protocol category. GRPs utilize the geographic positioning of the source and destination nodes in order to forward packets, utilizing positioning schemes like GPS. Because of this, geographic routing protocols are useful for frequently changing network topologies. To get the packet to the destination, the node determines the location of the destination node and forwards the packet to intermediate nodes nearest the destination node, one hop at a time. Each node maintains a table listing the locations of each node in the network [224]. The authors of [225] provided classifications and a detailed survey of various position based routing protocols and explored the strengths and weaknesses of each, and state that position based routing protocols can offer high efficiency and reliability when dealing with the high mobility of FANET nodes.

6) HIERARCHICAL ROUTING PROTOCOLS

Hierarchical routing consists of a two-layer architecture. There are two types of nodes: Cluster Heads (CHs), which are responsible for collecting and processing data, and Member Nodes (MNs), which are responsible for transmitting sensing data to head nodes. There are three types of hierarchical routing: block-based, tree-based, and chain-based [226]. New routing protocols are also being developed and researched. In [203], authors investigated the use of a new adaptive routing protocol for FANET based on the fuzzy system. Using Network Simulator, the authors were able to determine that the new routing protocol performed 300% better in terms of throughput when compared to optimized link state (OLSR) and ad-hoc on-demand distance vector (AODV) routing protocols. Khan et al in [227] developed a hybrid communication scheme for FANET. They were able to conclude that a multi-layer FANET was the best architecture for networking a group of various UAVs. The authors also determined Bluetooth 5.0 to be favored protocol as it is low cost, consumes little power, and has a longer transmission range. Simulations using the optimized network engineering tool (OPNET) supported these results. Authors in [194] proposed new protocols as well, first a position-prediction-based directional MAC protocol (PPMAC), which utilizes directional antennas to overcome directional deafness problems. The authors also proposed a self-learning routing protocol using reinforcement learning (RLSRP), which evolves automatically. Together, these protocols may be able to provide an intelligent and autonomous solution for FANET communications. For additional developments in routing protocols for FANET, authors in [194] provided extensive reviews.

7) ROUTING PROTOCOLS DISCUSSION

Although few studies such as [228], [229], [230], and [231] have considered load balancing routing protocols to address both complicated dynamic network environments as well as network traffic increase in future, it can be concluded from the comparison that majority of routing protocols do not take traffic load balancing into account [232]. Most of the routing protocols including multi-path routing have not been able to effectively balance the load of network as well as energy utilization. There have been several route matrices suggested, including the shortest path, the freshest path, and the one with the highest link quality [232], [233]. However, the development of routing protocols without taking into consideration the properties of data packets cannot construct an efficient network; network throughput may be increased to some extent by forwarding data packets in accordance with varying traffic demands [232]. UAV networks require reliable communication to operate properly. However, since radio link connectivity between drones can be disconnected due to high-speed, conventional routing protocols cannot work well in UAV networks [234]. If drones travel randomly in a multi-hop UAV network without pre-designing paths, it becomes challenging to select the next appropriate hop node for data relay [232]. In such scenarios, opportunistic routing protocols such as [235], [236], and [237] can be utilized. Opportunistic routing protocols are used to transfer data packets in dynamic UAV networks. Currently, the hierarchical network structure is used in research studies to investigate the routing protocols [238]. Although the hierarchical structure performs well in wired networks, it is insufficient for wireless

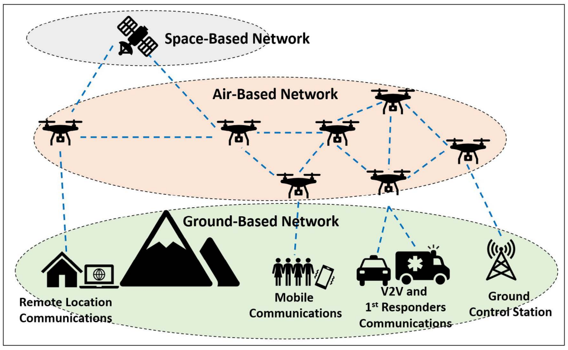


FIGURE 6. Research community proposed wireless UAV networks implementations.

networks [239]. However, it is argued that a cross-layer design would be preferable [240]. This is because the interaction between OSI layers may significantly enhance network performance. For instance, one of the most vital parameters of physical layer, which is link-state information, serve as an important foundation for routing forwarding [240]. Therefore, a more dependable path might be discovered using the cross-layer design or inter-layer information [232].

V. WIRELESS NETWORKING WITH UAVs - APPLICATION SCENARIOS

As already mentioned, UAV networks can be used in a variety of civil and commercial applications. From aerial base stations to surveying and mapping, search and rescue, and development of new user equipment. Therefore, businesses and researchers are developing new prototypes, models, algorithms, and more, to investigate and facilitate the use of UAVs in communications [5].

Figure 6 indicates a common architecture of wireless UAV networks and its applications. It is expected by the specialized research community to investigate different communication networks similar to the depicted in Figure 6 through UAV relay networks. As can be seen, there exist many areas of opportunity for drone technology in civil communications.

A. AERIAL BASE STATIONS, CELLULAR NETWORKS, 5G AND BEYOND

The incessantly growing need for high-speed wireless access has been fueled by the rapid proliferation of highly capable mobile devices such as smartphones, tablets, and more recently, drone-UEs and IoT-style gadgets [24]. As such, the capacity and coverage of existing wireless cellular networks have been extensively strained, which led to the emergence of a plethora of wireless technologies that seek to overcome this challenge, including 5G cellular systems [3]. As Li *et al.* summarize in their review paper, one of the main challenges of fifth generation (5G) and beyond 5G wireless communication technologies is providing connectivity to various types of wireless devices ubiquitously [241]. UAV systems are anticipated to be considered one of the essential components of 5G and beyond 5G wireless networks which can ideally provide reliable and high data-rate wireless connectivity not only for stationary users, but also for crowds of people moving in private and public transportation networks. As opposed to existing fourth generation (4G) cellular networks, fifth generation (5G) and beyond 5G cellular networks are projected to be able to ubiquitously connect various types of wireless devices with varied requirements. Emergence of new technologies such as IoT has triggered a rise in the number of wireless devices in 5G cellular networks which has led to the creation of higher data traffic [242], [243]. According to Khan *et al.* [244], the total global mobile traffic in 2028 is estimated to exceed 1 zettabyte/mo, that is about 200 GB per month for nearly 5 billion users globally. This demonstrates how existing cellular network infrastructures are unable to provide the necessary capacity for demand. Moreover, substantial increase in the data traffic can impose an additional burden in terms of operational costs and capital investments to telecommunication operators [241]. Existing terrestrial wireless systems that use heavily-congested radio spectrum bands below 6 GHz are unable to significantly increase the speed of data transfer for various emerging applications. mmWave communications can use unoccupied bandwidth that is available at mmWave frequencies to overcome the problem associated with congested frequency bands and to fulfill the requirements of 5G cellular network technology. mmWave communications technology can take advantage of UAVs to assist existing wireless networks for future 5G wireless applications [28]. Zhang *et al.* [28] provide a comprehensive review related to existing achievements for the incorporation of 5G mmWave communications into UAV-assisted wireless networks. The authors of [245] present an aerial base station prototype working at millimeter-wave bands to provide multi-beam multi-stream communications. The authors were able to verify good stability and reliability of the system during uplink and downlink at multi-giga-bit-per-second data rates during field testing. The authors in [211] presented a mmWave distributed phased-arrays architecture and designs for user equipment and UAVs to be used in 5G. The UAVs were used as aerial BSs and were able to achieve a 2.2 Gbps aggregated peak downlink rate in real-world field testing. In the case of downlink traffic overload, aerial base stations can be used to complement existing cellular networks. Authors in [246] proposed a weighted expectation maximization algorithm to determine the distribution of users and downlink traffic demand. Additionally, contract theory is used to guarantee correct information exchange between the UAVs and the base stations. Finally, an optimization problem is derived to send the appropriate UAV to the overload area to maximize the base station utility. The authors of [247] identified that while the nature of UAV systems allow for unobstructed communications with multiple base stations, multiple BSs invoke strong interference conditions for the UAV. In order to optimize the performance of the UAV systems in this environment, the authors proposed a supervised learning approach to mitigate the issue. With the proposed method, neural networks are trained to select the most suitable BSs to connect with based on signal power, distances from base stations, as well as the locations of possible interference. The scheme has shown a significant performance increase over simple heuristic schemes.

B. PUBLIC SAFETY AND NATURAL DISASTER USES

Many applications of UAVs as aerial base stations assume the UAVs are in fixed locations. However, UAVs can be deployed in search and rescue missions. They can be utilized by firefighters, police officers or volunteer rescue teams to search over large areas for finding missing people, crime victims or people in need of rescue in any environment. In case of a major disaster, when communication infrastructures has been destroyed, a key challenge in search and rescue (SAR) missions is to provide a very reliable and relatively flexible emergency communication platform for the survivors. Zhao *et al.* [248] proposed a unified framework for establishing an UAV-assisted emergency network in the disaster areas. In this work, flight trajectory, jointly with communication scheduling among UAVs, are optimized to offer reliable wireless service among survivors and the surviving ground BSs. In scenarios when ground BSs are demolished, multi-hop device-to-device (D2D) communication is established among survivors to effectively extend the wireless communication coverage of an UAV to outside its covered area. Moreover, to transfer the survivors' emergency information from a disaster zone to the outside area, a multi-hop UAV relaying mechanism is presented which optimizes the hovering positions of UAVs. Mayor *et al.* [249] optimally deployed UAVs equipped with WiFi access points which not only provide WiFi coverage but also the medium access control (MAC) sublayer (i.e., quality of service) for voice over internet protocol (VoIP) communications to ground users in disaster areas. A new method also was presented to reduce the energy consumption of survivors' WiFi interface cards to extend survivors' battery life as much as possible. Multi-UAV systems can also be used in conjunction with other technologies to support survivors in disaster areas. Lodeiro-Santiago *et al.* [250] proposed an integrated solution based on the use of drones, and the use of simulated beacons on smartphones for SAR missions. In this research, drones equipped with sensors fly in synchrony over a given area to scan Bluetooth Low Energy (BLE) [171], [251] beacon signals transmitting from smartphone of missing individuals; however, if BLE-enabled smartphones of missing individuals simultaneously transmit their beacon signals, there is a probability of signals collision which can cause transmitting signals being lost [252]. Erdelj *et al.* [253] jointly used wireless sensor networks (WSNs) along with multi-UAV systems to increase the efficiency of existing natural disaster management systems. Castellanos *et al.* [254] evaluated the performance of the direct-link backhaul in a realistic scenario for UAV-aided emergency networks. Castellanos' group described how resources can simultaneously be assigned to the backhaul network, access the network and ground users, within power constraints and backhaul capacity. This work also compared three different types of backhaul scenarios utilizing a 3.5 GHz link, 3.5 GHz link with carrier aggregation, and a 60 GHz link, using three different types of UAVs. The findings suggest that an optimal flight height of 80 m can meet both backhaul networks and access networks at the same time. Occasionally, in SAR missions, the pre-allocated radio spectrum is insufficient to deliver high data-rate transmissions such as real-time video streaming. The UAV network in such scenarios can borrow a portion of the radio spectrum of a terrestrial licensed network in return for offering relaying services. With the aim of improving the performance of the UAV network and extending the network lifetime at the same time, several UAVs operate as communication relays for the primary network whereas other UAVs perform their assigned tasks. Shamsoshoara *et al.* [255] proposed an algorithm for team reinforcement learning to be performed by UAV's controller unit to identify the optimum allocation of the radio spectrum for sensing and relaying tasks among UAVs in addition to their relocation strategy simultaneously. In order to guarantee the accuracy of the collected data from the disaster areas, Abdallah *et al.* [256] presented a security architecture for UAV networks. The proposed networking technique includes a two-tier cluster network which relies on IEEE 802.11ah to provide traffic isolation between tiers. The proposed security architecture also uses the lightweight ring-learning with errors (Ring-LWE) crypto-system to guarantee the confidentiality of the transferred information. The chances of finding survivors alive after occurring natural disasters such as earthquakes or hurricanes is highly dependent on the rapid response time of the rescue team. Coordination, situational awareness (SA) and information sharing are the most common challenges associated with natural disaster management which can be achieved in the most efficient manner through aerial assessment- UAV networks [253]. A vision for future UAV-assisted disaster management system was presented in [248], in which UAVs are not only focused to perform specific tasks such as surveying the affected area but also are assigned to assist in establishing wireless communication links between the survivors and the closest existing cellular infrastructure. In SAR missions, to minimize the valuable time of finding and saving victims, Waharte *et al.* [257] investigated a number of important parameters that can have an effect on the SAR tasks including the quality of collected sensory data, energy constraints of the UAVs, environmental hazards (e.g. trees, winds) and the level of information exchange between UAVs. The authors then assessed and compared the advantage of sharing information among UAVs with different search methods based on a greedy heuristic algorithm, potential fields and partially observable Markov decision technique. According to statistics [258], during an avalanche incident, the survival probability of entirely buried victims can decrease to below 80% after only 10 minutes of being buried. Silvagni *et al.* [259] presented an autonomous multipurpose UAV that can be easily deployed under harsh weather conditions for the purpose of avalanche rescue operations. Since social media, most importantly twitter, plays an important role in providing timely information when natural disasters occur, it can be used along with the UAVs' data for damage assessment purposes. Yuan *et al.* [260] proposed a framework of integration of twitter and UAVs for rapid damage assessment for hurricane Matthew in Florida. Authors in [35] designed a tool for deploying several UAVs to an area to provide coverage in the case of large scale disasters. Utilizing femtocell base stations mounted to the UAVs, the tool assigned locations for the UAVs to provide coverage to the users. The authors found that by doubling the number of drones, the coverage area can be doubled. By increasing the height of the drones by 10 m, 13% less drones were needed, however there were diminishing returns above 100 m. The authors tested this tool in a real-world urban environment (Ghent, Belgium).

C. INFORMATION DISSEMINATION

UAVs can be very useful in supporting existing terrestrial networks for data dissemination, and enhancing network connectivity. UAVs were considered by Fan *et al.* to complement existing VANETs where communication infrastructure was poor or unavailable [261]. The authors studied methods for maximizing network throughput when utilizing UAVs for facilitating data dissemination, as well as optimizing data transmission rates. They then proposed a polynomial time approximation scheme for a solution. In another study, Sharma *et al.* considered UAVs for integration with WSNs to solve the issue of energy depletion, as many WSNs utilize batteries for operation [262]. The authors studied the use of UAVs for data dissemination within WSNs, acting as manager nodes to provide continuous connectivity and improved coverage for WSNs. As energy efficiency was the primary concern, a new data dissemination approach using the attraction properties of fire fly optimization algorithm was presented to provide relaying while improving throughput, lifetime, coverage, average number of hops, and delays. When using UAVs for information dissemination for IoT applications lacking infrastructure, Tucci *et al.* proposed algorithms for maximizing the data dissemination to various IoT devices that were spatially dispersed [263]. To achieve this maximization, the authors optimized the UAV's mobility in 3-D space as well as the resource assignment strategy for the UAV, taking into consideration the IoT devices' data requirements, as well as the UAV's mobility constraints, and energy budgets.

D. INTERNET OF THINGS (IoT)

5G-powered IoT technology [264] will improve implementation of smart agriculture and precision farming [265]. This technology will be used for smart buildings [266] as well as virtual and augmented reality with no restrictions on range [265]. It will ultimately cover houses, corporations, and other large perimeters offering enormous and vital Machine-To-Machine-Type Communications (MTMC). This method of communication can be incorporated with the conventional Human-Type Communications (HTC) using appropriate gateway components in the 5G environment [267] as presented in [267]. Figure 7 shows UAV-enhanced 5G-enabled IoT services.

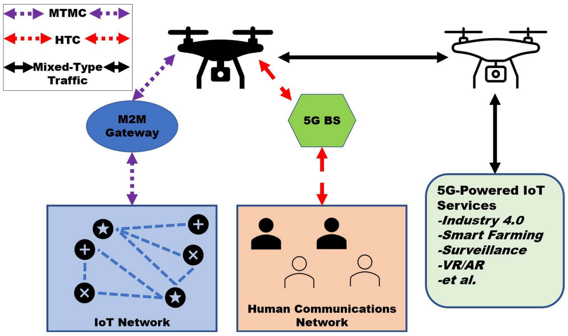


FIGURE 7. UAV-enhanced 5G-enabled IoT services [267].

Datta *et al.* investigated the use of UAV-IoT networks for the purposes of wildfire detection [268]. Current methods of wildfire detection such as satellite imaging and camera-based sensing are relatively slow and unreliable. In a UAV-IoT network, IoT devices were used to detect fires at an early stage, and the results were broadcast to nearby UAVs. The authors studied the optimization of the density of IoT devices as well as UAVs covering a given forested area. Using discrete-time Markov chain analysis, they found that a UAV-IoT network can offer more reliable and timely detection of wildfires than satellite imaging techniques. Bushnaq *et al.* implemented a cloud service to enable video streaming for use with emergency services, as well as control commands for the UAV systems within the cloud service [269]. The goal was to integrate a web application and mobile client into the EURECOM IoT platform for the command, control, and supervision of various missions. Martinez-Caro and Cano presented a case study for the use of Long-Range (LoRa), low-power wide-area network for the purposes of air quality monitoring [270]. The network consisted of UAVs equipped with sensors to measure air quality, as well as nodes incorporating LoRa for communications. The authors' goal was to determine the best mobility model for such a UAV-based IoT service. After extensive simulations, the authors determined that the ''Pathway'' model was the best performing, where LoRa nodes move in an orderly fashion through a coverage area.

UAV platforms suffer from limitations related to weight and autonomy, which impact their effectiveness for remote sensing when capturing and processing data for the use of collision avoidance and obstacle detection. Fraga-Lamas *et al.* [271] explored the utilization of deep learning techniques in UAV-IoT networks to improve real-time obstacle detection and avoidance. The authors conducted a survey of several deep learning techniques, as well as associated hardware, while enumerating the different challenges associated with such systems. As 5G communications becomes more widely available, IoT use cases are expected to grow, according to Marchese *et al.* [242]. Integrating several new IoT devices and services into the 5G network will prove difficult, so the authors present the use of UAVs and satellites to assist in the integration to overcome terrestrial infrastructure limitations.

Recurrent themes in multiple UAV based applications include trajectory optimization, efficient energy consumption / resource management, and effective communication / data transmission. Dai *et al.* approached multi-UAV deployment problem for IoT communication in dynamic environments from a game-theoretic learning perspective [272]. The authors considered the case when there is wireless connectivity through UAV-mounted BSs for terrestrial communication. The stochastic game was able to converge to an optimal solution for the UAV position selection problem. Yan *et al.* presented a task scheduling framework for data offloading via heterogeneous UAVs for IoT applications that minimized data queue length while maximizing UAV operation time [273]. The authors used a differential evolution-based dynamic objective approximation method to achieve optimal solution from user data analysis, user status information update and UAV scheduling strategy. Their work is potentially applicable for smart farms and factories. Xu *et al.* implemented k-means and deep reinforcement learning algorithms to optimize multi-UAV trajectory for uplink data collection in IoT networks [274]. The algorithm aimed to minimize data collection time while considering criteria such as maximum speed, maximum acceleration, collision avoidance, and UAV communication interference with promising results. Another trajectory planning algorithm was implemented by Lyu *et al.* for UAV-based maritime IoT systems [275]. In their work, the authors use unmanned surface vehicles to construct Delaunay triangles, and then calculate the Fermat point as a hovering point. Trajectory planning is then treated as vehicle routing problem with pickup and solved with the Clarke and Wright (C-W) saving method. Although these studies are theoretical in nature, they present successful frameworks that can be implemented in real-time applications moving forward.

Bera *et al.* proposed an access control protocol applicable for battlefield surveillance in UAV-assisted Internet of Things environment (ACPBS-IoT) [276]. The access control allows a drone and its ground station server to authenticate each other and secure communication. This ACPBS-IoT is designed to be anonymous and untraceable. Trusted certificates are created in the process for verification and protects the system from attacks such as privileged-insider, impersonation, MiTM, replay, and ESL, all required for the intended application. The authors performed detailed security analysis verification using automated software simulation tool to show the robustness of their system in terms of functionality and when exposed to active and passive attacks. Even though this particular example is not a civil application, it is included here to show some of the security issues which are also relevant to other UAV-based IoT systems.

Punia *et al.* present a single UAV-based IoT application for precision agriculture [277]. The system is composed of wireless autonomous sub-systems that collect and integrate multiple sensor data which can then be used for soil and crop management. A base station, UAV and multi-sensor soil probe communicate and are user interfaced through a wireless protocol. The individual sub-systems are designed as modular point-to-point communication nodes. By combining data from ground and UAV sensors in real time, the system presents itself as an effective assessment and management tool for agricultural resources.

E. UAVs AS USER EQUIPMENT

In the case where UAVs interact with ground user equipment (UE), such as those discussed in Sharma *et al.* [278], where one UAV in a fixed position will communicate with the ground UE, and other UAVs within the vicinity do not communicate with the UE but are able to move about in 3-D space, these UAVs will be seen as interference. First characterizing the interference received by the ground UE, then evaluating the coverage probability, the authors proposed both random and uniform waypoint mobility models to characterize the UAV movement process. In their work, Zhang *et al.* investigated UAV-based emergency communication networks where ground power systems are not operational after a disaster and UE energy is limited [279]. The authors consider this UE energy limitation as well as physical obstacles to UAV flights to develop a trajectory optimization solution by simplifying this problem as a constrained Markov decision-making process and propose a Lyapunov-based deep learning trajectory design algorithm, where the UAV is the agent. The authors' work shows convergence in the uplink throughput in simulation results, with satisfactory trade-off in energy consumption. This work can be extended to multiple UAV deployment in larger disaster areas with UAVs as UEs.

Another UE application of UAVs in disaster response is described in an earlier publication by Yin *et al.* who analyzed uplink performance of UAV UEs in dense cellular networks [280]. The group investigated system performance with respect to parameters such as with (non-line-of-sight) and without (line of sight) flight obstacles, antenna height difference between UAVs and base stations, and idle mode capabilities that affect inter-cell interference. They found that, as is intuitive, the probability of coverage can be improved by idle mode capability; when distance between antennas and base stations increases system performance degraded, and finally when this distance is large, the fractional power control factor is not that impactful on UAVs' performance. Pai and Sainath [281] presented their study on tethered UAV-assisted hybrid cooperative communication to improve the performance of the links between BSs and UEs through a UAV selection policy without the channel state information (CSI), and a link switching policy based on a hybrid PHY layer (RF or mmWave or FSO). The Authors' simulations resulted in a recommended selection policy for a single UAV from a swarm of UAvs. The group also investigated combining selections in PHY layer links with appropriate switching thresholds. This work could potentially serve as an analytical benchmark for UAV-assisted wireless systems as UAVs are used as BS and UEs in multiple applications.

F. SCALING MULTI-UAV OPERATIONS

As described in Section 4, FANETs can be extremely useful in scenarios where infrastructure is limited or nonexistent as discussed by Bekmezci *et al.* [282]. When access to infrastructure is limited, FANETs using both UAV to UAV communication as well as UAV to GCS communication can be used to extend the reach of existing infrastructure to communicate with UAVs outside the range of existing infrastructure. This can also be used to bridge a gap between several existing infrastructures that may be out of range with one another. With a FANET system, infrastructure communication can be relayed from one UAV to another to reach areas not covered by existing infrastructure as explained by Bekmezci *et al.* in an earlier article [185].

Wu *et al.* investigated large-scale wireless recharge networks enabled by multiple UAVs [283]. In this scenario, multiple UAVs were considered to serve as mobile wireless power transfer agents as well as information collection systems for a set of ground sensor nodes that are low power. The authors studied the trade-off between power transfer and communication delay through trajectory optimization that would maximize the UAVs' energy utilization efficiency. They implemented a heuristic algorithm that combines evolutionary algorithm and variable neighborhood search to achieve optimal sequence for visiting the sensor nodes as part of their feasibility analysis. The authors concluded that the used MAVNS algorithm converges towards the optimal solution. The authors also looked at trajectory length distribution when UAVs increase in number, shedding light on a scheme to select the minimum number of capacity-constrained UAVs to charge the targeted sensor nodes.

G. TRAFFIC MONITORING AND SURVEILLANCE

There are several applications for UAVs for monitoring traffic and for surveillance. For example, Jin *et al.* [284] introduced a UAV prototype that could be deployed to the scene of a major traffic accident to speed up the process of surveying the accident. The paper showed that by using a UAV armed with a high-resolution camera, a high-frequency GPS sensor, and a HD transmitter, data could be transmitted from the UAV to a ground station. By using this data, a proposed software could reconstruct a 3D model of the scene of the accident. By implementing this UAV platform at a mock traffic accident, the authors were able to show promising potential for their future works. While this paper used only a single UAV, Elloumi *et al.* applied a network of multiple UAVs for traffic monitoring [184]. Elloumi *et al.* were able to create adaptive trajectories for the UAVs by tracking different moving points within the UAVs' field of view. The UAVs then collect traffic data on a city road and send this information to a processing center. When compared to a single UAV with a fixed trajectory, the multi-UAV system is shown to outperform the single UAV system in terms of event detection and coverage rates.

Huang *et al.* presented one such application where the group investigated the deployment of a UAV network for the purposes of monitoring road traffic in a decentralized navigation scheme [285]. In this work, the UAVs performed four actions, including initial tasks, searching, accumulating, and monitoring. When the UAV network detects blockage, the UAVs can then move to the area for further visual investigation of ground vehicles. The UAVs capture measurements from the scene, and share their location with one another. The simulations are implemented in a single plane, which can be expanded to 3D movement and potentially be implemented in real time. In their parallel paper, Savkin and Huang discussed navigation of a UAV network for surveillance using a distributed navigation algorithm. Each UAV in the network uses individual local information to determine its movement with minimal involvement from the central controller, and converge to an optimal location [286].

Other groups have also implemented the use of UAV networks for traffic monitoring and surveillance. Khan *et al.* proposed a UAV-based smart traffic surveillance system [287]. The proposed technique was introduced as a smart system that made use of 5G technology. The UAV is designed to track speeding vehicles on the highway. Layer 1 involves the UAV which is deployed for traffic monitoring. Layer 2 represents a communication bridge between base station and layer 1. Layer 3 is the monitored traffic. Alioua *et al.* considered UAV data processing as applied for multi-UAV traffic monitoring [288]. The authors' approach involved computation offloading and sharing related decision making problems to reduce computational delay and optimization of energy overhead and computation/communication cost. The authors use a theoretical game approach as a three-player sequential game seeking Nash equilibrium, with simulation results showing improvements over previously used algorithms. Deep learning approaches were employed by Gupta and Verma for urban traffic surveillance using imagery from low-flying UAVs [289]. Ahmed *et al.* looked into modeling mobility of multiple UAVs in urban traffic surveillance [290]. Araujo *et al.* described observer (UAV) and target (road vehicle robots) for a monitoring application in a cooperative UAV scheme for urban traffic monitoring scenario [291]. Pedestrian traffic monitoring is also described by multiple authors including Huang and Savkin [292] and Wang *et al.* [293]. In both traffic monitoring and surveillance applications, the final goal is to improve the safety of traffic under efficient and effective UAV path planning, image processing, communication as well as energy considerations.

Crowd monitoring and control at large public events is vital since it guarantees safety of individuals and also improves public security. An increase in crowd density and also abnormal behavior of individuals in the crowd may lead to unpleasant incidents [294]. Strict spatiotemporal restrictions, such as those used in religious festivals including Hajj, increase the likelihood of dangers [295], [296]. In addition, potential public health hazards in such large crowds may even be more serious, including the spread of infectious illnesses, heat-related disorders, the potential for terrorist attacks, and aggressive mob behavior brought on by alcohol and/or drug usage [297]. UAVs can be utilized for crowd control and monitoring activities [298]. DeMoraes *et al.* in [298] introduced a multi-UAV based crowd monitoring system that utilizes UAVs to regularly monitor moving individuals. The proposed system can distribute the UAVs' target monitoring tasks among different drones in order to efficiently be able to monitor all of the targets. Husman *et al.* [294] presented a comprehensive review on the current literature in regard to the use of UAVs for crowd control and monitoring activities.

H. SURVEYING/MAPPING/INSPECTION

Several applications exist for UAVs in surveying, mapping, and inspection. For example, Meng *et al.* utilized a UAV carrying a camera to study volcano tectonics in an active rift in Iceland using an aerial Structure from Motion (SfM) digital photogrammetry technique [183]. The study obtained 1,098 different structural data from mapping 397 structures in the Theistareykir Fissure Swarm. Additionally, several flying altitudes were tested to determine that an altitude of 100 meters was sufficient for studying fracture dilation and kinematics.

Martinez-Carricondo *et al.* developed a fixed wing UAV for the purposes of surveying calving glaciers in Greenland [299]. The UAV was capable of producing accurately geo-referenced and high spatial resolution ortho-images and digital elevation models, surveying up to four tidewater glaciers in a single flight, and performing repeat mapping surveys of six calving glacier termini in 2017 and 2018. Not only can UAVs be useful in mapping applications but also perform in such applications more efficiently. Christiansen *et al.* compared the data obtained from a UAV as well as from traditional surveying methods and found that the UAV SfM methods provided better results than the traditional methods in addition to requiring substantially less time to perform the operation: 4 hours instead of 1 week [300]. Furthermore, UAVs minimize human errors. Tucci *et al.* used a drone to measure the volume of stockpiles of materials from differentiated waste collection added to the recycling chain [263]. The authors utilized photogrammetry to generate 3D models of the stockpiles from point clouds, and used two different software to calculate the volumes.

Meng *et al.* developed an object-oriented classification ensemble algorithm to improve the classification of landscapes and terrain estimation under dense vegetation [183]. The researchers were able to successfully implement their algorithm during experiments using a wetland restoration site and showed an increase in classification from 83.98% to 96.12%, as well as reduced the mean error in terrain models from 0.302 to -0.002 in low vegetation, and from 1.305 to 0.057 in tall vegetation.

UAVs can also be used for surveying vertical walls. Martinez-Carricondo *et al.* used a drone for this purpose, using photogrammetry to gather point clouds of vertical walls [299]. The authors varied the number of Ground Control Points (GCPs) as well as the orientation of the photographs and found that under certain conditions, the UAV could provide similar accuracy to that of a Terrestrial Laser Scanner (TLS).

In agriculture, there are many uses for UAVs. For example, Christiansen *et al.* used a UAV to measure the height of crops on a wheat farm in order to determine the correct level of nitrogen treatment [300]. By combining the data obtained from a Light Detection and Ranging (LiDAR) unit, Global Navigation Satellite System (GNSS), and an Inertial Measurement Unit (IMU), the authors could then generate a point cloud, which was recorded, mapped, and analyzed using functionalities within the Robot Operating System (ROS) as well as the Point Cloud Library (PCL). The authors could also estimate crop volume from this data as well.

UAVs can also be used for inspecting pipelines, power transmission lines, wind turbines, and more. As stated earlier, Gammill *et al.* report that drones can be 97% more efficient in solar farm inspections when compared to manual inspections [67]. Similarly, Patel *et al.* report the use of drones for image capture from solar farms for defect detection in photovoltaic (PV) arrays [301]. In wind turbines inspection, Aquilina *et al.* show that drones are able to inspect all 3 blades in just 40 minutes [302]. Wu *et al.* developed a parameter reconstruction method for power transmission lines [303]. Using magnetic field data, and combining a metaheuristic algorithm and interior point method into their own algorithm, the authors were able to reconstruct the position and current parameters of the transmission lines. The algorithm was shown in experimentation to be useful for transmission line monitoring and controlling the trajectory of the UAV for such purposes.

Elmokadem *et al.* [304] provide a comprehensive review of some of the recent advancements in the field of UAVs in regard to safe autonomous navigation. A significant portion of this article is focused on the state-of-the-art techniques capable of producing three-dimensional avoidance maneuvers and safe trajectories.

I. LOGISTICS/DELIVERY

There are several applications for UAV networks in logistics. Li *et al.* investigated the use of a network of several UAVs for an automated delivery system in an urban environment [305]. The study identified scheduling of multiple UAVs and multiple flights to be problematic within the system. They proposed a multiple objectives decision-making method and special encoding method to tackle the problem, and was able to experimentally determine that the proposed algorithms were able to solve the problem on a small scale.

Another application of multi-UAV systems is explored by Maza *et al.* where an architecture for a cooperative system of UAVs used for joint payload delivery is presented [306]. A control system was proposed to enable several UAVs to work together to transport a single load.

Logistics carriers attempt to perform the last-mile parcel delivery through the air to customers to benefit from its flexibility and convenience. However, there are still some constrains in achieving this goal. Currently, drone-based package delivery systems suffer from having limited battery capacities and short delivery ranges. To overcome these limitations, they require to take advantage of a large fleet of drones simultaneously for commercial operations [307]. This method however can lead to air traffic in low altitude. She and Ouyang [307] investigated the self-organized drone traffic flow in low altitude 3D airspace.

The recent COVID-19 pandemic has encouraged scientists to investigate new implementation techniques that can take advantage of drones for the delivery of medicines. Authors in [308] showed that the use of drones can assist in eliminating contamination with exceptionally high percentage. Xing *et al.* [309] also attempted to find an optimal path for delivering of the COVID-19 test kits to people with a high likelihood of having infection in the shortest time.

Similar to the use of UAVs for delivering physical items such as parcels, medicines, or parts, UAVs can also be used for delay-tolerant bulk data transfer. Cheng *et al.* investigated the use of UAVs for a method called ''load-carry-and-deliver'' [310]. In this method a source node uploads data onto a UAV platform. The UAV is then used to carry and deliver the data to the destination node which is out of reach of other communications. The study compared this method to other methods such as multi-hop and store-and-forward. The study identified important aspects of creating a framework that maximized throughput while working within the allowable constraints of delay and UAV maneuverability.

J. CYBER-PHYSICAL APPLICATIONS

Cyber-physical systems (CPSs) are described as systems that involve synergic cooperation between computational and physical worlds that can interact with humans through different mechanisms [36]. As an incorporation of embedded systems with computation capacities and communication protocols and control units, the UAV network can construct a closed loop system that includes data analysis and interpretation, information transmission, decision making and the final implementation. This kind of system strongly integrates cyber mechanisms into physical devices. Thus, the UAV network can be considered as a CPS [311]. UAV networks are predicted to play an important role in the development of cyber-physical applications [36].

There are many cyber-physical system applications of UAV networks [5], [36]. For instance, Han explored the use of multi-UAV systems for the detection of nuclear radiation, proposing a contour mapping algorithm and cooperative source seeking scenarios for radioactive signal fields [312]. Khosravi and Samadi described UAV-borne video-SAR in the context of radar systems as cyber-physical systems [313]. The authors investigated mobile computing for cyber-physical surveillance services for radar systems and also presented design considerations for such systems. In an earlier and in-depth survey of design challenges of multi-UAV systems in cyber-physical applications, Shakeri *et al.* summarized such challenges to belong categorically to area and target coverage; path planning, collision avoidance in swarming, swarm formation and energy planning; collection, analysis and visualization of visual data; network design, network connectivity, quality of service, and general safety and security; and flight control and controllers and learning-based methods [36]. All these challenges create opportunities to enable cyber-physical applications in large UAV networks.

K. OTHER USES

Erdelj *et al.*, [253], Andre *et al.*, [314], and Zeng *et al.* [172] examined the application of UAV-enabled wireless powered communication networks. By using radio frequency wireless power transfer, UAVs can be employed to wirelessly charge devices on the ground such as IoT devices, and use the power to transmit data. The studies asserted new frameworks for optimizing the throughput of such systems. The first framework targeted developing a two stage iteration optimization algorithm to optimize transmitted power and energy transfer time. During simulations, the algorithm was shown to have a significant gain in performance over Q-learning method as well as other schemes. The second framework attempted to jointly optimize the hover-and-fly trajectories as well as the wireless resource allocations.

A swarm of UAVs can also be used for entertainment, such as light shows [315], [316]. This was exemplified in 2018, when Intel made history at the PyeongChang Olympic Games with a display of 1,218 UAVs flying in formation to create a record setting light show [316].

Shahmoradi *et al.* outlined a detailed review of the application of UAVs in the mining industry [317]. Shahmoradi *et al.* reviewed a list of UAV applications that can potentially be used in mining industry including 3D mapping, mine safety, rock size distribution, mine operation, scope stability, construction monitoring, facility management, geotechnical characterization, gas detection, mine rescue, acid drainage monitoring, landscape mapping, subsidence monitoring, abandoned mine recultivation, as well as gas storage detection.

Because of the rapid advancement in the field of cellular communication technologies and also the necessity for dense deployment of cellular infrastructure, integrating UAV systems into the fifth generation (5G) and beyond networks is becoming a viable solution [318]. Wu *et al.* confirm that to meet the requirements of the next generation of the wireless systems, advanced techniques will be required when integrating UAVs into cellular networks [318]. Such techniques involve intelligent reflecting surfaces, transmission of short packets, energy harvesting, communication and radar sensing as well as edge intelligence. The authors' review reveals that irregardless of the UAV category based on size, weight, flight time, wing configuration, payload, etc., secure and ultra-reliable wireless communication with high data rates for the communication links is the key for the success of UAV applications in this filed. 5G networks will support enhanced mobile broadband (eMBB) for data-intensive applications, ultra-reliable and low-latency communications (URLLC) for remote and autonomous use cases, and massive machine-type communications (mMTC). Intelligent reflective surfaces (IRSs) present themselves as a solution for improved power transmission and air-ground interference in UAV communications. Authors expect that the use of machine learning and AI techniques in general will be an important part of future cellular networks. The advancements in UAV integration in such cellular networks are therefore expected to increase the use cases for UAVs even further.

VI. CHALLENGES AND COMMUNICATION DEMANDS FOR UAV APPLICATIONS

Requirements for communications may increase or decrease depending on the level of autonomy. The lower the degree of autonomy of the UAV system, the higher the requirements are for communications to ground users [172]. UAV communications can be broken down into two broad categories: control and non-payload communications (CNPC), and payload communications [186], [199]. CNPC pertains to the communications between the UAV and ground station for purposes of controlling and monitoring. This would include telemetry data, command and control messages, navigation and sense-and-avoid information, and air traffic control information. CNPC usually operates on low data rates but must be low latency, highly reliable, and very secure. In other hand, payload communications encompasses the communications between ground users and all mission-related data, including things such as video, imagery, and data relaying [204]. In addition, at present, many research projects are mostly focused on UAV-assisted communication networks, specifically in unanticipated events [248], [319], [320]. When the existing ground network is damaged or not entirely functional during such emergency events, drones can be used to bolster the communication infrastructure [321]. This section investigates several well-known challenges in the area of UAV communications that need to be addressed.

A. PHYSICAL LAYER TECHNIQUES

The UAV communication network is typically constructed using a layered approach, generally including the physical layer that deals with channel modeling [138], [322] and antenna architectures [322]; the data link layer that incorporates medium access control (MAC) protocol [323] and channel allocation [324], [325]; the network layer that deals with route selection [232] and QoS [326]; the transport layer that includes congestion control and flow control; and various other cross-layer approaches [311]. To obtain satisfactory network performance, each layer must be adequately tuned because problems in one layer will affect the others. Numerous studies have been conducted with the goal of obtaining the communication reliability for different UAV communication scenarios at different layers. More specifically, in physical layer, there have been lots of work focused on improving the performance of UAV communication in 5G networks [241]. There are several potential main technologies at physical layer. This article considers three of them, namely millimeter wave (mmWave) communication [28], non-orthogonal multiple access (NOMA) technology [327] and Cognitive Radio (CR) communication [328].

1) 5G mmWave UAV-ASSISTED COMMUNICATION NETWORKS

The use of drones has been considered as a complement to the existing cellular networks, in order to obtain higher transmission efficiency with improved communication coverage and channel capacity. However, the extensively used microwave frequency bands below 6 GHz employed by conventional wireless networks cannot sufficiently provide a significant improvement in terms of data rates for many upcoming emerging applications. Using the vast amounts of unutilized bandwidth present at millimeter wave frequencies (over 30–300 GHz) is one possible solution to the spectrum crunch dilemma and to address the needs of 5G and beyond for mobile communications [28]. By considering the use of UAV-assisted cellular networks in mmWave spectrum, an important challenge is very high propagation loss at millimeter wave. In other words, the mmWave spectrum's propagated signals suffer from significant propagation loss and susceptibility to obstruction, which can lead to a high likelihood of outages and a low signal-to-noise ratio (SNR) [329]. Nevertheless, multiple antennas can be built into a small UAV due to the short wavelength of mmWave signals which can help in mitigating the propagation loss issue [330]. In addition, many works have been done to model the multiple-input multiple-output (MIMO) channel for mmWave communications. For instance, Ma *et al.* in [331] investigated a Non-Stationary geometry-based MIMO channel model for millimeter-Wave UAV networks. Multiple antenna technologies have shown to have promising future. Zhang *et al.* [332] provided a comprehensive review regarding three novel multiple antenna technologies that might be significant and play important roles in beyond 5G networks: These technologies are cell-free massive MIMO [333], beamspace massive MIMO [334], and intelligent reflecting surfaces [334]. Another approach that can be used to deal with high propagation loss is to beamforming technique. In this method, directional antennas or antenna arrays are used to obtain high beam gains in order to increase the communication coverage [335]. Xiao *et al.* [335] provided a comprehensive survey on mmWave Beamforming enabled UAV communications. Moreover, Zhang *et al.* [336] presented a novel D2D-based UAV mmWave communication framework where the flying drones had severe energy limitations. The authors showed that there is a need to use a duty cycling mechanism such that drones' radio can only be turned on when it is necessary and also demonstrated that it is necessary to overcome the beam misalignments that caused by the radio OFF periods. Authors then suggested a new fast beam tracking discontinuous reception method to deal with these issue.

2) UAV NON-ORTHOGONAL MULTIPLE ACCESS (NOMA) TRANSMISSION

NOMA has been presented as a solution to the bandwidth, latency, connectivity and throughput requirements associated with UAV communications [337], in particular, with multiple UAVs. Improved latency, connections and connectivity as well throughput bring about challenges related to reliability and security that must be addressed. In their recent publication, Li *et al.* described methods to improve NOMA-UAV based security for secure downlink transmission by limiting the number of connections to the closest line-of-sight UAVs while introducing artificial jamming and passive eavesdropping [338]. The authors separated the power consumption and trajectory optimization into two sub-problems. Their simulation results that involved converting the problem into two convex problems to investigate the trade-off between the two suggested that security of NOMA-UAV networks can be improved via artificial jamming while optimizing power allocation to transmission power and the jamming power, and the UAV trajectory. Another group also employed friendly jamming (FJ) with almost the same methods to improve physical layer security of a downlink cooperative NOMA system with the goal to enhance the secrecy sum rate [339]. The authors described power optimization and iteratively solved two sub-problems, with similar results that achieved improved secrecy sum rates [339]. Jiao *et al.* investigated maximizing the rate of strong users at the same time when guaranteeing the rate of weak users with respect to UAV optimal horizontal positioning using a design with intelligent reflecting surface (IRS) based UAVs that incorporated multiple-input single-output NOMA downlink network [340]. In their design and simulations, the authors first optimized the position, then the IRS based beamforming and phase shifting. In this manner, UAV allowed IRS assisted NOMA network with added flexibility. Their iterative solution demonstrated improvements in data rate performance, which is expected to enable further more complex designs to address additional challenges.

In the civil applications arena, Jiang *et al.* investigated optimal power allocation schemes for NOMA in a high-speed railway scenarios [341] and showed that NOMA performance is better than the traditional orthogonal multiple access (OMA) schemes. Adam *et al.* investigated 3D placement optimization in UAV-assisted NOMA industrial IoT (IIoT) networks for smart traffic management [342]. The authors suggested that path aggregation networks (PANet) show promise in real-time applications when solving non-convex problems associated with optimal 3D placement in communication networks. A Multi-UAV assisted NOMA wireless network uplink communication for IoT devices is proposed by Barick and Singhal for disaster scenarios [343]. NOMA allows the improvement of the uplink capacity of the system by jointly optimizing the position of the UAVs and the power control of the IoT devices. In UAV-NOMA based networks, the optimization problem focuses on power allocation and efficiency, as well as trajectory and placement, and is the focus of ongoing research [344], [345], [346], [347], [348].

3) UAV-BASED COGNITIVE RADIO (CR)

Frequency spectrum allocation and management of radio waves have been an important challenge for a couple decades. Telecommunication companies keep needing more frequency spectrum for their devices such as smart phones. Cognitive Radio (CR) became a theoretical solution in which those Primary Users (PU) or licensed users that own the specific band can share their resources with Secondary Users (SU) or unlicensed users. The papers from Saleem *et al.* [328] and Santana *et al.* [349] provided a comprehensive overview of the technology trends that involve the mix of UAVs and CR. Specially the authors in [349] provided a more up-to-date perspective in which the main concern was focused on how UAVs that were operating in unlicensed frequency spectrum bands were able to compete with mobile communication technologies. The main perspective was how to implement CR into the UAVs. Allowing UAVs to utilize PU resources as SU shows a good opportunity for the emerging technology. Another proposed approach of implementing CR into UAVs involves the employment of energy harvesting techniques. The paper by Xiao *et al.* [335] introduced the perspective of UAV-assisted energy harvesting wireless networks. In their paper, they claimed that they could obtain a significant frequency spectrum and energy efficiency through UAV-assisted energy harvesting cognitive radio network (UAV-EH-CRN). This work showed how a drone could adjust its communication transmissions to a dedicated receiver based on the positive identification of a PU in the frequency spectrum band. The authors in [350] proposed a technique to integrate the capabilities of spectrum sharing within drones to assist with mission-critical services. In addition, CR can be utilized in natural disaster scenarios. During the lack or destruction of network resources due to a disaster, it might be possible for Cognitive Radio Networks (CRN) to use UAVs as relays. Nguyen *et al.* proposed a technique to optimize the implementation of such drone relays for both PUs and SUs within the CR schema. Another interesting research work for radio spectrum resource optimization can be seen in [351]. Wang *et al.* suggested the implementation of a UAV relay network that could assist with the communication between a secondary base station and a SU. As a result, the SU could coexist with the PU at the same band. Nobar *et al.* [352] developed an updated perspective into the resource allocation with CR enabled UAV communications. They presented a similar perspective to the work that Wang *et al.* proposed but with further results and an optimized algorithm. It can be seen, that a significant work has been done for implementing CR into UAVs to assist with the spectrum scarcity. An SU capability to accessed licensed PU spectrum without affecting the integrity of its communication is a great capability that can be enhanced with UAVs.

To conclude this section it is important to show the work that has been done by Vo *et al.* [353] into securing the CR Physical layer using UAVs. In their system, they proposed to equip a UAV with a reconfiguration intelligent surfaces (RIS) named as UAV-RIS. Such framework enabled the SU to send confidential information through the UAV-RIS. Their proposed enhancement is expected to increase the secrecy of performance of CRN for IoT implementations. This research opens a new area of opportunity to implement cybersecurity enhancements for CRN through drones.

Other interesting works have been done at the physical layer. For instance, the effect of fading has been extensively investigated. Fading (the impact of random fluctuation on radio channel) is another important challenge in UAV networks that affect the performance of the UAV channels. Equalization techniques can be used to combat fading. Authors in [354] presented a low-overhead blind equalization technique to mitigate the effects of frequency-selective fading in air-to-ground UAV communication channels. Authors in [355] proposed equalization methods for CNPC Links. Authors in this work investigated specifically continuous phase modulated signals for CNPC group of UAV links functioning over doubly-selective channels. Limited power supply is another considerable challenge. Limited power supply can restrict the communication coverage of a drone. To overcome this problem, relay-based transmission strategies can be used [356]. Authors in [356] investigated the number of relays a drone required by using two different kinds of models: infrastructure-based dynamic routing model with unpredictable path and track-based dynamic routing model with predetermined path. Additionally, authors in [357] explored this topic further and developed an existing relay-based transmission system that used simultaneous transmission and reception technique employing different frequency bands. Although, UAVs' limited power supply still is a challenge and has remained as an open research topic, there have been promising approaches to take advantage of drones to transfer power to low-power ground devices wirelessly. Authors in [358] provided a comprehensive review on UAV-enabled wireless power transfer and its interesting applications. Authors in [359] also investigated UAV-enabled wireless powered communication networks and proposed a system that drones could wirelessly charge low-power Internet-of-things (IoT)-devices on the ground and collect information from them. Authors in [360] investigated another important issue associated with transmission and reception techniques. The author's objective in this study was to enhance the quantity of data that a drone could gather throughout a variety of time intervals [360]. The authors investigated two different methods in order to maximize the number of devices that are transmitting data to the drone at each data collecting site to achieve this goal [360]. The role of machine learning techniques is becoming popular in UAV-based 5G radio access networks. Authors in [361] investigated the usefulness of different types of machine learning techniques that could be applied into UAV-based 5G radio access networks.

B. CHANNEL MODELING

When compared to frequently used cellular or satellite systems, UAV communication channels have unique characteristics. Therefore, for better and more cost-effective design and also improvement in performance of UAV communication, it is critical to be accurately investigated some of the most important features of the UAV channels. Several challenges still exist for modeling of UAV channels. For instance, in non-stationary channels, the propagation properties of channels for temporal and spatial fluctuations are still under investigated. Furthermore, airframe shadowing characteristics of tiny UAVs with rotary-wing has yet to be studied [138]. The following are the most distinct properties that differentiate UAV communication from traditional wireless communication: 1) highly dynamic properties of communication channel of UAV for radio propagation of air-to-air and air-to-ground that is caused as a result of UAV high mobility [162], [362]; 2) Airframe shadowing which is one of the less-studied characteristics of the air-to-ground channels. It occurs when the airplane's line-of-sight signal is blocked during certain maneuvers [138], [363], [364]; 3) uncontrolled and excessive temporal and spatial variations caused by non-stationary communication channels due to movement of aerial and ground base stations [138], [187]. To assess the performance of various wireless communication systems, reliable analytical models are required. Modeling methodologies for air to ground channels in UAV communication may be divided into three types [138], [362]. The first technique is to take advantage of environmental factors to create deterministic models. These models may be used to investigate large–scale fading phenomena that have a direct impact on the performance of wireless communication channels [365], [366]. Hence, influence of changing signal propagation conditions in the communication channel which determine how far a radio wave propagates, can provide an approximate analysis of the UAV wireless coverage, and as a result it can predict optimal UAV position [162], [367]. The second method is to use a model named as tapped delay line (TDL) to determine direct line-of-sight path and also multipath components [138], [322], [368]. The channel impulse response may then be used to construct wideband frequency–selective parameters [172], [369]. This method is especially valuable when there are non-stationary properties in the air-to-ground channel. Lastly, geometric–based stochastic models can provide effective tools for assessing temporal-spatial features in a geometric simulation environments. For describing the air-to-ground channels in a 3D plane with less environmental factors, these methods are preferred [370], [371]. The air–to–air propagation channel, unlike the air–to–ground channel, is primarily used in multi–hop UAV networks for the purpose of autonomous coordinating and managing between UAVs, as well as supporting back–haul radio connectivity to complement current communication systems [138], [372]. Furthermore, the propagation properties of air-to-air channels are comparable to propagation characteristics in free space and are heavily reliant on line-of-sight propagation and ground reflection effects [138]. Authors in [373] investigated the propagation characteristics of air-to-air channels in urban environments. Authors in [374] proposed a wideband non-stationary air-to-air channel model for UAV communications. In this work, authors suggested to use a three-dimensional (3D) non-stationary geometry-based stochastic model for air-to-air channels in UAV communication. In current literature, Broadly used low-power radios that are designed based on IEEE 802.15.4 [375], IEEE 802.11 [376], [377] and LoRa standards [378] have been used to experimentally characterize the air-to-air propagation channel [379]. However, the influence of the Doppler spectrum and antenna orientation of air-to-air channels have been poorly addressed in the literature and required further investigation [138].

C. SPECTRUM MANAGEMENT

Increasing use of drones for civil and commercial applications will eventually impose a variety of challenges on management of the radio frequency spectrum. Thus, to ensure efficient utilization of spectrum, safe operation of UAVs, and coexistence of drones with existing wireless networks, spectrum management challenges need to be addressed [324]. Unfortunately, current spectrum allocation techniques cannot be used for UAV networks. This is because UAV communication networks are dynamic in nature [372] and used frequency spectrum during the flight may need to be changed continuously to be able to provide reliable services to the end users [380]. Prior to the advent of drone networks, the use of radio frequency spectrum was reserved primarily for terrestrial networks (e.g., personal, indoor, cellular, etc.) in addition to a small number of aerial networks (military UAVs, satellites, radars, etc.). Currently, existing spectrum management methods such as passive sharing (pre-assignment of time slots) are designed for terrestrial networks which have fixed network infrastructures. The design of these methods depends on factors such as models of terrain and propagation, high density of users, type of application, and safety regulations. However, currently used spectrum management techniques and solutions are not very effective when they are applied to UAV networks. In particular, the dynamic nature of UAVs such as their lifetime and speed require the use of cell shapes that change dynamically, i.e., associated with number of subscribers, bandwidth demands and various services [324]. Dependable and secure operation of UAVs within a wireless network is significantly relied on valuable spectrum management techniques that can obtain spectrum efficiency gain at minimized interference, increased capacity, maximum coverage, and high quality of service (QoS). Above-mentioned techniques that demonstrate adaptability and agility, must be able to manage rapid fluctuations in the UAV network environment. They must be able to handle rapid fluctuations of channels, and varying network topologies. The new spectrum management methods will greatly affect the physical and medium access control (MAC) layers of networks, RF circuitry (e.g., antenna), network capacity, communication coverage and cost [324]. Jasim *et al.* [324] provided a comprehensive review on spectrum management techniques for UAV networks. Jasim *et al.* listed appropriate management techniques that align with drones' requirements and characteristics to ensure efficient usage of the radio spectrum. Authors' investigation in this work was based on this assumption that drones are coexisted with ubiquitous wireless communication technologies that usually occupy the spectrum. Shamsoshoara *et al.* [381] investigated the spectrum shortage problem in a UAV network during important operations such as search and rescue missions, wildfire, and disaster monitoring.

D. CyberSecurity AND PRIVACY

As commercial drones become ever more popular and their operational range grow rapidly, their security issues become more important. Typically, during the flight, drones require to operate within a wireless communication network to achieve their operational goals [382]. Drones may also be controlled remotely, in which case, can lead to an unique opportunity for the cyber-attacks (e.g., taking over control or denial-of-service (DoS)) [383]. Ly *et al.* [384] provided a comprehensive review on different types of cyber threats. The types of cyber-attacks reviewed in this work were categorized into three groups: model of threats, the type of challenges they pose, and the required tools for the attack.

Many scientists have investigated various security vulnerabilities of wireless protocols. For instance, authors in [385] investigated the security vulnerabilities imposed by the use of wireless protocols and then proposed effective methods for increasing the wireless network security. Pelechrinis *et al.* [386] introduced different mechanisms for detection of jamming attacks in wireless networks and then proposed various techniques to defend network from these attacks.

In cellular networks, drones can either be utilized as aerial base stations to complement the terrestrial base stations in order to provide wireless services to ground users; or be used as independent aerial users within the network consisting of terrestrial base stations. However, since drones are only operational at high altitude in cellular networks, they are able to effectively establish direct line-of-sight communication links with other terrestrial users, which in return can pose new challenges for security of cellular networks [387]. On the one hand, jamming attacks and eavesdropping by malevolent nodes on the ground are more likely to occur during UAV-ground communications. On the other hand, malicious drones are more capable of intercepting and disrupting ground communications than malicious ground nodes [387]. Wu *et al.* [387] explored aforementioned new concerns from the perspective of physical-layer security and provided creative solutions to effectively address them. Figure 8 shows an example of occurring eavesdropping and jamming attacks by malicious nodes on the ground. Drones can also be integrated into WSNs to deal with potential threats and attacks such as jamming attacks as shown in [388].

The Internet of Drones (IoD) is relatively new architecture designed recently for providing managed access to controlled airspace for UAVs [389], [390]. Internet of Drone Things

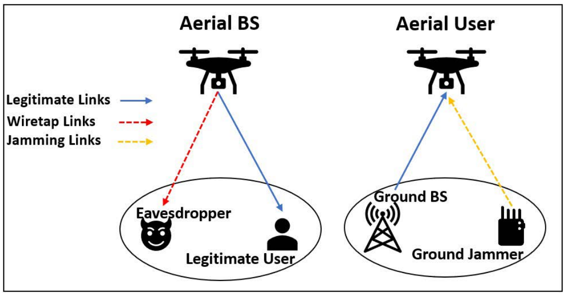


FIGURE 8. Eavesdropping and jamming attacks conducted by malicious nodes on the ground in a cellular network [387].

(IoDT) is also expected to be the potential future path of UAVs backend through IoT, big data, cloud computing, smart computer vision, advanced wireless protocols, and high-end security methods [391]. The main goal of the IoDT is to make UAVs technology applicable to several challenging usages such as rural area monitoring, underground coal and gas mines and even underwater monitoring, in which monitoring is not currently feasible [391]. Security and privacy issues in IoD and IoDT technologies are highly critical and need to be addressed.

Intrusion Detection Systems (IDS) have long been a crucial tool for securing networks and information systems. However, due to the IoT's unique features including having resource-constrained devices, special protocol stacks, and standards, applying typical IDS approaches to them is challenging [392]. Zarpelao *et al.* [392] provided a comprehensive review in regard to IDS research efforts for IoT. Lin *et al.* [393] investigated security and privacy requirements of drones and proposed possible solutions to deal with issues such as data confidentiality protection, privacy leakage and flexible accessibility. Allouch *et al.* [394] suggested a method for the safety assurance of UAVs over IoD. Two approaches were proposed in this work for performing the safety analysis. First approach was based on the qualitative security analysis using the international security standards and the second approach relied on the quantitative security analysis technique using the Bayesian network. Lv *et al.* [382] investigated the network security of IoDs. In this work, Lv *et al.* compared convolutional neural network (CNN) algorithm with autonomous IoD and then used wireless communication technologies to obtain an optimized model for performance of system security. Moreover, with the nonstop increase of using the IoD and IoDT technologies and increase in the number of performing collaborative tasks, the deployment of large fleets of drones for monitoring of smart cities will unsurprisingly confront the challenge of relay and transfer of UAV control. To address this issue, Liao *et al.* in [395] proposed a model that utilizes smart contracts and blockchain to ensure reliable collaboration between controllers of software defined IoD (SD-IoD). The importance of the communication protocol security between UAV and ground control station is outlined in [396], where Khan *et al.* [396] point out that while several common communication protocols such as MAVLink, UAVCan, and UranasLink, can offer good communication, they are also vulnerable to various security threats including eavesdropping, man-in-the-middle attacks, packet data injection, and DoS attacks. To combat this issue, Khan *et al.* [396] introduced a new and secure communication protocol for UAVs.

1) SOFTWARE-DEFINED NETWORKING (SDN)

Although, the use of meshed ad hoc networks has often been among one of the traditional options for establishment of wireless connectivity in multi-drone communication links; but the demand for implementing multi-drone networks has recently been expanded, and thus the design of a more secure and reliable networking architecture has become a necessity [397]. In this context, specifically, Software-Defined Networking (SDN) technology has proved itself to be one of the alternative solutions for multi-drone communication as it can provide flexible services for management and control due to its distinctive characteristics such as network visibility and programmability and also decoupling control from UAVs [398], [399].

SDN is considered as the next generation of networking model that is hardware-independent. In other words, it can be used to control all networking devices made by various vendors [398]. SDN architecture consists of three main layers: decoupled application layer, controller layer and infrastructure layer. Moreover, the SDN controller layer is responsible for management of the overall network operations. The networking model has made simpler by this layered structure, thus it offers potential to enhance network management practices [399]. This networking model can take apart the control portion of the networking from the underlying infrastructure layer [398], [400]. To do this, a programmable control layer has taken the role of the division between the network's control structure and communication infrastructure, enabling setting of the network's behavior. However, in conventional networking practices, the network itself is in charge of both communication and control operations. In contrast to the conventional networks, in which, the whole system must be reconfigured in order to upgrade the system, in the SDN, only the software requires an update, which is a more efficient approach for upgrading the system and reduction of the overall cost [398], [400]. SDN has shown to be a flexible platform and it can also be programmed by high-level programming languages [401]. In order to enhance overall network performance and also identify defects, SDN enables network parameters to be adjusted based on the operating environment. SDN can improve network security including anomaly attacks [402], [403] SDN Intrusion Prevention System (IPS) [404], [405], [406], as well as energy efficiency [407], [408].

VII. SIMULATION PLATFORMS

Undertaking research and application development projects on UAVs is often a challenging task. The fast mobility, 3D navigational spaces, dynamically changing environments, and the possibility of having multiple drones in the system with their communication demands, all add to the complexity of the design and validation of drone applications. Therefore, it has become a common practice to utilize software simulation techniques to evaluate UAVs before actually deploying the system on physical hardware platform. This approach offers relatively low-cost and flexible options to evaluate single and multiple UAV scenarios with varying degrees of mobility, in different types of environmental scenes that can be easily selected from within the software system. Even though there are a number of simulators that could be considered for UAV systems, this paper will primary focus on simulators that allow the user to explore and evaluate the communication network between the UAV(s) and the operator, as well as the inter-UAV communications. A few characteristics that need to be considered for the selection of UAV simulators include: flight dynamics model, system model, graphical model, control system, flight route identification, UAV types and models supported, network communication models, and application-specific requirements [409], [410], [411]. The following subsections review some of the commonly used UAV simulators [412].

2) FlightGear

FlightGear [413] is a free and open-source flight simulator that is intended to create a sophisticated and open flight simulator framework for use in research or academic environments, pilot training, and more. It can be run on common operating system platforms including Windows, Mac OS-X, and Linux, allowing the user to run it on their platform of preference. FlightGear supports dynamic models that involve equations to calculate the physical forces, such as thrust, drag, and lift forces, acting in a simulated UAV. The flight dynamics model is what determines how the aircraft moves and flies. The user can choose from a few flight dynamics models including JSBSim [414] and YASim [415]. FlightGear supports Software-in-the-loop (SITL) and Hardware-in-the-loop (HITL) simulations [411]. A number of networking options allow FlightGear to communicate with other instances of FlightGear, GPS receivers, external flight dynamics modules, and external autopilot or control modules.

FlightGear might be a good choice to obtain immediate visualization into what to expect of the UAV operation. The software contains multiple options or selections into aviation systems or planes. The SITL and HITL options are critical for developers and designers. However, the software seem more dedicated into focused in aviation training rather than supporting research and development of UAV algorithms. Other software such as MATLAB might have more options to implement machine learning or control algorithms. FlightGear is a good visualization and training tool to get immediate feedback but in the long term some other software might need to be utilized for for validation and verification of experiments among other needed tasks.

3) jMAVSim

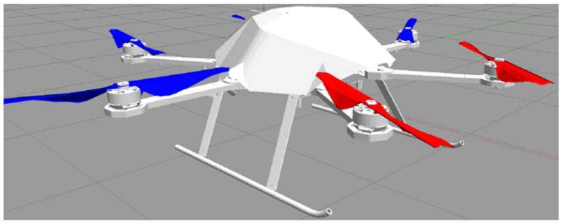
jMAVSim [410] is a simple multirotor simulator that allows flying copter type vehicles running PX4 around a simulated world. It can be easily setup for testing quad-copters for taking-off, flying, landing, and monitoring appropriate response for various fail conditions. The jMAVSim can be integrated with ROS and flight controller firmware. It can be setup for use with the SITL version of PX4, and also for HITL simulation. The SITL runs the complete system on the host machine and simulates the autopilot. It uses the UDP protocol for communication. jMAVSim can also be configured for simulating multiple UAVs in SITL, using the Micro Air Vehicle Communication (MAVLink) Protocol [412].

jMAVSim is more dedicated to developing and simulating UAVs. The strong point of the software is its capability to allow ROS into the simulation. This feature allows the users to develop control algorithms. The software is for more dedicated researchers who perform work with Linux-based computers and not as flexible as other simulators which can be utilized with Windows systems. The learning curve for entry-level or inexperienced researchers makes this tool more complicated to get an immediate visualization of a pursued UAV project.

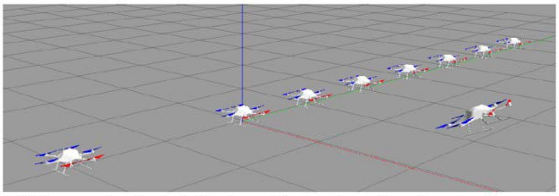
4) GAZEBO

Gazebo [416] is a free, open-source, software tool that gives the ability to accurately and efficiently simulate populations of robots and UAVs in a complex indoor and outdoor environments. It incorporates a robust physics engine, high-quality graphics, and convenient API and graphical interfaces. ArduPilot [417] is among the main open-source software projects that is used to carry out the control of different UAVs in Gazebo simulation as well as on actual drones. Recent advances in simulation techniques are demonstrating capability to support simulation of multiple UAVs in co-operative application scenarios [418]. One of the key elements in such multi-UAV systems is the communication among the UAVs. This can be implemented by employing software components that extend ArduPilot to provide capabilities for sending/receiving MAVLink messages between the UAVs and executing the multi-UAV coordination algorithm [418], [419].

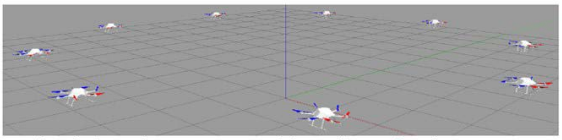
Gazebo has become an essential component when working with ROS. Through the literature of development of robotic and autonomous systems ROS is constantly paired with ROS. The support for robotic swarms is also and added enhancement for developers that have to be taken in consideration. The support or ArduPilot is also critical for researchers developing their own drone for specific research tasks. Similar to jMAVSim the utilization of this software requires the researcher to be more experience with Linux systems. Figure 9 shows an example of working with Gazebo simulator with swarm drones.



(a) AscTec Firefly in Gazebo Simulator



(b) Drones in their initial position when Gazebo starts



In simulation, drones are positioned in a circular pattern

FIGURE 9. Gazebo simulator with swarm drones [420].

5) MICROSOFT AirSim

Microsoft AirSim [421] is a free, open-source, cross-platform simulator for drones, cars, and more, built on Unreal Engine. It supports an SITL simulation with popular flight controllers such as PX4 and ArduPilot, and HITL with PX4 for physically and visually realistic simulations. The developers intend to support AI research to explore deep learning, computer vision, and reinforcement learning algorithms for autonomous operations. To facilitate this, AirSim provides APIs to retrieve data that can be processed to control vehicles. AirSim includes a physics engine that can operate fast enough for real-time HITL simulations with support for popular protocols such as MAVLink [412], [421].

Microsoft AirSim main focus is on AI development. Also, it might be more familiar for individuals that rely more on Microsoft products. The utilization of the Unreal Engine help to create photo realistic visualizations. However, the more dedicated UAV research community focus more on the robotic algorithm development and utilize visualization as secondary. The clarity of the image might not be as important as long as the algorithm can be implemented and data can be obtained to validate results. The ROS and Gazebo community have been stronger and consistent with task. It is still an effort of a major company such as Microsoft to collaborate with the community.

6) MATHWORKS UAV TOOLBOX

The Mathworks UAV Toolbox [422] provides tools and reference applications for designing, simulating, testing, and deploying unmanned aerial vehicle (UAV) and drone applications. Figure 10 shows an example scenario of working with MathWorks simulator environment.

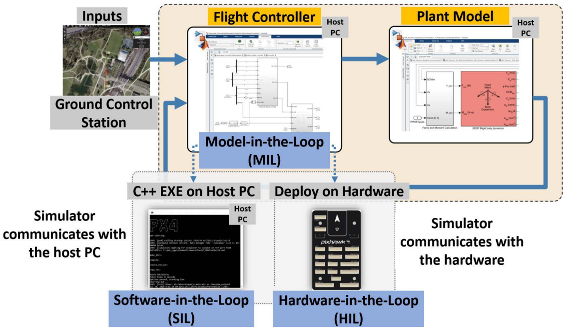


FIGURE 10. MathWorks UAV simulator environment [422].

Researchers can use this toolbox to design autonomous flight algorithms, UAV missions, and flight controllers. An accompanying Flight Log Analyzer app lets developers to interactively analyze 3D flight paths, telemetry information, and sensor readings from common flight log formats. Users can also generate and simulate UAV scenarios with an HITL testing of autonomous flight algorithms and flight controllers. Sensors such as camera, lidar, IMU, and GPS can be incorporated within the simulation in a photorealistic 3D environment. The UAV Toolbox also provides reference application examples for common UAV usages, such as autonomous drone package delivery with multirotor UAV. The toolbox supports C/C++ code generation for rapid prototyping, HITL testing, and standalone deployment to hardware, such as the Pixhawk® Autopilot.

Mathworks has been a constant innovator and producer of tools for academia, scientific and industry development of technology. Their UAV Toolbox has many options and the company keeps investing on upgrading the tools trying to meet the user needs. The mathematical capability and flexibility to produce results and models with their MATLAB and Simulink components still very critical in the scientific community. However, it takes time and training to implement their tools. A researcher has to be dedicated into learning MATLAB and Simulink to develop results. Every year, the company produce versions alpha and beta of their products making it sometimes complicated catching up with changes. Still the tools produce by Mathworks are very useful and flexible with the development of technology. Is just important for the user to understand that time has to be invested into understanding the tools and programming style in MATLAB and Simulink in order to get actual results. This software can be most essential and critical due to the dedication of Mathworks into constantly adding more tools that can simulate not only UAVs. Their developers keep creating tools capable to interact or interconnect with each other. The UAV tool can be connected with Machine Learning, networking, antenna design, circuit design, mechanical design, Fuzzy Logic, or ROS implementations. Mathworks allow for a designer flexibility to be enhance through the implementation and support of multi-domain modeling.

7) NetSim

NetSim is a network simulator that enables users to virtually create a network comprising of devices, links, applications, etc. and study the behavior and performance of the network [422]. The NetSim network simulator enables the following tasks: protocol performance analysis, application modeling and analysis, network design and planning, research and development of new networking technologies, test and verification. The software provides support for mobile Ad-hoc networks, software defined networks, wireless sensor networks, IoTs, cognitive radio networks, and more. A number of applications can be developed and simulated within the NetSim environment, such as UAV drone communications, where UAV flight dynamics can be modeled using MATLAB UAV toolbox [422].

This software is more dedicated to networking analysis and can be a complement to some of the other tools previously listed. It can be beneficial to a deeper analysis and development of network topology, networks and algorithms.

8) NS-3

NS-3 is a free and open software simulation environment for networking research [411], [422]. It is a discrete-event network simulator that supports research for both IP and non-IP based networks. Most of the focus by the majority of its users involve wireless/IP simulations with a variety of static and dynamic routing protocols. In multi-UAV scenarios, the NS-3 software could be employed for the simulation and evaluation of the underlying communication protocol between the nodes in the system. As an example, FlyNetSim [423] is an open-source simulation software that integrates ArduPilot and NS-3, creating individual data paths between the devices operating in the system. It utilizes publish/subscribe based communication framework to create end-to-end data paths and provide temporal synchronization between the UAV and network operations.

NS-3 is similar to NetSim into their capabilities of focus in the study of UAV based networks. However, through FlyNEtSim it has an edge into having a more dedicated perspective into UAVs. The integration of ArduPilot is critical for developers creating their own UAV system.

VIII. FUTURE RESEARCH DIRECTIONS

This section highlights some of the interesting research directions in this field for the future.

A. *FUTURE DIRECTIONS FOR UAV-ASSISTED WIRELESS NETWORKS*

Despite the benefits of merging UAVs with 5G and possibly 6G technologies, research on UAV-assisted cellular networks is still in its early stages, with numerous outstanding questions that need to be addressed. Authors in [28] and [241] provided comprehensive reviews on future directions for further research in this field. Authors in [424] and [425] specifically investigated resource optimization issues in UAV-assisted wireless networks. They discussed open research issues and future research directions to improve UAV-assisted wireless networks in the context of optimization.

1) FUTURE ROLE OF ROUTING PROTOCOLS, QUALITY OF SERVICE (QoS) AND ENERGY CONSUMPTION FOR UAV-ASSISTED WIRELESS NETWORKS

Routing protocols play an important role in UAV networks. Although research on routing protocols for ad hoc networks has grown significantly in recent years, they cannot be directly applied to drones. Designing an effective routing protocol to manage mobility, specifically for high-speed drones, is a difficult challenge [232]. The repeated change of topology as well as disconnection of radio links owing to high-speed result in the UAV network routing issues [426]. Therefore, there should be a routing protocol that efficiently resolves these issues such as [203], [429], and [430]. Little research has been done on cross-layer design routing protocols. Cross layer design enables interaction between OSI layers and assists in obtaining numerous routing metrics [429], [430]. New cross-layer routing protocols such as [432], [433], and [434] has recently been introduced for improvement of routing protocols. Authors in [240] provided a comprehensive review on routing protocols from a cross-layer design perspective. Furthermore, security risks are not taken into account by present routing protocols [433]. For improving UAV communication security in both the physical and network levels, authors in [435] and [436] provided a thorough evaluation of the security countermeasures already in place. Ensuring efficient QoS is a challenging issue in UAV communication networks. Therefore, there should be a requirement for a system that can enhance the performance of the UAV Communication Network to guarantee efficient QoS [426]. Future study may be focused on minimizing the ratio of packet loss or routing failure caused by the intermittent connectivity as a result of the rapid mobility of UAVs. For instance, geographic position mobility-oriented routing (GPMOR) utilizes a prediction algorithm in order to designate the next forwarding UAV based on a Gauss-Markov mobility model [435]. In addition to the Generic algorithms, further QoS algorithms might be investigated by leveraging hybrid routing protocols to find the best path [436]. Delay is another important factor that affects the QoS. The researchers might investigate the QoS-preserving and delay-minimizing routing strategies, nevertheless [426]. In contrast to on-ground old-style transmitters and receivers that were powered by external power sources, UAVs are powered by batteries with limited capacity, which means that the energy available for carrying out different operations such as sensing information, on-board computation, wireless data transmission and flight control is limited. According to scientists [437], [438], the battery life of low-cost drones is typically limited to less than 30 minutes. The limited battery capacity restricts drones' operation time which includes flight time and hovering time. As a result, drones are required to frequently return to charging station for battery charging. This issue is important but at the same time it is also challenging to ensure stable communication services can be achieved. Therefore, it needs to be properly addressed [241].

2) QUANTUM CRYPTOGRAPHY FOR ENHANCED UAV COMMUNICATION SECURITY

Quantum cryptography can be used in drones to enhance security [439]. It combines the principles of encoding with those of quantum physics [439]. In terms of security, Quantum communication protocols can provide improvements over classical methods [440]. These protocols can establish communication links between remote quantum computers in order to transmit information securely. Although, quantum communication channels usually make use of wired communication such as fiber optics, it is also possible to utilize them in wireless communication links [439]. These wireless communication links can be established by small mobile platforms, such as multi-rotor UAVs, which also allow for quick reconfiguration [439]. Isaac *et al.* [439] created an optical quantum channel that uses several drones to exchange quantum-secured random keys up to 10 kilometers apart. To prevent various types of cyber-attacks (e.g., spoofing, eavesdropping, jamming, etc.), it is important to secure the radio communication between UAVs in-flight [440]. Conrad *et al.* [440] presented their progress in utilizing Quantum Key Distribution (QKD) between two UAVs during flight. Although QKD has been used successfully in a variety of contexts, including fiber-to-fiber, free-space ground-to-ground, and ground-to-air communications, the implementation of these protocols on small UAVs has proven to be a difficult task due to limitations in size, weight, and energy consumption [441]. Authors in [441] developed a low size, weight and power QKD system in order to be used in small UAVs.

3) UAV-ASSISTED WIRELESS POWER TRANSFER

Power consumption is one of the challenging issues in UAV-assisted wireless networks [424]. Since UAVs are usually battery-powered, they have limited energy storage for operations. Although, machine learning techniques can be used to have control over power in multi-UAV assisted wireless networks such as the work that has been done in [442], prolonging the operational time of UAVs still is a challenging task. Generally, the energy consumption of the battery-powered UAVs is divided into two parts: energy consumed for wireless communication and energy consumed for powering the hardware and real-time data processing [146], [443]. Energy harvesting techniques such the works that have been done in [444] and [445] can potentially be utilized to prolong the flight operation without adding any significant volume or size to the fuel system. Another potential approach to address this issue is to transfer power wirelessly to the UAVs, so that energy be supplied sustaniable. Some works have been done in the past in [446], [447], and [448]

4) UAV-ASSISTED WIRELESS NETWORKS USING MACHINE LEARNING ALGORITHMS

In future, UAV-assisted wireless networks will possibly be combined with mmwave communications to not merely obtain higher transmission efficiency, increasing coverage range and network capacity but also be utilized to provide support to a broad range of 5G and beyond wireless applications [28]. With high data transmission throughput, ultra-fast speed, large wireless bandwidth, super-low transmission latency and increased connectivity, these new applications are projected to unleash a gigantic IoT ecosystem. Considering these interesting opportunities and new applications, it will be difficult and challenging to design, control and optimize UAV-assisted wireless networks incorporated with mmWave communications [28]. Machine learning algorithms can be used to assist in intelligent decision making. Many machine learning algorithms have been used to support UAV-assisted wireless networks. As an example, based on the prediction of users' mobility information, a framework was proposed by [442] for the trajectory design of numerous UAVs. Authors in [449] presented a deep reinforcement learning-based resource allocation technique in cooperative UAV-assisted wireless networks. Authors in [450] proposed several deep learning based AI methods to improve the energy-efficiency of UAV-assisted wireless networks. It is expected that many machine learning algorithms, such as multi-agent deep reinforcement learning be heavily used in future research [28], [442], [449], [451], [452].

B. FUTURE DIRECTIONS FOR UAV-TO-UAV AND SATELLITE-TO-UAV COMMUNICATIONS

To be able to offer wireless communication services to ground users over a substantially large geographical area, a swarm of UAVs is required to form a multi-hop wireless network. Information packets will then be sent to different UAVs with different trajectories. Although, UAVs must keep their radio communication links close to the ground users, however, because of fast mobility, the radio links between nearby UAVs are interrupted frequently. As a result of these interruptions, many current conventional routing protocols will not work properly in FANETs. Hence, the main challenge is the manner in which flight of UAVs are controlled to provide acceptable services. Furthermore, when UAVs decide to collaborate with each other, avoidance of collisions also become a major issue and needs to be considered in order to guarantee UAVs safe operation. On the other hand, cutting-edge satellite-to-UAV channel characteristics require detailed information regarding the propagation effects. The development of cutting-edge propagation models for satellite-to-UAV communication is yet in its early stages and will be a subject for future research [442].

IX. CONCLUSION

Not very long ago, unmanned Aerial Vehicles (UAVs), also known as drones, were a technology primarily used for military applications. As rapid advancements in technology, design, and production of UAVs and UAV systems have brought down the cost of UAVs, the use of drones is continually increasing across a wide variety of civil applications. With their intrinsic attributes such as rapid deployment, high mobility, and flexible altitude, UAVs have the potential to be utilized in many wireless system applications. On the one hand, UAVs can operate within a wireless/cellular network as flying mobile terminals to support applications such as goods delivery, search and rescue missions, precision agriculture monitoring, and remote sensing. On the other hand, drones can be utilized individually or work in a team as aerial base stations (BSs) to increase coverage, reliability and capacity of wireless communication systems without investment in wireless system infrastructures. While UAVs have become reliable platforms, there continues to be challenges for various applications, leading many in industry and academia to perform new research on exciting new technologies.

REFERENCES

[1] S. Hayat, E. Yanmaz, and R. Muzaffar, "Survey on unmanned aerial vehicle networks for civil applications: A communications viewpoint," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2624–2661, 4th Quart., 2016.

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

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

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

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

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

[7] Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: Opportunities and challenges," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 36–42, May 2016.

[8] V. Roberge, M. Tarbouchi, and G. Labonte, "Fast genetic algorithm path planner for fixed-wing military UAV using GPU," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 54, no. 5, pp. 2105–2117, Oct. 2018.

[9] E. T. Alotaibi, S. S. Alqefari, and A. Koubaa, "LSAR: Multi-UAV collaboration for search and rescue missions," *IEEE Access*, vol. 7, pp. 55817–55832, 2019.

[10] M. A. Rahman, S. Azad, A. T. Asyhari, M. Z. A. Bhuiyan, and K. Anwar, "Collab-SAR: A collaborative avalanche search-and-rescue missions exploiting hostile Alpine networks," *IEEE Access*, vol. 6, pp. 42094–42107, 2018.

[11] N. Geng, Q. Meng, D. Gong, and P. W. H. Chung, "How good are distributed allocation algorithms for solving urban search and rescue problems? A comparative study with centralized algorithms," *IEEE Trans. Autom. Sci. Eng.*, vol. 16, no. 1, pp. 478–485, Jan. 2019.

[12] S. V. Sibanyoni, D. T. Ramotsoela, B. J. Silva, and G. P. Hancke, "A 2-D acoustic source localization system for drones in search and rescue missions," *IEEE Sensors J.*, vol. 19, no. 1, pp. 332–341, Jan. 2019.

[13] D. Murugan, A. Garg, and D. Singh, "Development of an adaptive approach for precision agriculture monitoring with drone and satellite data," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 10, no. 12, pp. 5322–5328, Dec. 2017.

[14] X. He, J. R. Bourne, J. A. Steiner, C. Mortensen, K. C. Hoffman, C. J. Dudley, B. Rogers, D. M. Cropek, and K. K. Leang, "Autonomous chemical-sensing aerial robot for urban/suburban environmental monitoring," *IEEE Syst. J.*, vol. 13, no. 3, pp. 3524–3535, Sep. 2019.

[15] Z. Lin, H. H. T. Liu, and M. Wotton, "Kalman filter-based large-scale wildfire monitoring with a system of UAVs," *IEEE Trans. Ind. Electron.*, vol. 66, no. 1, pp. 606–615, Jan. 2019.

[16] K. Kuru, D. Ansell, W. Khan, and H. Yetgin, "Analysis and optimization of unmanned aerial vehicle swarms in logistics: An intelligent delivery platform," *IEEE Access*, vol. 7, pp. 15804–15831, 2019.

[17] S. Sawadsitang, D. Niyato, P.-S. Tan, and P. Wang, "Joint ground and aerial package delivery services: A stochastic optimization approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 6, pp. 2241–2254, Jun. 2019.

[18] K. Peng, J. Du, F. Lu, Q. Sun, Y. Dong, P. Zhou, and M. Hu, "A hybrid genetic algorithm on routing and scheduling for vehicle-assisted multi-drone parcel delivery," *IEEE Access*, vol. 7, pp. 49191–49200, 2019.

[19] K. Dorling, J. Heinrichs, G. G. Messier, and S. Magierowski, "Vehicle routing problems for drone delivery," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 47, no. 1, pp. 70–85, Jan. 2017.

[20] Y. Li, B. Peng, L. He, K. Fan, and L. Tong, "Road segmentation of unmanned aerial vehicle remote sensing images using adversarial network with multiscale context aggregation," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 12, no. 7, pp. 2279–2287, Jul. 2019.

[21] L. Deng, X. Hao, Z. Mao, Y. Yan, J. Sun, and A. Zhang, "A subband radiometric calibration method for UAV-based multispectral remote sensing," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 11, no. 8, pp. 2869–2880, Aug. 2018.

[22] A. H. Sawalmeh, N. S. Othman, H. Shakhatreh, and A. Khreishah, "Wireless coverage for mobile users in dynamic environments using UAV," *IEEE Access*, vol. 7, pp. 126376–126390, 2019.

[23] J. Cui, H. Shakhatreh, B. Hu, S. Chen, and C. Wang, "Power-efficient deployment of a UAV for emergency indoor wireless coverage," *IEEE Access*, vol. 6, pp. 73200–73209, 2018.

[24] X. Zhang and L. Duan, "Fast deployment of UAV networks for optimal wireless coverage," *IEEE Trans. Mobile Comput.*, vol. 18, no. 3, pp. 588–601, Mar. 2019.

[25] M. Xiao, S. Mumtaz, Y. Huang, L. Dai, Y. Li, M. Matthaiou, G. K. Karagiannidis, E. Bjornson, K. Yang, I. Chih-Lin, and A. Ghosh, "Millimeter wave communications for future mobile networks," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 9, pp. 1909–1935, Sep. 2017.

[26] X. Wang, L. Kong, F. Kong, F. Qiu, M. Xia, S. Arnon, and G. Chen, "Millimeter wave communication: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 1616–1653, Jun. 2018.

[27] L. Kong, L. Ye, F. Wu, M. Tao, G. Chen, and A. V. Vasilakos, "Autonomous relay for millimeter-wave wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 9, pp. 2127–2136, Sep. 2017.

[28] L. Zhang, H. Zhao, S. Hou, Z. Zhao, H. Xu, X. Wu, Q. Wu, and R. Zhang, "A survey on 5G millimeter wave communications for UAV-assisted wireless networks," *IEEE Access*, vol. 7, pp. 117460–117504, 2019.

[29] H. Kim and J. Ben-Othman, "A collision-free surveillance system using smart UAVs in multi domain IoT," *IEEE Commun. Lett.*, vol. 22, no. 12, pp. 2587–2590, Dec. 2018.

[30] T. Yu, X. Wang, and A. Shami, "UAV-enabled spatial data sampling in large-scale IoT systems using denoising autoencoder neural network," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1856–1865, Apr. 2019.

[31] N. H. Motlagh, M. Bagaa, and T. Taleb, "Energy and delay aware task assignment mechanism for UAV-based IoT platform," *IEEE Internet Things J.*, vol. 6, no. 4, pp. 6523–6536, Aug. 2019.

[32] J. Chakareski, "UAV-IoT for next generation virtual reality," *IEEE Trans. Image Process.*, vol. 28, no. 12, pp. 5977–5990, Dec. 2019.

[33] V. Sharma, R. Kumar, and R. Kaur, "UAV-assisted content-based sensor search in IoTs," *Electron. Lett.*, vol. 53, no. 11, pp. 724–726, May 2017.

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

[35] M. Deruyck, J. Wyckmans, W. Joseph, and L. Martens, "Designing UAV-aided emergency networks for large-scale disaster scenarios," *EURASIP J. Wireless Commun. Netw.*, vol. 2018, no. 1, pp. 1–12, Dec. 2018.

[36] R. Shakeri, M. A. Al-Garadi, A. Badawy, A. Mohamed, T. Khattab, A. K. Al-Ali, K. A. Harras, and M. Guizani, "Design challenges of multi-UAV systems in cyber-physical applications: A comprehensive survey and future directions," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 4, pp. 3340–3385, 4th Quart., 2019.

[37] Z. Wang, L. Liu, T. Long, and Y. Wen, "Multi-UAV reconnaissance task allocation for heterogeneous targets using an opposition-based genetic algorithm with double-chromosome encoding," *Chin. J. Aeronaut.*, vol. 31, no. 2, pp. 339–350, Feb. 2018.

[38] Y. Lu, Z. Xue, G. S. Xia, and L. Zhang, "A survey on vision-based UAV navigation," *Geo-Spatial Inf. Sci.*, vol. 21, no. 2, pp. 21–32, 2018.

[39] A. Savkin and H. Huang, "Asymptotically optimal deployment of drones for surveillance and monitoring," *Sensors*, vol. 19, no. 9, p. 2068, May 2019.

[40] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Efficient deployment of multiple unmanned aerial vehicles for optimal wireless coverage," *IEEE Commun. Lett.*, vol. 20, no. 8, pp. 1647–1650, Aug. 2016.

[41] A. Dhekne, M. Gowda, and R. R. Choudhury, "Extending cell tower coverage through drones," in *Proc. 18th Int. Workshop Mobile Comput. Syst. Appl.*, Feb. 2017, pp. 7–12.

[42] D. Popescu, C. Dragana, F. Stoican, L. Ichim, and G. Stamatescu, "A collaborative UAV-WSN network for monitoring large areas," *Sensors*, vol. 18, no. 12, p. 4202, Nov. 2018.

[43] D. Ebrahimi, S. Sharafeddine, P.-H. Ho, and C. Assi, "UAV-aided projection-based compressive data gathering in wireless sensor networks," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1893–1905, Apr. 2019.

[44] V. K. Quy, V. H. Nam, D. M. Linh, N. T. Ban, and N. D. Han, "Communication solutions for vehicle ad-hoc network in smart cities environment: A comprehensive survey," *Wireless Pers. Commun.*, vol. 122, no. 3, pp. 2791–2815, Feb. 2022.

[45] S. Zaidi, M. Atiquzzaman, and C. T. Calafate, "Internet of Flying Things (IoFT): A survey," *Comput. Commun.*, vol. 165, pp. 53–74, Jan. 2021.

[46] A. Srivastava and J. Prakash, "Future FANET with application and enabling techniques: Anatomization and sustainability issues," *Comput. Sci. Rev.*, vol. 39, Feb. 2021, Art. no. 100359.

[47] *Teal Group Predicts Worldwide Civil Drone Production Will Almost Triple Over the Next Decade*, Teal Group, Fairfax, VA, USA, 2019.

[48] B. Silver, M. Mazur, A. Wiśniewski, and A. Babicz, "Welcome to the era of drone-powered solutions: A valuable source of new revenue streams for telecoms operators," *Commun. Rev.*, vol. 2017, pp. 1–12, Jul. 2017.

[49] *Commercial UAV Market Analysis 2020: Size, Growth & Forecast*, INSIDER, New York, NY, USA, 2020.

[50] M. Buscemi, "The use of unarmed drones in UN peacekeeping operations: Issues of attribution," in *Use and Misuse of New Technologies*, E. Carpanelli and N. Lazzerini, Eds. Cham, Switzerland: Springer, 2019, doi: 10.1007/978-3-030-05648-3_13.

[51] *Agricultural Drones: Why a Modern Farmer Needs a Drone*, Nailex Africa Publishing Ltd, Nairobi, Kenya, 2020. [Online]. Available: https://www.africasurveyorsonline.com/2020/07/21/agricultural-drones-why-a-modern-farmer-needs-a-drone/

[52] *Drones in the Construction Industry*, The ASEAN Post, Shah Alam, Malaysia, 2019.

[53] M. Mazur, A. Wisniewski, and J. McMillan, "Clarity from above: PwC global report on the commercial applications of drone technology," Drone Powered Solutions, PriceWaterhouseCoopers, Warsaw, Poland, 2016. [Online]. Available: https://pwc.blogs.com/files/clarity-from-above-pwc.pdf

[54] J. Y. Park, S. T. Kim, J. K. Lee, J. W. Ham, and K. Y. Oh, "Method of operating a GIS-based autopilot drone to inspect ultrahigh voltage power lines and its field tests," *J. Field Robot.*, vol. 37, pp. 345–361, Apr. 2020.

[55] G. V. Bogel, L. Cousin, N. Iversen, E. S. M. Ebeid, and A. Hennig, "Drones for inspection of overhead power lines with recharge function," in *Proc. Euromicro Conf. Digit. Syst. Design*, Aug. 2020, pp. 497–502.

[56] D. Day, "Drones for transmission infrastructure inspection and mapping improve efficiency," *Natural Gas Electr.*, vol. 33, pp. 7–11, Jul. 2017.

[57] D. Moreno-Jacobo, G. Toledo-Nin, A. Ochoa-Zezzatti, V. Torres, and F. Estrada-Otero, "Evaluation of drones for inspection and control in industry 4.0," in *Technological and Industrial Applications Associated with Intelligent Logistics* (Lecture Notes in Intelligent Transportation and Infrastructure), A. Ochoa-Zezzatti, D. Oliva, and A. J. Perez, Eds. Cham, Switzerland: Springer, 2021, doi: 10.1007/978-3-030-68655-0_29.

[58] V. Sudevan, A. Shukla, and H. Karki, "Current and future research focus on inspection of vertical structures in oil and gas industry," in *Proc. 18th Int. Conf. Control, Automat. Syst. (ICCAS)*, Oct. 2018, pp. 144–149.

[59] G. Buffi, P. Manciola, S. Grassi, M. Barberini, and A. Gambi, "Survey of the Ridracoli dam: UAV–based photogrammetry and traditional topographic techniques in the inspection of vertical structures," *Geomatics, Natural Hazards Risk*, vol. 8, pp. 1562–1579, Dec. 2017.

[60] E. Ridolfi, G. Buffi, S. Venturi, and P. Manciola, "Accuracy analysis of a dam model from drone surveys," *Sensors*, vol. 17, p. 1777, Aug. 2017.

[61] J. Seo, L. Duque, and J. Wacker, "Drone-enabled bridge inspection methodology and application," *Autom. Construct.*, vol. 94, pp. 112–126, Oct. 2018.

[62] F. Flammini, R. Naddei, C. Pragliola, and G. Smarra, "Towards automated drone surveillance in railways: State-of-the-art and future directions," in *Proc. Int. Conf. Adv. Concepts Intell. Vis. Syst.*, in Lecture Notes in Computer Science, vol. 10016. Cham, Switzerland: Springer, Oct. 2016, pp. 336–348.

[63] G. M. Dering, S. Micklethwaite, S. T. Thiele, S. A. Vollgger, and A. R. Cruden, "Review of drones, photogrammetry and emerging sensor technology for the study of dykes: Best practises and future potential," *J. Volcanol. Geothermal Res.*, vol. 373, pp. 148–166, Mar. 2019.

[64] C. Caillouet, F. Giroire, and T. Razafindralambo, "Efficient data collection and tracking with flying drones," *Ad Hoc Netw.*, vol. 89, pp. 35–46, Jun. 2019.

[65] L. Capital, "The future of the drone economy," Levitate Capital, Menlo Park, CA, USA, 2020. Accessed: Oct. 10, 2021. [Online]. Available: https://levitatecap.com/levitate/wp-content/uploads/2020/12/White-Paper-v4.pdf

[66] *Drones Market in Energy Industry*, Market Research Future, Pune, India, Jul. 2019.

[67] M. Gammill, M. Sherman, A. Raissi, and M. Hassanalian, "Energy harvesting mechanisms for a solar photovoltaic plant monitoring drone: Thermal soaring and bioinspiration," in *Proc. AIAA Scitech Forum*, Jan. 2021, pp. 1–8.

[68] A. Kulsinskas, P. Durdevic, and D. Ortiz-Arroyo, "Internal wind turbine blade inspections using UAVs: Analysis and design issues," *Energies*, vol. 14, no. 2, p. 294, Jan. 2021.

[69] A. S. Shihavuddin, X. Chen, V. Fedorov, A. N. Christensen, N. A. B. Riis, K. Branner, A. B. Dahl, and R. R. Paulsen, "Wind turbine surface damage detection by deep learning aided drone inspection analysis," *Energies*, vol. 12, p. 676, Feb. 2019.

[70] M. De Miguel Molina and V. S. Campos, *Ethics and Civil Drones: European Policies and Proposals for the Industry* (SpringerBriefs in Law). Cham, Switzerland: Springer, 2018.

[71] C. Lamberton, D. Brigo, and D. Hoy, "Impact of robotics, RPA and AI on the insurance industry: Challenges and opportunities," *J. Financial Perspect.*, vol. 4, pp. 1–13, May 2017.

[72] P. Brown, *Changing the Landscape of the Insurance Market*, IEEE Spectrum, Dec. 2018. [Online]. Available: https://spectrum.ieee.org/changing-the-landscape-of-the-insurance-market

[73] *Global Drone Package Delivery Market Size Will Reach USD 6,051 Million by 2026*, Facts & Factors, New York, NY, USA, Nov. 2020.

[74] Z. Dukowitz, "Drones in mining: How drones are helping visualize underground spaces too dangerous to enter," Tech. Rep., Jul. 2020. [Online]. Available: https://uavcoach.com/drones-mining/

[75] *Reaching for the Sky: Using Drones to Propel the Mining Industry Forward*, Tata Consultancy Services, Mumbai, India, 2018.

[76] *Commercial Drone Market Size, Share Trends Analysis Report by Product (Fixed-Wing, Rotary Blade, Hybrid), by Application, by End-Use, by Region, and Segment Forecasts, 2021–2028*, Grand View Research, Pune, India, Apr. 2021.

[77] D. Jenkins and B. Vasigh, "The economic impact of unmanned aircraft systems integration in the United States," Assoc. Unmanned Vehicle Syst. Int. (AUVSI), Washington, DC, USA, Tech. Rep., Mar. 2013. [Online]. Available: https://higherlogicdownload.s3.amazonaws.com/AUVSI/958c920a-7f9b-4ad2-9807-f9a4e95d1ef1/UploadedImages/New_Economic%20Report%202013%20Full.pdf

[78] A. C. Watts, V. G. Ambrosia, and E. A. Hinkley, "Unmanned aircraft systems in remote sensing and scientific research: Classification and considerations of use," *Remote Sens.*, vol. 4, no. 6, pp. 1671–1692, 2012.

[79] S. G. Gupta, M. Ghonge, and P. M. Jawandhiya, "Review of unmanned aircraft system (UAS)," *Int. J. Adv. Res. Comput. Eng. Technol.*, vol. 2, pp. 1–13, Apr. 2013.

[80] A. G. Korchenko and O. S. Illyash, "The generalized classification of unmanned air vehicles," in *Proc. IEEE 2nd Int. Conf. Actual Problems Unmanned Air Vehicles Develop. Proc. (APUAVD)*, Oct. 2013, pp. 28–34.

[81] R. Weibel and R. J. Hansman, "Safety considerations for operation of different classes of UAVs in the NAS," in *Proc. AIAA 3rd 'Unmanned Unlimited' Tech. Conf., Workshop Exhib.*, Sep. 2004, pp. 1–11.

[82] A. Cavoukian, "Privacy and drones: Unmanned aerial vehicles," in *Ontario: Information and Privacy Commissioner of Ontario*, Ottawa, ON, Canada, 2012.

[83] N. Homainejad and C. Rizos, "Application of multiple categories of unmanned aircraft systems (UAS) in different airspaces for bushfire monitoring and response," *Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci.*, vol. 40, pp. 55–60, Aug. 2015.

[84] M. Hassanalian and A. Abdelkefi, "Classifications, applications, and design challenges of drones: A review," *Progr. Aerosp. Sci.*, vol. 91, pp. 99–131, May 2017.

[85] J. M. Kahn, R. H. Katz, and K. S. J. Pister, "Next century challenges: Mobile networking for 'smart dust,'" in *Proc. 5th Annu. ACM/IEEE Int. Conf. Mobile Comput. Netw.*, Aug. 1999, pp. 271–278.

[86] L. Sun, S. Baek, and D. Pack, "Distributed probabilistic search and tracking of agile mobile ground targets using a network of unmanned aerial vehicles," in *Human Behavior Understanding in Networked Sensing*, P. Spagnolo, P. Mazzeo, and C. Distante, Eds. Cham, Switzerland: Springer, 2014, doi: 10.1007/978-3-319-10807-0_14.

[87] K. Römer, "Tracking real-world phenomena with smart dust," in *Proc. Eur. Workshop Wireless Sensor Netw.*, 2004, pp. 28–43.

[88] A. Tahir, J. Böling, M. H. Haghbayan, H. T. Toivonen, and J. Plosila, "Swarms of unmanned aerial vehicles—A survey," *J. Ind. Inf. Integr.*, vol. 16, Dec. 2019, Art. no. 100106.

[89] O. Adepoju, "Drone/unmanned aerial vehicles (UAVs) technology," in *Re-Skilling Human Resources for Construction 4.0* (Springer Tracts in Civil Engineering). Cham, Switzerland: Springer, 2022, doi: 10.1007/978-3-030-85973-2_4.

[90] V. Chamola, P. Kotesh, A. Agarwal, N. Gupta, and M. Guizani, "A comprehensive review of unmanned aerial vehicle attacks and neutralization techniques," *Ad Hoc Netw.*, vol. 111, Feb. 2021, Art. no. 102324.

[91] T. Templin, D. Popielarczyk, and R. Kosecki, "Application of low-cost fixed-wing UAV for Inland lakes shoreline investigation," *Pure Appl. Geophys.*, vol. 175, no. 9, pp. 3263–3283, Sep. 2018.

[92] C. Pfeifer, A. Barbosa, O. Mustafa, H. U. Peter, M. C. Rümmler, and A. Brenning, "Using fixed-wing UAV for detecting and mapping the distribution and abundance of penguins on the South Shetlands Islands, Antarctica," *Drones*, vol. 3, p. 39, Apr. 2019.

[93] M. Coombes, T. Fletcher, W.-H. Chen, and C. Liu, "Decomposition-based mission planning for fixed-wing UAVs surveying in wind," *J. Field Robot.*, vol. 37, no. 3, pp. 440–465, Dec. 2020.

[94] Z. Wang, Q. Gao, J. Xu, and D. Li, "A review of UAV power line inspection," in *Advances in Guidance, Navigation and Control* (Lecture Notes in Electrical Engineering), vol. 644, L. Yan, H. Duan, and X. Yu, Eds. Singapore: Springer, 2022, doi: 10.1007/978-981-15-8155-7_263.

[95] S. Asadzadeh, W. J. D. Oliveira, and C. R. D. S. Filho, "UAV-based remote sensing for the petroleum industry and environmental monitoring: State-of-the-art and perspectives," *J. Petroleum Sci. Eng.*, vol. 208, Jan. 2022, Art. no. 109633.

[96] W. Thielicke, W. Hübert, U. Müller, M. Eggert, and P. Wilhelm, "Towards accurate and practical drone-based wind measurements with an ultrasonic anemometer," *Atmos. Meas. Techn.*, vol. 14, no. 2, pp. 1303–1318, Feb. 2021.

[97] B. Galkin, B. Omoniwa, and I. Dusparic, "Multi-agent deep reinforcement learning for optimising energy efficiency of fixed-wing UAV cellular access points," 2021, *arXiv:2111.02258*.

[98] C. Xie and X.-L. Huang, "Energy-efficiency maximization for fixed-wing UAV-enabled relay network with circular trajectory," *Chin. J. Aeronaut.*, vol. 35, no. 9, pp. 71–80, Sep. 2022.

[99] A. Townsend, I. N. Jiya, C. Martinson, D. Bessarabov, and R. Gouws, "A comprehensive review of energy sources for unmanned aerial vehicles, their shortfalls and opportunities for improvements," *Heliyon*, vol. 6, no. 11, Nov. 2020, Art. no. e05285.

[100] B. Zhang, Z. Song, F. Zhao, and C. Liu, "Overview of propulsion systems for unmanned aerial vehicles," *Energies*, vol. 15, no. 2, p. 455, Jan. 2022.

[101] J. Suh and Y. Choi, "Mapping hazardous mining-induced sinkhole subsidence using unmanned aerial vehicle (drone) photogrammetry," *Environ. Earth Sci.*, vol. 76, no. 4, pp. 1–12, Feb. 2017.

[102] G. Jouvet, Y. Weidmann, E. van Dongen, M. P. Lüthi, A. Vieli, and J. C. Ryan, "High-endurance UAV for monitoring calving glaciers: Application to the Inglefield Bredning and Eqip Sermia, Greenland," *Frontiers Earth Sci.*, vol. 7, pp. 1–15, Aug. 2019.

[103] T. Elijah, R. S. Jamisola, Z. Tjiparuro, and M. Namoshe, "A review on control and maneuvering of cooperative fixed-wing drones," *Int. J. Dyn. Control*, vol. 9, no. 3, pp. 1332–1349, Nov. 2020.

[104] R. Rashad, J. Goerres, R. Aarts, J. B. C. Engelen, and S. Stramigioli, "Fully actuated multirotor UAVs: A literature review," *IEEE Robot. Autom. Mag.*, vol. 27, no. 3, pp. 97–107, Sep. 2020.

[105] H. Yang, Y. Lee, S. Y. Jeon, and D. Lee, "Multi-rotor drone tutorial: Systems, mechanics, control and state estimation," *Intell. Service Robot.*, vol. 10, pp. 79–93, Apr. 2017.

[106] D. Kotarski, P. Piljek, M. Pranjić, C. G. Grlj, and J. Kasać, "A modular multirotor unmanned aerial vehicle design approach for development of an engineering education platform," *Sensors*, vol. 21, no. 8, p. 2737, Apr. 2021.

[107] B. Vergouw, H. Nagel, G. Bondt, and B. Custers, "Drone technology: Types, payloads, applications, frequency spectrum issues and future developments," in *The Future of Drone Use* (Information Technology and Law Series), vol. 27, B. Custers, Ed. The Hague, The Netherlands: T. M. C. Asser Press, 2016, doi: 10.1007/978-94-6265-132-6_2.

[108] G. Dekoulis, *Autonomous Vehicles*. Vienna, Austria: IntechOpen, Sep. 2020.

[109] M. Biczyski, R. Sehab, J. F. Whidborne, G. Krebs, and P. Luk, "Multirotor sizing methodology with flight time estimation," *J. Adv. Transp.*, vol. 2020, Jan. 2020, Art. no. 9689604.

[110] B. Alkouz, B. Shahzaad, and A. Bouguettaya, "Service-based drone delivery," in *Proc. IEEE 7th Int. Conf. Collaboration Internet Comput. (CIC)*, Dec. 2021, pp. 68–76.

[111] S. W. Jackson, N. A. Riccoboni, A. H. A. Rahim, R. V. Tobin, J. E. Bluman, A. N. Kopeikin, P. Manjunath, and E. M. Prosser, "Autonomous airborne multi-rotor UAS delivery system," in *Proc. Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, Athens, Greece, Sep. 2020, pp. 702–708.

[112] J. E. Scott and C. H. Scott, *Drone Delivery Models for Medical Emergencies*. Cham, Switzerland: Springer, 2020.

[113] J. K. Stolaroff, C. Samaras, E. R. O'Neill, A. Lubers, A. S. Mitchell, and D. Ceperley, "Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery," *Nature Commun.*, vol. 9, no. 1, pp. 1–13, Feb. 2018.

[114] Y. Li, D. Yang, Y. Xu, L. Xiao, and H. Chen, "Throughput maximization for UAV-enabled relaying in wireless powered communication networks," *Sensors*, vol. 19, no. 13, pp. 1690–1703, 2019.

[115] Q. Yang and J. H. Yang, "HD video transmission of multi-rotor unmanned aerial vehicle based on 5G cellular communication network," *Comput. Commun.*, vol. 160, pp. 688–696, Jul. 2020.

[116] G. Rohi, O. Ejofodomi, and G. Ofualagba, "Autonomous monitoring, analysis, and countering of air pollution using environmental drones," *Heliyon*, vol. 6, no. 1, Jan. 2020, Art. no. e03252.

[117] M. Alvarado, F. Gonzalez, P. Erskine, D. Cliff, and D. Heuff, "A methodology to monitor airborne PM10 dust particles using a small unmanned aerial vehicle," *Sensors*, vol. 17, no. 2, p. 343, Feb. 2017.

[118] M. Ghamari, C. Soltanpur, P. Rangel, W. A. Groves, and V. Kecojevic, "Laboratory and field evaluation of three low-cost particulate matter sensors," *IET Wireless Sensor Syst.*, vol. 12, pp. 21–32, Feb. 2022.

[119] M. Ghamari, H. Kamangir, K. Arezoo, and K. Alipour, "Evaluation and calibration of low-cost off-the-shelf particulate matter sensors using machine learning techniques," *IET Wireless Sensor Syst.*, to be published.

[120] M. Shafiee, Z. Zhou, L. Mei, F. Dinmohammadi, J. Karama, and D. Flynn, "Unmanned aerial drones for inspection of offshore wind turbines: A mission-critical failure analysis," *Robotics*, vol. 10, no. 1, p. 26, Feb. 2021.

[121] U. R. Mogili and B. B. V. L. Deepak, "Review on application of drone systems in precision agriculture," *Proc. Comput. Sci.*, vol. 133, pp. 502–509, Jul. 2018.

[122] S. Anush Lakshman and D. Ebenezer, "Integration of Internet of Things and drones and its future applications," *Mater. Today, Proc.*, vol. 47, pp. 944–949, Jan. 2021.

[123] N. Elmeseiry, N. Alshaer, and T. Ismail, "A detailed survey and future directions of unmanned aerial vehicles (UAVs) with potential applications," *Aerospace*, vol. 8, no. 12, p. 363, Nov. 2021.

[124] J. Chen, H. Liu, J. Zheng, M. Lv, B. Yan, X. Hu, and Y. Gao, "Damage degree evaluation of earthquake area using UAV aerial image," *Int. J. Aerosp. Eng.*, vol. 2016, Jun. 2016, Art. no. 2052603.

[125] C. Yinka-Banjo and O. Ajayi, *Sky-Farmers: Applications of Unmanned Aerial Vehicles (UAV) in Agriculture*. Vienna, Austria: IntechOpen, Dec. 2019.

[126] S. Wen, N. Shen, J. Zhang, Y. Lan, J. Han, X. Yin, Q. Zhang, and Y. Ge, "Single-rotor UAV flow field simulation using generative adversarial networks," *Comput. Electron. Agricult.*, vol. 167, Dec. 2019, Art. no. 105004.

[127] A. S. Saeed, A. B. Younes, C. Cai, and G. Cai, "A survey of hybrid unmanned aerial vehicles," *Progr. Aerosp. Sci.*, vol. 98, pp. 91–105, Apr. 2018.

[128] A. S. Saeed, A. B. Younes, S. Islam, J. Dias, L. Seneviratne, and G. Cai, "A review on the platform design, dynamic modeling and control of hybrid UAVs," in *Proc. Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, Jun. 2015, pp. 806–815.

[129] A. R. Serrano, "Design methodology for hybrid (VTOL + fixed wing) unmanned aerial vehicles," *Aeronaut. Aerosp. Open Access J.*, vol. 2, no. 3, pp. 165–176, Jun. 2018.

[130] A. Muratoğlu, "Design, modeling and control of a hybrid UAV," M.S. thesis, Dept. Aerosp. Eng., Middle East Tech. Univ., Ankara, Turkey, 2019.

[131] G. J. J. Ducard and M. Allenspach, "Review of designs and flight control techniques of hybrid and convertible VTOL UAVs," *Aerosp. Sci. Technol.*, vol. 118, Nov. 2021, Art. no. 107035.

[132] Y. Ke, K. Wang, and B. M. Chen, "Design and implementation of a hybrid UAV with model-based flight capabilities," *IEEE/ASME Trans. Mechatronics*, vol. 23, no. 3, pp. 1114–1125, Jun. 2018.

[133] Y. Zhou, H. Zhao, and Y. Liu, "An evaluative review of the VTOL technologies for unmanned and manned aerial vehicles," *Comput. Commun.*, vol. 149, pp. 356–369, Jan. 2020.

[134] A. Al-Hourani, S. Kandeepan, and A. Jamalipour, "Modeling air-to-ground path loss for low altitude platforms in urban environments," in *Proc. IEEE Global Commun. Conf.*, Dec. 2014, pp. 2898–2904.

[135] L. Y. Sorensen, L. T. Jacobsen, and J. P. Hansen, "Low cost and flexible UAV deployment of sensors," *Sensors*, vol. 17, no. 12, pp. 1–13, Jan. 2017.

[136] B. Galkin, J. Kibilda, and L. A. DaSilva, "Coverage analysis for low-altitude UAV networks in urban environments," in *Proc. IEEE Global Commun. Conf.*, Dec. 2017, pp. 1–6.

[137] F. A. D'Oliveira, F. C. L. D. Melo, and T. C. Devezas, "High-altitude platforms—Present situation and technology trends," *J. Aerosp. Technol. Manage.*, vol. 8, no. 3, pp. 249–262, Aug. 2016.

[138] A. A. Khuwaja, Y. Chen, N. Zhao, M.-S. Alouini, and P. Dobbins, "A survey of channel modeling for UAV communications," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 4, pp. 2804–2821, 4th Quart., 2018.

[139] M. Fladeland, S. Schoenung, and M. Lord, "UAS platforms," in *Proc. NCAR/EOL Workshop-Unmanned Aircraft Syst. Atmos. Res.*, Boulder, CO, USA, 2017, pp. 21–24. [Online]. Available: https://www.eol.ucar.edu/system/files/UAS.Workshop.20180206.pdf

[140] F. Hu, D. Ou, and X.-L. Huang, *UAV Swarm Networks: Models, Protocols, and Systems*. Abingdon, U.K.: Taylor & Francis, Oct. 2020.

[141] C. Gómez and D. R. Green, "Small unmanned airborne systems to support oil and gas pipeline monitoring and mapping," *Arabian J. Geosci.*, vol. 10, no. 9, pp. 1–17, May 2017.

[142] Y. C. Hsieh, C. H. Kuo, Y. T. Wang, C. C. Shen, Y. C. Wang, Y. C. Chen, Y. C. Kuang, J. W. Qui, P. S. Hsieh, and C. Kuo, "Stabilities study of the current agriculture use UAV and future design," in *Proc. IEEE Int. Conf. Appl. Syst. Invention (ICASI)*, Apr. 2018, pp. 746–749.

[143] C. Koparan, A. B. Koc, C. V. Privette, and C. B. Sawyer, "*In situ* water quality measurements using an unmanned aerial vehicle (UAV) system," *Water*, vol. 10, no. 3, p. 264, 2018.

[144] S. Yang, X. Yang, and J. Mo, "The application of unmanned aircraft systems to plant protection in China," *Precis. Agricult.*, vol. 19, no. 2, pp. 278–292, Apr. 2018.

[145] B. Rabta, C. Wankmüller, and G. Reiner, "A drone fleet model for last-mile distribution in disaster relief operations," *Int. J. Disaster Risk Reduction*, vol. 28, pp. 107–112, Jun. 2018.

[146] A. Thibbotuwawa, P. Nielsen, B. Zbigniew, and G. Bocewicz, "Energy consumption in unmanned aerial vehicles: A review of energy consumption models and their relation to the UAV routing," in *Proc. Int. Conf. Inf. Syst. Archit. Technol.*, vol. 853. Cham, Switzerland: Springer, 2019, pp. 173–184.

[147] D. Giordan, M. S. Adams, I. Aicardi, M. Alicandro, P. Allasia, M. Baldo, P. D. Berardinis, D. Dominici, D. Godone, P. Hobbs, V. Lechner, T. Niedzielski, M. Piras, M. Rotilio, R. Salvini, V. Segor, B. Sotier, and F. Troilo, "The use of unmanned aerial vehicles (UAVs) for engineering geology applications," *Bull. Eng. Geol. Environ.*, vol. 79, no. 7, pp. 3437–3481, 2020.

[148] B. Li, Y. Jiang, J. Sun, L. Cai, and C.-Y. Wen, "Development and testing of a two-UAV communication relay system," *Sensors*, vol. 16, no. 10, p. 1696, Oct. 2016.

[149] R. Ps and M. L. Jeyan, "Mini unmanned aerial systems (UAV)—A review of the parameters for classification of a mini UAV," *Int. J. Aviation, Aeronaut., Aerosp.*, vol. 7, pp. 1–5, Jan. 2020.

[150] P. van Blyenburgh, "UAVs—Current situation and considerations for the way forward," Eur. Unmanned Vehicle Assoc., Paris, France, Tech. Rep., Apr. 2000. [Online]. Available: https://apps.dtic.mil/sti/pdfs/ADP010752.pdf

[151] G. Singhal, B. Bansod, and L. Mathew, "Unmanned aerial vehicle classification, applications and challenges: A review," Preprints, 2018, Art. no. 2018110601, doi: 10.20944/preprints201811.0601.v1.

[152] R. A. Chisholm, J. Cui, S. K. Y. Lum, and B. M. Chen, "UAV LiDAR for below-canopy forest surveys," *J. Unmanned Veh. Syst.*, vol. 1, no. 1, pp. 61–68, 2013.

[153] D. Erdenebat and D. Waldmann, "Application of the DAD method for damage localisation on an existing bridge structure using close-range UAV photogrammetry," *Eng. Struct.*, vol. 218, Sep. 2020, Art. no. 110727.

[154] Q. Wu, J. Xu, and R. Zhang, "Capacity characterization of UAV-enabled two-user broadcast channel," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 9, pp. 1955–1971, Sep. 2018.

[155] J. Gong, T.-H. Chang, C. Shen, and X. Chen, "Flight time minimization of UAV for data collection over wireless sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 9, pp. 1942–1954, Sep. 2018.

[156] *Part 107—Small Unmanned Aircraft Systems*, Federal Aviation, Washington, DC, USA, Jun. 2016.

[157] Z. Cui, C. Briso-Rodriguez, K. Guan, Z. Zhong, and F. Quitin, "Multi-frequency air-to-ground channel measurements and analysis for UAV communication systems," *IEEE Access*, vol. 8, pp. 110565–110574, 2020.

[158] *Characteristics of Unmanned Aircraft Systems and Spectrum Requirements to Support Their Safe Operation in Non-Segregated Airspace*, ITU-R, Geneva, Switzerland, Dec. 2009.

[159] M. Asadpour, D. Giustiniano, and K. A. Hummel, "From ground to aerial communication: Dissecting WLAN 802.11n for the drones," in *Proc. 8th ACM Int. Workshop Wireless Netw. Testbeds, Exp. Eval. Characterization*, 2013, pp. 25–32.

[160] N. Schneckenburger, T. Jost, D. Shutin, M. Walter, T. Thiasiriphet, M. Schnell, and U. C. Fiebig, "Measurement of the L-band air-to-ground channel for positioning applications," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 52, no. 5, pp. 2281–2297, Oct. 2016.

[161] Y. S. Meng and Y. H. Lee, "Measurements and characterizations of air-to-ground channel over sea surface at C-band with low airborne altitudes," *IEEE Trans. Veh. Technol.*, vol. 60, no. 4, pp. 1943–1948, May 2011.

[162] W. Khawaja, I. Guvenc, D. W. Matolak, U.-C. Fiebig, and N. Schneckenburger, "A survey of air-to-ground propagation channel modeling for unmanned aerial vehicles," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2361–2391, 3rd Quart., 2019.

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

[164] M. M. Azari, F. Rosas, K.-C. Chen, and S. Pollin, "Optimal UAV positioning for terrestrial-aerial communication in presence of fading," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Washington, DC, USA, Dec. 2016, pp. 1–7.

[165] S. A. Hadiwardoyo, J.-M. Dricot, C. T. Calafate, J.-C. Cano, E. Hernández-Orallo, and P. Manzoni, "UAV mobility model for dynamic UAV-to-car communications in 3D environments," *Ad Hoc Netw.*, vol. 107, Oct. 2020, Art. no. 102193.

[166] R. Amorim, H. Nguyen, P. Mogensen, I. Z. Kovács, J. Wigard, and T. B. Sørensen, "Radio channel modeling for UAV communication over cellular networks," *IEEE Wireless Commun. Lett.*, vol. 6, no. 4, pp. 514–517, Aug. 2017.

[167] W. Khawaja, O. Ozdemir, and I. Guvenc, "UAV air-to-ground channel characterization for mmWave systems," in *Proc. IEEE 86th Veh. Technol. Conf. (VTC-Fall)*, Toronto, ON, Canada, Sep. 2017, pp. 1–5.

[168] X. Zhou, S. Durrani, J. Guo, and H. Yanikomeroglu, "Underlay drone cell for temporary events: Impact of drone height and aerial channel environments," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1704–1718, Apr. 2019.

[169] S. A. H. Mohsan, M. A. Khan, F. Noor, I. Ullah, and M. H. Alsharif, "Towards the unmanned aerial vehicles (UAVs): A comprehensive review," *Drones*, vol. 6, no. 6, p. 147, Jun. 2022.

[170] F. Adelstein, S. K. Gupta, G. Richard, and L. Schwiebert, *Fundamentals of Mobile and Pervasive Computing*, 1st ed. New York, NY, USA: McGraw-Hill, Nov. 2004.

[171] M. Ghamari, B. Janko, R. S. Sherratt, W. Harwin, R. Piechockic, and C. Soltanpur, "A survey on wireless body area networks for ehealthcare systems in residential environments," *Sensors*, vol. 16, no. 6, p. 831, 2016.

[172] Y. Zeng, J. Lyu, and R. Zhang, "Cellular-connected UAV: Potential, challenges, and promising technologies," *IEEE Wireless Commun.*, vol. 26, no. 1, pp. 120–127, Feb. 2019.

[173] A. Chriki, H. Touati, H. Snoussi, and F. Kamoun, "FANET: Communication, mobility models and security issues," *Comput. Netw.*, vol. 163, Nov. 2019, Art. no. 106877.

[174] M. H. Tareque, M. S. Hossain, and M. Atiquzzaman, "On the routing in flying ad hoc networks," in *Proc. Federated Conf. Comput. Sci. Inf. Syst. (FedCSIS)*, vol. 5, 2015, pp. 1–9.

[175] R. Bruzgiene, L. Narbutaite, and T. Adomkus, *MANET Network in Internet of Things System*. Vienna, Austria: IntechOpen, May 2017.

[176] D. S. Gaikwad and M. Zaveri, "VANET routing protocols and mobility models: A survey," in *Proc. Int. Conf. Web Semantic Technol.*, vol. 197. Berlin, Germany: Springer, 2011, pp. 334–342.

[177] H. Badis and A. Rachedi, "Modeling tools to evaluate the performance of wireless multi-hop networks," *Veh. Ad Hoc Netw.*, vol. 15, pp. 653–682, Apr. 2015.

[178] A. T. Albu-Salih and H. A. Khudhair, "ASR-FANET: An adaptive SDN-based routing framework for FANET," *Int. J. Electr. Comput. Eng.*, vol. 11, no. 5, pp. 4403–4412, 2021.

[179] M. A. Al-Absi, A. A. Al-Absi, M. Sain, and H. Lee, "Moving ad hoc networks—A comparative study," *Sustainability*, vol. 13, no. 11, p. 6187, May 2021.

[180] A. R. Ragab, "A new classification for ad-hoc network," *Int. J. Interact. Mobile Technol.*, vol. 14, no. 14, pp. 214–223, 2020.

[181] F. L. Bonali, A. Tibaldi, F. Marchese, L. Fallati, E. Russo, C. Corselli, and A. Savini, "UAV-based surveying in volcano-tectonics: An example from the Iceland rift," *J. Struct. Geol.*, vol. 121, pp. 46–64, 2019.

[182] A. Fotouhi, M. Ding, and M. Hassan, "Dynamic base station repositioning to improve performance of drone small cells," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2016, pp. 1–6.

[183] X. Meng, N. Shang, X. Zhang, C. Li, K. Zhao, X. Qiu, and E. Weeks, "Photogrammetric UAV mapping of terrain under dense coastal vegetation: An object-oriented classification ensemble algorithm for classification and terrain correction," *Remote Sens.*, vol. 9, no. 11, p. 1187, Nov. 2017.

[184] M. Elloumi, R. Dhaou, B. Escrig, H. Idoudi, and L. A. Saidane, "Monitoring road traffic with a UAV-based system," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2018, pp. 1–6.

[185] I. Bekmezci, O. K. Sahingoz, and Ş. Temel, "Flying ad-hoc networks (FANETs): A survey," *Ad Hoc Netw.*, vol. 11, no. 3, pp. 1254–1270, 2013.

[186] X. Chen, J. Tang, and S. Lao, "Review of unmanned aerial vehicle swarm communication architectures and routing protocols," *Appl. Sci.*, vol. 10, no. 10, p. 3661, May 2020.

[187] C. Cheng, G. Bai, Y.-A. Zhang, and J. Tao, "Resilience evaluation for UAV swarm performing joint reconnaissance mission," *Chaos, Interdiscipl. J. Nonlinear Sci.*, vol. 29, no. 5, May 2019, Art. no. 053132.

[188] Z. Wei, H. Wu, S. Huang, and Z. Feng, "Scaling laws of unmanned aerial vehicle network with mobility pattern information," *IEEE Commun. Lett.*, vol. 21, no. 6, pp. 1389–1392, Jun. 2017.

[189] C. Sampedro, H. Bavle, J. L. Sanchez-Lopez, R. A. S. Fernandez, A. Rodriguez-Ramos, M. Molina, and P. Campoy, "A flexible and dynamic mission planning architecture for UAV swarm coordination," in *Proc. Int. Conf. Unmanned Aircr. Syst. (ICUAS)*, Jun. 2016, pp. 355–363.

[190] J. G. Manathara, P. B. Sujit, and R. W. Beard, "Multiple UAV coalitions for a search and prosecute mission," *J. Intell. Robot. Syst.*, vol. 62, no. 1, pp. 125–158, 2010.

[191] A. Sathyan, N. Boone, and K. Cohen, "Comparison of approximate approaches to solving the travelling salesman problem and its application to UAV swarming," *Int. J. Unmanned Syst. Eng.*, vol. 3, no. 6, pp. 1–16, Jan. 2015.

[192] Y. Wei, M. B. Blake, and G. R. Madey, "An operation-time simulation framework for UAV swarm configuration and mission planning," *Proc. Comput. Sci.*, vol. 18, pp. 1949–1958, Jan. 2013.

[193] Y. Zhang, W. Feng, G. Shi, F. Jiang, M. Chowdhury, and S. H. Ling, "UAV swarm mission planning in dynamic environment using consensus-based bundle algorithm," *Sensors*, vol. 20, no. 8, p. 2307, Apr. 2020.

[194] O. S. Oubbati, M. Atiquzzaman, P. Lorenz, M. H. Tareque, and M. S. Hossain, "Routing in flying ad hoc networks: Survey, constraints, and future challenge perspectives," *IEEE Access*, vol. 7, pp. 81057–81105, 2019.

[195] H. Skinnemoen, "UAV & satellite communications live mission-critical visual data," in *Proc. IEEE Int. Conf. Aerosp. Electron. Remote Sens. Technol.*, Nov. 2014, pp. 12–19.

[196] J. Zhao, F. Gao, Q. Wu, S. Jin, Y. Wu, and W. Jia, "Beam tracking for UAV mounted SatCom on-the-move with massive antenna array," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 2, pp. 363–375, Feb. 2018.

[197] A. Guillen-Perez and M.-D. Cano, "Flying ad hoc networks: A new domain for network communications," *Sensors*, vol. 18, no. 10, p. 3571, Oct. 2018.

[198] K. Kumari, B. Sah, and S. Maakar, "A survey: Different mobility model for FANET," *Int. J. Adv. Res. Comput. Sci. Softw. Eng.*, vol. 5, no. 6, pp. 1170–1173, 2015.

[199] A. A. Ateya, A. Muthanna, I. Gudkova, Y. Gaidamaka, and A. D. Algarni, "Latency and energy-efficient multi-hop routing protocol for unmanned aerial vehicle networks," *Int. J. Distrib. Sensor Netw.*, vol. 15, no. 8, Aug. 2019, Art. no. 155014771986639.

[200] A. R. Ragab and P. Flores, "Adapting ad-hoc routing protocol for unmanned aerial vehicle systems," *Int. J. Data Sci.*, vol. 2, no. 1, pp. 1–8, Apr. 2021.

[201] M. A. Khan, A. Safi, I. M. Qureshi, and I. U. Khan, "Flying ad-hoc networks (FANETs): A review of communication architectures, and routing protocols," in *Proc. 1st Int. Conf. Latest Trends Electr. Eng. Comput. Technol. (INTELLECT)*, Nov. 2017, pp. 1–9.

[202] J. S. Raj, "A novel hybrid secure routing for flying ad-hoc networks," *J. Trends Comput. Sci. Smart Technol.*, vol. 2, no. 3, pp. 155–164, Aug. 2020.

[203] Z. Zheng, A. K. Sangaiah, and T. Wang, "Adaptive communication protocols in flying ad hoc network," *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 136–142, Jan. 2018.

[204] M. F. Khan, K. L. A. Yau, R. M. Noor, and M. A. Imran, "Routing schemes in FANETs: A survey," *Sensors*, vol. 20, no. 1, pp. 1–33, 2020.

[205] J. Hong and D. Zhang, "TARCS: A topology change aware-based routing protocol choosing scheme of FANETs," *Electronics*, vol. 8, no. 3, p. 274, Mar. 2019.

[206] B. Zheng, Y. Li, W. Cheng, H. Wu, and W. Liu, "A multi-channel load awareness-based MAC protocol for flying ad hoc networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2020, no. 1, pp. 1–18, Dec. 2020.

[207] X. Hong, K. Xu, and M. Gerla, "Scalable routing protocols for mobile ad hoc networks," *IEEE Netw.*, vol. 16, no. 4, pp. 11–21, Jul./Aug. 2002.

[208] I. Mahmud and Y.-Z. Cho, "Adaptive hello interval in FANET routing protocols for green UAVs," *IEEE Access*, vol. 7, pp. 63004–63015, 2019.

[209] A. Nadeem, A. Mehmood, and M. S. Siddiqui, "A review and classification of flying ad-hoc network (fanet) routing strategies," *Int. J. Sci., Basic Appl. Res.*, vol. 8, no. 3, pp. 1–8, 2018.

[210] M. M. Azari, F. Rosas, and S. Pollin, "Cellular connectivity for UAVs: Network modeling, performance analysis, and design guidelines," *IEEE Trans. Wireless Commun.*, vol. 18, no. 7, pp. 3366–3381, Apr. 2019.

[211] J. J. Carrera-Hernández, G. Levresse, and P. Lacan, "Is UAV-SFM surveying ready to replace traditional surveying techniques?" *Int. J. Remote Sens.*, vol. 41, pp. 4818–4835, Jun. 2020.

[212] J.-A. Maxa, M.-S. B. Mahmoud, N. Larrieu, J.-A. Maxa, M.-S. B. Mahmoud, N. Larrieu, U. Routing, J.-A. Maxa, M. Slim, B. Mahmoud, and N. Larrieu, "Survey on UAANET routing protocols and network security challenges," *Ad Hoc Sensor Wireless Netw.*, vol. 37, pp. 1–41, Apr. 2017.

[213] B. D. Soni, J. H. Jobanputra, and L. Saraswat, "A comprehensive survey on communication protocols for FANET," *IJSRD-Int. Journal Sci. Res. Develop.*, vol. 1, no. 3, pp. 31–34, Mar. 2016.

[214] G. A. Kakamoukas, P. G. Sarigiannidis, and A. A. Economides, "FANETs in agriculture—A routing protocol survey," *Internet Things*, vol. 18, May 2022, Art. no. 100183.

[215] T. P. Venkatesan, P. Rajakumar, and A. Pitchaikkannu, "Overview of proactive routing protocols in MANET," in *Proc. 4th Int. Conf. Commun. Syst. Netw. Technol.*, Apr. 2014, pp. 173–177.

[216] K. Singh and A. K. Verma, "Experimental analysis of AODV, DSDV and OLSR routing protocol for flying Adhoc networks (FANETs)," in *Proc. IEEE Int. Conf. Electr., Comput. Commun. Technol. (ICECCT)*, Mar. 2015, pp. 9–12.

[217] B. D. Shivahare, C. Wahi, and S. Shivhare, "Comparison of proactive and reactive routing protocols in mobile Adhoc network using routing protocol property," *Int. J. Emerg. Technol. Adv. Eng.*, vol. 2, no. 3, pp. 356–359, 2012.

[218] N. Patel, A. Pawar, and N. Shekokar, "A survey on routing protocols for MANET," *Int. J. Comput. Appl.*, vol. 110, no. 11, pp. 5–7, Jan. 2015.

[219] S. Maakar and A. L. Sangal, "Performance evaluation of two reactive routing protocols of MANET using group mobility model," *Int. J. Comput. Sci. Issues*, vol. 7, no. 3, pp. 38–43, 2010.

[220] M. Alshowkan, E. A. Fattah, and A. Odeh, "Performance evaluation of DYMO, AODV and DSR routing protocols in MANET," *Int. J. Comput. Appl.*, vol. 49, no. 11, pp. 29–33, Jul. 2012.

[221] N. Beijar, "Zone routing protocol (ZRP)," Netw. Lab., Helsinki Univ. Technol., Espoo, Finland, Tech. Rep., 2002, p. 12, vol. 9, no. 1.

[222] H. Kaur, H. Singh, and A. Sharma, "Geographic routing protocol: A review," *Int. J. Grid Distrib. Comput.*, vol. 9, no. 2, pp. 245–254, 2016.

[223] O. S. Oubbati, A. Lakas, F. Zhou, M. Günes, and M. B. Yagoubi, "A survey on position-based routing protocols for flying ad hoc networks (FANETs)," *Veh. Commun.*, vol. 10, pp. 29–56, Oct. 2017.

[224] N. Sabor, S. Sasaki, M. Abo-Zahhad, and S. M. Ahmed, "A comprehensive survey on hierarchical-based routing protocols for mobile wireless sensor networks: Review, taxonomy, and future directions," *Wireless Commun. Mobile Comput.*, vol. 2017, pp. 1–23, Mar. 2017.

[225] J. Souza, J. Jailton, T. Carvalho, J. Araújo, and R. Francês, "A proposal for routing protocol for FANET: A fuzzy system approach with QoE/QoS guarantee," *Wireless Commun. Mobile Comput.*, vol. 2019, pp. 1–10, Nov. 2019.

[226] M. A. Khan, I. M. Qureshi, and F. Khanzada, "A hybrid communication scheme for efficient and low-cost deployment of future flying AD-HOC network (Fanet)," *Drones*, vol. 3, no. 1, pp. 1–20, 2019.

[227] Q. Sang, H. Wu, L. Xing, and P. Xie, "Review and comparison of emerging routing protocols in flying ad hoc networks," *Symmetry*, vol. 12, no. 6, pp. 1–24, 2020.

[228] B.-S. Roh, M.-H. Han, J.-H. Ham, and K.-I. Kim, "Q-LBR: Q-learning based load balancing routing for UAV-assisted VANET," *Sensors*, vol. 20, no. 19, p. 5685, Oct. 2020.

[229] C. Singhal and K. Rahul, "LB-UAVnet: Load balancing algorithm for UAV based network using SDN," in *Proc. 22nd Int. Symp. Wireless Pers. Multimedia Commun. (WPMC)*, Lisbon, Portugal, Nov. 2019, pp. 1–5.

[230] Z. Luan, H. Jia, P. Wang, R. Jia, and B. Chen, "Joint UAVs' load balancing and UEs' data rate fairness optimization by diffusion UAV deployment algorithm in multi-UAV networks," *Entropy*, vol. 23, no. 11, p. 1470, Nov. 2021.

[231] H. Guo, X. Zhou, Y. Wang, and J. Liu, "Achieve load balancing in multi-UAV edge computing IoT networks: A dynamic entry and exit mechanism," *IEEE Internet Things J.*, early access, Mar. 23, 2022, doi: 10.1109/JIOT.2022.3161703.

[232] J. Jiang and G. Han, "Routing protocols for unmanned aerial vehicles," *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 58–63, Jan. 2018.

[233] C. Pu, "Link-quality and traffic-load aware routing for UAV ad hoc networks," in *Proc. IEEE 4th Int. Conf. Collaboration Internet Comput. (CIC)*, Philadelphia, PA, USA, Oct. 2018, pp. 71–79.

[234] A. Katiyar, D. Singh, and R. S. Yadav, "State-of-the-art approach to clustering protocols in VANET: A survey," *Wireless Netw.*, vol. 26, no. 7, pp. 5307–5336, Oct. 2020.

[235] X. Pang, M. Liu, Z. Li, B. Gao, and X. Guo, "Geographic position based hopless opportunistic routing for UAV networks," *Ad Hoc Netw.*, vol. 120, Sep. 2021, Art. no. 102560.

[236] Q. Sang, H. Wu, L. Xing, H. Ma, and P. Xie, "An energy-efficient opportunistic routing protocol based on trajectory prediction for FANETs," *IEEE Access*, vol. 8, pp. 192009–192020, 2020.

[237] Y. He, X. Tang, R. Zhang, X. Du, D. Zhou, and M. Guizani, "A course-aware opportunistic routing protocol for FANETs," *IEEE Access*, vol. 7, pp. 144303–144312, 2019.

[238] R. Zhuo, S. Song, and Y. Xu, "UAV communication network modeling and energy consumption optimization based on routing algorithm," *Comput. Math. Methods Med.*, vol. 2022, pp. 1–10, Jun. 2022.

[239] Z. Chu, L. Zhang, Z. Ye, F. Hu, and B. Ke, *Skeleton Extraction of Routing Topology in UAV Networks*. Boca Raton, FL, USA: CRC Press, Dec. 2020.

[240] G. Amponis, T. Lagkas, P. Sarigiannidis, V. Vitsas, P. Fouliras, and S. Wan, "A survey on FANET routing from a cross-layer design perspective," *J. Syst. Archit.*, vol. 120, Nov. 2021, Art. no. 102281.

[241] B. Li, Z. Fei, and Y. Zhang, "UAV communications for 5G and beyond: Recent advances and future trends," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 2241–2263, Apr. 2019.

[242] M. Marchese, A. Moheddine, and F. Patrone, "IoT and UAV integration in 5G hybrid terrestrial-satellite networks," *Sensors*, vol. 19, no. 17, p. 3704, Aug. 2019.

[243] S. Marwat, Y. Mehmood, A. Khan, S. Ahmed, A. Hafeez, T. Kamal, and A. Khan, "Method for handling massive IoT traffic in 5G networks," *Sensors*, vol. 18, no. 11, p. 3966, Nov. 2018.

[244] F. Khan, "Multi-comm-core architecture for terabit-per-second wireless," *IEEE Commun. Mag.*, vol. 54, no. 4, pp. 124–129, Apr. 2016.

[245] B. Galkin, R. Amer, E. Fonseca, and L. A. DaSilva, "Intelligent base station association for UAV cellular users: A supervised learning approach," in *Proc. IEEE 3rd 5G World Forum (5GWF)*, Sep. 2020, pp. 383–388.

[246] Y. Huo and X. Dong, "Millimeter-wave for unmanned aerial vehicles networks: Enabling multi-beam multi-stream communications," 2018, *arXiv:1810.06923*.

[247] Y. Huo, F. Lu, F. Wu, and X. Dong, "Multi-beam multi-stream communications for 5G and beyond mobile user equipment and UAV proof of concept designs," in *Proc. IEEE 90th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2019, pp. 1–5.

[248] N. Zhao, W. Lu, M. Sheng, Y. Chen, J. Tang, F. R. Yu, and K. K. Wong, "UAV-assisted emergency networks in disasters," *IEEE Wireless Commun.*, vol. 26, no. 1, pp. 45–51, Feb. 2019.

[249] V. Mayor, R. Estepa, A. Estepa, and G. Madinabeitia, "Deploying a reliable UAV-aided communication service in disaster areas," *Wireless Commun. Mobile Comput.*, vol. 2019, pp. 1–20, Apr. 2019.

[250] M. Lodeiro-Santiago, I. Santos-González, P. Caballero-Gil, and C. Caballero-Gil, "Secure system based on UAV and BLE for improving SAR missions," *J. Ambient Intell. Humanized Comput.*, vol. 11, no. 8, pp. 3109–3120, Oct. 2017.

[251] M. Ghamari, H. Arora, R. S. Sherratt, and W. Harwin, "Comparison of low-power wireless communication technologies for wearable health-monitoring applications," in *Proc. Int. Conf. Comput., Commun., Control Technol.*, Apr. 2015, pp. 1–6.

[252] M. Ghamari, E. Villeneuve, C. Soltanpur, J. Khangosstar, B. Janko, R. S. Sherratt, and W. Harwin, "Detailed examination of a packet collision model for Bluetooth low energy advertising mode," *IEEE Access*, vol. 6, pp. 46066–46073, 2018.

[253] M. Erdelj, M. Król, and E. Natalizio, "Wireless sensor networks and multi-UAV systems for natural disaster management," *Comput. Netw.*, vol. 124, pp. 72–86, Sep. 2017.

[254] G. Castellanos, M. Deruyck, L. Martens, and W. Joseph, "Performance evaluation of direct-link backhaul for UAV-aided emergency networks," *Sensors*, vol. 19, no. 15, p. 3342, Jul. 2019.

[255] A. Shamsoshoara, M. Khaledi, F. Afghah, A. Razi, J. Ashdown, and K. Turck, "A solution for dynamic spectrum management in mission-critical UAV networks," in *Proc. 16th Annu. IEEE Int. Conf. Sens., Commun., Netw. (SECON)*, Jun. 2019, pp. 1–10.

[256] A. Abdallah, M. Ali, J. Mišić, and V. Mišić, "Efficient security scheme for disaster surveillance UAV communication networks," *Information*, vol. 10, no. 2, p. 43, Jan. 2019.

[257] S. Waharte and N. Trigoni, "Supporting search and rescue operations with UAVs," in *Proc. Int. Conf. Emerg. Secur. Technol.*, Sep. 2010, pp. 142–147.

[258] P. Haegeli, M. Falk, H. Brugger, H.-J. Etter, and J. Boyd, "Comparison of avalanche survival patterns in Canada and Switzerland," *Can. Med. Assoc. J.*, vol. 183, no. 7, pp. 789–795, Apr. 2011.

[259] M. Silvagni, A. Tonoli, E. Zenerino, and M. Chiaberge, "Multipurpose UAV for search and rescue operations in mountain avalanche events," *Geomatics, Natural Hazards Risk*, vol. 8, no. 1, pp. 18–33, 2017.

[260] F. Yuan and R. Liu, "Integration of social media and unmanned aerial vehicles (UAVs) for rapid damage assessment in hurricane Matthew," in *Proc. Construct. Res. Congr.*, Mar. 2018, pp. 513–523.

[261] X. Fan, C. Huang, B. Fu, S. Wen, and X. Chen, "UAV-assisted data dissemination in delay-constrained VANETs," *Mobile Inf. Syst.*, vol. 2018, pp. 1–12, Oct. 2018.

[262] V. Sharma, I. You, and R. Kumar, "Energy efficient data dissemination in multi-UAV coordinated wireless sensor networks," *Mobile Inf. Syst.*, vol. 2016, pp. 1–13, Jan. 2016.

[263] G. Tucci, A. Gebbia, A. Conti, L. Fiorini, and C. Lubello, "Monitoring and computation of the volumes of stockpiles of bulk material by means of UAV photogrammetric surveying," *Remote Sens.*, vol. 11, no. 12, p. 1471, Jun. 2019.

[264] P. Mor and S. B. Bajaj, "Enabling technologies and architecture for 5G-enabled IoT," in *Blockchain for 5G-Enabled IoT*. Cham, Switzerland: Springer, 2021, pp. 223–259.

[265] P. Manju, D. Pooja, and V. Dutt, "Drones in smart cities," in *AI and IoT-Based Intelligent Automation in Robotics*, A. K. Dubey, A. Kumar, S. R. Kumar, N. Gayathri, and P. Das, Eds. Hoboken, NJ, USA: Wiley, 2021, doi: 10.1002/9781119711230.ch12.

[266] C. Scardovi, "From smart to meta cities," in *Sustainable Cities*. Cham, Switzerland: Springer, 2021, doi: 10.1007/978-3-030-68438-9_1.

[267] T. Lagkas, V. Argyriou, S. Bibi, and P. Sarigiannidis, "UAV IoT framework views and challenges: Towards protecting drones as 'things,'" *Sensors*, vol. 18, pp. 1–21, Nov. 2018.

[268] S. K. Datta, J.-L. Dugelay, and C. Bonnet, "IoT based UAV platform for emergency services," in *Proc. Int. Conf. Inf. Commun. Technol. Converg. (ICTC)*, Oct. 2018, pp. 144–147.

[269] O. M. Bushnaq, A. Chaaban, and T. Y. Al-Naffouri, "The role of UAV-IoT networks in future wildfire detection," *IEEE Internet Things J.*, vol. 8, no. 23, pp. 16984–16999, Dec. 2021.

[270] J.-M. Martinez-Caro and M.-D. Cano, "IoT system integrating unmanned aerial vehicles and LoRa technology: A performance evaluation study," *Wireless Commun. Mobile Comput.*, vol. 2019, pp. 1–12, Nov. 2019.

[271] P. Fraga-Lamas, L. Ramos, V. Mondéjar-Guerra, and T. M. Fernández-Caramés, "A review on IoT deep learning UAV systems for autonomous obstacle detection and collision avoidance," *Remote Sens.*, vol. 11, no. 18, p. 2144, Sep. 2019.

[272] H. Dai, H. Zhang, C. Li, and B. Wang, "Efficient deployment of multiple UAVs for IoT communication in dynamic environment," *China Commun.*, vol. 17, no. 1, pp. 89–103, Jan. 2020.

[273] H. Yan, W. Bao, X. Zhu, J. Wang, and L. Liu, "Data offloading enabled by heterogeneous UAVs for IoT applications under uncertain environments," *IEEE Internet Things J.*, early access, Feb. 14, 2022, doi: 10.1109/JIOT.2022.3151053.

[274] S. Xu, X. Zhang, C. Li, D. Wang, and L. Yang, "Deep reinforcement learning approach for joint trajectory design in multi-UAV IoT networks," *IEEE Trans. Veh. Technol.*, vol. 71, no. 3, pp. 3389–3394, Mar. 2022.

[275] L. Lyu, Z. Chu, B. Lin, Y. Dai, and N. Cheng, "Deep reinforcement learning approach for joint trajectory design in multi-UAV IoT network," *IEEE Wireless Commun. Lett.*, vol. 11, no. 5, pp. 328–332, Feb. 2022.

[276] B. Bera, A. K. Das, S. Garg, M. J. Piran, and M. S. Hossain, "Access control protocol for battlefield surveillance in drone-assisted IoT environment," *IEEE Internet Things J.*, vol. 9, no. 4, pp. 2708–2721, Feb. 2022.

[277] S. Punia, H. Krishna, V. Navada, and A. Sajjad, "Agrosquad—An IoT based precision agriculture using UAV and low-power soil multi-sensor," in *Proc. IEEE Int. Conf. Electron., Comput. Commun. Technol. (CONECCT)*, Jul. 2021, pp. 1–6.

[278] P. K. Sharma and D. I. Kim, "Coverage probability of 3-D mobile UAV networks," *IEEE Wireless Commun. Lett.*, vol. 8, no. 1, pp. 97–100, Feb. 2019.

[279] T. Zhang, J. Lei, Y. Liu, C. Feng, and A. Nallanathan, "Trajectory optimization for UAV emergency communication with limited user equipment energy: A safe-DQN approach," *IEEE Trans. Green Commun. Netw.*, vol. 5, no. 3, pp. 1236–1247, Sep. 2021.

[280] Z. Yin, J. Li, M. Ding, F. Shu, F. Song, Y. Qian, and D. López-Pérez, "Uplink performance analysis of UAV user equipments in dense cellular networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Jul. 2019, pp. 1–7.

[281] V. U. Pai and B. Sainath, "UAV selection and link switching policy for hybrid tethered UAV-assisted communication," *IEEE Commun. Lett.*, vol. 25, no. 7, pp. 2410–2414, Jul. 2021.

[282] I. Bekmezci, I. Sen, and E. Erkalkan, "Flying ad hoc networks (FANET) test bed implementation," in *Proc. 7th Int. Conf. Recent Adv. Space Technol. (RAST)*, Jun. 2015, pp. 665–668.

[283] P. Wu, F. Xiao, H. Huang, and R. Wang, "Load balance and trajectory design in multi-UAV aided large-scale wireless rechargeable networks," *IEEE Trans. Veh. Technol.*, vol. 69, no. 11, pp. 13756–13767, Nov. 2020.

[284] P. J. Jin, S. M. Ardestani, Y. Wang, and W. Hu, "Unmanned aerial vehicle (UAV) based traffic monitoring and management," Center Adv. Infrastruct. Transp., Rutgers Univ., Tech. Rep. CAIT-UTC-NC8, 2016. [Online]. Available: https://Users/arash/Downloads/dot_36710_DS1.pdf

[285] H. Huang, A. V. Savkin, and C. Huang, "Decentralized autonomous navigation of a UAV network for road traffic monitoring," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 57, no. 4, pp. 2558–2564, Aug. 2021.

[286] A. V. Savkin and H. Huang, "Navigation of a UAV network for optimal surveillance of a group of ground targets moving along a road," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 7, pp. 9281–9285, Jul. 2022.

[287] N. A. Khan, N. Z. Jhanjhi, S. N. Brohi, R. S. A. Usmani, and A. Nayyar, "Smart traffic monitoring system using unmanned aerial vehicles (UAVs)," *Comput. Commun.*, vol. 157, pp. 434–443, May 2020.

[288] A. Alioua, H. E. Djeghri, M. E. T. Cherif, S.-M. Senouci, and H. Sedjelmaci, "UAVs for traffic monitoring: A sequential game-based computation offloading/sharing approach," *Comput. Netw.*, vol. 177, pp. 1–15, Aug. 2020.

[289] H. Gupta and O. P. Verma, "Monitoring and surveillance of urban road traffic using low altitude drone images: A deep learning approach," *Multimedia Tools Appl.*, vol. 81, no. 14, pp. 19683–19703, Jun. 2021.

[290] F. Ahmed, H. Mahmood, and Y. Niaz, "Mobility modelling for urban traffic surveillance by a team of unmanned aerial vehicles," *Int. J. Ad Hoc Ubiquitous Comput.*, vol. 36, no. 2, pp. 89–100, 2021.

[291] M. S. Araujo, J. P. B. Andrade, T. F. Da Silva Junior, L. F. Da Costa, R. J. C. F. Junior, G. F. L. Melo, D. A. Da Silva, and G. A. L. De Campos, "Cooperative observation of malicious targets in a 3D urban traffic environment using UAVs," in *Proc. Latin Amer. Robot. Symp. (LARS), Brazilian Symp. Robot. (SBR), Workshop Robot. Educ. (WRE)*, Oct. 2021, pp. 60–65.

[292] H. Huang and A. Savkin, "Navigating UAVs for optimal monitoring of groups of moving pedestrians or vehicles," *IEEE Trans. Veh. Technol.*, vol. 70, no. 4, pp. 3891–3896, Apr. 2021.

[293] W. Wang, Y. Peng, G. Cao, X. Guo, and N. Kwok, "Low-illumination image enhancement for night-time UAV pedestrian detection," *IEEE Trans. Ind. Informat.*, vol. 17, no. 8, pp. 5208–5217, Aug. 2021.

[294] M. A. Husman, W. Albattah, Z. Z. Abidin, Y. M. Mustafah, K. Kadir, S. Habib, M. Islam, and S. Khan, "Unmanned aerial vehicles for crowd monitoring and analysis," *Electronics*, vol. 10, no. 23, p. 2974, Nov. 2021.

[295] Y. A. Alaska, A. D. Aldawas, N. A. Aljerian, Z. A. Memish, and S. Suner, "The impact of crowd control measures on the occurrence of stampedes during mass gatherings: The Hajj experience," *Travel Med. Infectious Disease*, vol. 15, pp. 67–70, Jan. 2017.

[296] F. T. Illiyas, S. K. Mani, A. P. Pradeepkumar, and K. Mohan, "Human stampedes during religious festivals: A comparative review of mass gathering emergencies in India," *Int. J. Disaster Risk Reduction*, vol. 5, pp. 10–18, Sep. 2013.

[297] Z. A. Memish, R. Steffen, P. White, O. Dar, E. I. Azhar, A. Sharma, and A. Zumla, "Mass gatherings medicine: Public health issues arising from mass gathering religious and sporting events," *Lancet*, vol. 393, no. 10185, pp. 2073–2084, May 2019.

[298] R. S. de Moraes and E. P. de Freitas, "Multi-UAV based crowd monitoring system," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 56, no. 2, pp. 1332–1345, Apr. 2020.

[299] P. Martínez-Carricondo, F. Agüera-Vega, and F. Carvajal-Ramírez, "Use of UAV-photogrammetry for quasi-vertical wall surveying," *Remote Sens.*, vol. 12, no. 14, p. 2221, Jul. 2020.

[300] M. Christiansen, M. Laursen, R. Jørgensen, S. Skovsen, and R. Gislum, "Designing and testing a UAV mapping system for agricultural field surveying," *Sensors*, vol. 17, no. 12, p. 2703, Nov. 2017.

[301] A. V. Patel, L. McLauchlan, and M. Mehrubeoglu, "Defect detection in PV arrays using image processing," in *Proc. Int. Conf. Comput. Sci. Comput. Intell. (CSCI)*, Dec. 2020, pp. 1653–1657.

[302] J. P. Aquilina, R. N. Farrugia, and T. Sant, "On the energy requirements of UAVs used for blade inspection in offshore wind farms," in *Proc. Offshore Energy Storage Summit (OSES)*, Brest, France, Jul. 2019, pp. 1–7.

[303] Y. Wu, G. Zhao, and J. Hu, "Overhead transmission line parameter reconstruction for UAV inspection based on tunneling magnetoresistive sensors and inverse models," *IEEE Trans. Power Del.*, vol. 34, no. 3, pp. 819–827, Mar. 2019.

[304] T. Elmokadem and A. V. Savkin, "Towards fully autonomous UAVs: A survey," *Sensors*, vol. 21, no. 18, p. 6223, Sep. 2021.

[305] Y. Li, X. Yuan, J. Zhu, H. Huang, and M. Wu, "Multi-objective scheduling of logistics UAVs based on simulated annealing," *Commun. Comput. Inf. Sci.*, vol. 1163, pp. 287–298, Jan. 2020.

[306] I. Maza, K. Kondak, M. Bernard, and A. Ollero, ''Multi-UAV cooperation and control for load transportation and deployment,'' *J. Intell. Robot. Syst.*, vol. 57, pp. 417–449, Jan. 2010.

[307] R. She and Y. Ouyang, ''Efficiency of UAV-based last-mile delivery under congestion in low-altitude air,'' *Transp. Res. C, Emerg. Technol.*, vol. 122, Jan. 2021, Art. no. 102878.

[308] J. Euchi, ''Do drones have a realistic place in a pandemic fight for delivering medical supplies in healthcare systems problems?'' *Chin. J. Aeronaut.*, vol. 34, pp. 182–190, Feb. 2021.

[309] Y. Xing, C. Carlson, and H. Yuan, ''Optimize path planning for UAV COVID-19 test kits delivery system by hybrid reinforcement learning,'' in *Proc. IEEE 12th Annu. Comput. Commun. Workshop Conf. (CCWC)*, Las Vegas, NV, USA, Jan. 2022, pp. 177–183.

[310] C.-M. Cheng, P.-H. Hsiao, H. T. Kung, and D. Vlah, ''Maximizing throughput of UAV-relaying networks with the load-carry-and-deliver paradigm,'' in *Proc. IEEE Wireless Commun. Netw. Conf.*, Mar. 2007, pp. 4420–4427.

[311] H. Wang, H. Zhao, J. Zhang, D. Ma, J. Li, and J. Wei, ''Survey on unmanned aerial vehicle networks: A cyber physical system perspective,'' *IEEE Commun. Surveys Tuts.*, vol. 22, no. 2, pp. 1027–1070, Apr. 2020.

[312] J. Han, ''Cyber-physical systems with multi-unmanned aerial vehicle-based cooperative source seeking and contour mapping,'' Utah State Univ., 2014.

[313] M. R. Khosravi and S. Samadi, ''Mobile multimedia computing in cyber-physical surveillance services through UAV-borne video-SAR: A taxonomy of intelligent data processing for IoMT-enabled radar sensor networks,'' *Tsinghua Sci. Technol.*, vol. 27, pp. 288–302, Apr. 2022.

[314] T. Andre, K. A. Hummel, A. P. Schoellig, E. Yanmaz, M. Asadpour, C. Bettstetter, P. Grippa, H. Hellwagner, S. Sand, and S. Zhang, ''Application-driven design of aerial communication networks,'' *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 129–137, May 2014.

[315] J. Huang, G. Tian, J. Zhang, and Y. Chen, ''On unmanned aerial vehicles light show systems: Algorithms, software and hardware,'' *Appl. Sci.*, vol. 11, no. 16, p. 7687, Aug. 2021.

[316] M. Campion, P. Ranganathan, and S. Faruque, ''UAV swarm communication and control architectures: A review,'' *J. Unmanned Vehicle Syst.*, vol. 7, no. 2, pp. 93–106, Jun. 2019.

[317] J. Shahmoradi, E. Talebi, P. Roghanchi, and M. Hassanalian, ''A comprehensive review of applications of drone technology in the mining industry,'' *Drones*, vol. 4, no. 3, pp. 1–25, 2020.

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

[319] Y. Lin, T. Wang, and S. Wang, ''UAV-assisted emergency communications: An extended multi-armed bandit perspective,'' *IEEE Commun. Lett.*, vol. 23, no. 5, pp. 938–941, May 2019.

[320] X. Zhou, J. Guo, S. Durrani, and H. Yanikomeroglu, ''Uplink coverage performance of an underlay drone cell for temporary events,'' in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kansas City, MO, USA, May 2018, pp. 1–6.

[321] F. Lagum, I. Bor-Yaliniz, and H. Yanikomeroglu, ''Strategic densification with UAV-BSs in cellular networks,'' *IEEE Wireless Commun. Lett.*, vol. 7, no. 3, pp. 384–387, Jun. 2018.

[322] C. Yan, L. Fu, J. Zhang, and J. Wang, ''A comprehensive survey on UAV communication channel modeling,'' *IEEE Access*, vol. 7, pp. 107769–107792, 2019.

[323] S. Vashisht, S. Jain, and G. S. Aujla, ''MAC protocols for unmanned aerial vehicle ecosystems: Review and challenges,'' *Comput. Commun.*, vol. 160, pp. 443–463, Jul. 2020.

[324] M. A. Jasim, H. Shakhatreh, N. Siasi, A. H. Sawalmeh, A. Aldalbahi, and A. Al-Fuqaha, ''A survey on spectrum management for unmanned aerial vehicles (UAVs),'' *IEEE Access*, vol. 10, pp. 11443–11499, 2022.

[325] Z. Feng, L. Ji, Q. Zhang, and W. Li, ''Spectrum management for mmWave enabled UAV swarm networks: Challenges and opportunities,'' *IEEE Commun. Mag.*, vol. 57, no. 1, pp. 146–153, Jan. 2019.

[326] W. Chen, B. Liu, H. Huang, S. Guo, and Z. Zheng, ''When UAV swarm meets edge-cloud computing: The QoS perspective,'' *IEEE Netw.*, vol. 33, no. 2, pp. 36–43, Mar. 2019.

[327] Y. Liu, Z. Qin, Y. Cai, Y. Gao, G. Y. Li, and A. Nallanathan, ''UAV communications based on non-orthogonal multiple access,'' *IEEE Wireless Commun.*, vol. 26, no. 1, pp. 52–57, Feb. 2019.

[328] Y. Saleem, M. H. Rehmani, and S. Zeadally, ''Integration of cognitive radio technology with unmanned aerial vehicles: Issues, opportunities, and future research challenges,'' *J. Netw. Comput. Appl.*, vol. 50, pp. 15–31, Apr. 2015.

[329] Z. Lin, X. Du, H.-H. Chen, B. Ai, Z. Chen, and D. Wu, ''Millimeter-wave propagation modeling and measurements for 5G mobile networks,'' *IEEE Wireless Commun.*, vol. 26, no. 1, pp. 72–77, Feb. 2019.

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

[331] Z. Ma, B. Ai, R. He, Z. Zhong, and M. Yang, ''A non-stationary geometry-based MIMO channel model for millimeter-wave UAV networks,'' *IEEE J. Sel. Areas Commun.*, vol. 39, no. 10, pp. 2960–2974, Oct. 2021.

[332] J. Zhang, E. Bjornson, M. Matthaiou, D. W. K. Ng, H. Yang, and D. J. Love, ''Prospective multiple antenna technologies for beyond 5G,'' *IEEE J. Sel. Areas Commun.*, vol. 38, no. 8, pp. 1637–1660, Aug. 2020.

[333] S. Elhoushy, M. Ibrahim, and W. Hamouda, ''Cell-free massive MIMO: A survey,'' *IEEE Commun. Surveys Tuts.*, vol. 24, no. 1, pp. 492–523, 1st Quart., 2022.

[334] M. A. Albreem, A. H. A. Habbash, A. M. Abu-Hudrouss, and S. S. Ikki, ''Overview of precoding techniques for massive MIMO,'' *IEEE Access*, vol. 9, pp. 60764–60801, 2021.

[335] Z. Xiao, L. Zhu, Y. Liu, P. Yi, R. Zhang, X.-G. Xia, and R. Schober, ''A survey on millimeter-wave beamforming enabled UAV communications and networking,'' *IEEE Commun. Surveys Tuts.*, vol. 24, no. 1, pp. 557–610, 2022.

[336] Z. Zhang, Q. Zhu, and P. Zhang, ''Fast beam tracking discontinuous reception for D2D-based UAV mmWave communication,'' *IEEE Access*, vol. 7, pp. 110487–110498, 2019.

[337] Z. Ding, X. Lei, G. K. Karagiannidis, R. Schober, J. Yuan, and V. K. Bhargava, ''A survey on non-orthogonal multiple access for 5G networks: Research challenges and future trends,'' *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2181–2195, Oct. 2018.

[338] Y. Li, W. Wang, M. Liu, N. Zhao, X. Jiang, Y. Chen, and X. Wang, ''Joint trajectory and power optimization for jamming-aided NOMA-UAV secure networks,'' *IEEE Syst. J.*, 2022.

[339] J. Li, X. Lei, P. D. Diamantoulakis, L. Fan, and G. K. Karagiannidis, ''Security optimization of cooperative NOMA networks with friendly jamming,'' *IEEE Trans. Veh. Technol.*, early access, Aug. 19, 2022, doi: 10.1109/TVT.2022.3200253.

[340] S. Jiao, F. Fang, X. Zhou, and H. Zhang, ''Joint beamforming and phase shift Design in downlink UAV networks with IRS-assisted NOMA,'' *J. Commun. Inf. Netw.*, vol. 5, no. 2, pp. 138–149, Jun. 2020.

[341] T. Jiang, X. Liu, Y. Wang, and W. Wang, ''Research on optimal energy efficient power allocation for NOMA system in high-speed railway scenarios,'' in *Proc. 4th Int. Conf. Commun., Inf. Syst. Comput. Eng. (CISCE)*, May 2022, pp. 1–4.

[342] A. B. M. Adam, M. S. A. Muthanna, A. Muthanna, T. N. Nguyen, and A. A. A. El-Latif, ''Toward smart traffic management with 3D placement optimization in UAV-assisted NOMA IIoT networks,'' *IEEE Trans. Intell. Transp. Syst.*, early access, Jun. 23, 2022, doi: 10.1109/TITS.2022.3182651.

[343] S. Barick and C. Singhal, ''Multi-UAV assisted IoT NOMA uplink communication system for disaster scenario,'' *IEEE Access*, vol. 10, pp. 34058–34068, 2022.

[344] D. Zhai, H. Li, X. Tang, R. Zhang, Z. Ding, and F. R. Yu, ''Height optimization and resource allocation for NOMA enhanced UAV-aided relay networks,'' *IEEE Trans. Commun.*, vol. 69, no. 2, pp. 962–975, Feb. 2021, doi: 10.1109/TCOMM.2020.3037345.

[345] Z. Na, Y. Liu, J. Shi, C. Liu, and Z. Gao, ''UAV-supported clustered NOMA for 6G-enabled Internet of Things: Trajectory planning and resource allocation,'' *IEEE Internet Things J.*, vol. 8, no. 20, pp. 15041–15048, Oct. 2021.

[346] T. Zhang, Z. Wang, Y. Liu, W. Xu, and A. Nallanathan, ''Joint resource, deployment, and caching optimization for AR applications in dynamic UAV NOMA networks,'' *IEEE Trans. Wireless Commun.*, vol. 21, no. 5, pp. 3409–3422, 2021.

[347] N. Nouri, J. Abouei, A. R. Sepasian, M. Jaseemuddin, A. Anpalagan, and K. N. Plataniotis, ''Three-dimensional multi-UAV placement and resource allocation for energy-efficient IoT communication,'' *IEEE Internet Things J.*, vol. 9, no. 3, pp. 2134–2152, Feb. 2022.

[348] A. Rahmati, Y. Yapici, N. Rupasinghe, I. Guvenc, H. Dai, and A. Bhuyan, "Energy efficiency of RSMA and NOMA in cellular-connected mmWave UAV networks," in *Proc. IEEE Int. Conf. Commun. Workshops (ICC Workshops)*, May 2019, pp. 1–6.

[349] G. M. D. Santana, R. S. de Cristo, and K. R. L. J. C. Branco, "Integrating cognitive radio with unmanned aerial vehicles: An overview," *Sensors*, vol. 21, no. 3, pp. 1–27, 2021.

[350] M.-H.-T. Nguyen, E. Garcia-Palacios, T. Do-Duy, L. D. Nguyen, S. T. Mai, and T. Q. Duong, "Spectrum-sharing UAV-assisted mission-critical communication: Learning-aided real-time optimisation," *IEEE Access*, vol. 9, pp. 11622–11632, 2021.

[351] Z. Wang, F. Zhou, Y. Wang, and Q. Wu, "Joint 3D trajectory and resource optimization for a UAV relay-assisted cognitive radio network," *China Commun.*, vol. 18, no. 6, pp. 184–200, Jun. 2021.

[352] S. K. Nobar, M. H. Ahmed, Y. Morgan, and S. A. Mahmoud, "Resource allocation in cognitive radio-enabled UAV communication," *IEEE Trans. Cognit. Commun. Netw.*, vol. 8, no. 1, pp. 296–310, Mar. 2022.

[353] V. N. Vo, N. Q. Long, V.-H. Dang, C. So-In, A.-N. Nguyen, and H. Tran, "Physical layer security in cognitive radio networks for IoT using UAV with reconfigurable intelligent surfaces," in *Proc. 18th Int. Joint Conf. Comput. Sci. Softw. Eng. (JCSSE)*, Jun. 2021, pp. 1–5.

[354] M. Liu, N. Qu, B. Shang, Y. Chen, and F. Gong, "Energy and spectrum efficient blind equalization with unknown constellation for air-to-ground multipath UAV communications," *IEEE Trans. Green Commun. Netw.*, vol. 5, no. 3, pp. 1357–1368, Sep. 2021.

[355] D. Darsena, G. Gelli, I. Iudice, and F. Verdes, "Equalization techniques of control and non-payload communication links for unmanned aerial vehicles," *IEEE Access*, vol. 6, pp. 4485–4496, 2018.

[356] H. Lu, X. Wei, H. Qian, and M. Chen, "A cost-efficient elastic UAV relay network construction method with guaranteed QoS," *Ad Hoc Netw.*, vol. 107, Oct. 2020, Art. no. 102219.

[357] A. Hanyu, Y. Kawamoto, and N. Kato, "Adaptive channel selection and transmission timing control for simultaneous receiving and sending in relay-based UAV network," *IEEE Trans. Netw. Sci. Eng.*, vol. 7, no. 4, pp. 2840–2849, Oct. 2020.

[358] L. Xie, X. Cao, J. Xu, and R. Zhang, "UAV-enabled wireless power transfer: A tutorial overview," *IEEE Trans. Green Commun. Netw.*, vol. 5, no. 4, pp. 2042–2064, Dec. 2021.

[359] L. Xie, J. Xu, and Y. Zeng, "Common throughput maximization for UAV-enabled interference channel with wireless powered communications," *IEEE Trans. Commun.*, vol. 68, no. 5, pp. 3197–3212, May 2020.

[360] Y. Zheng and K.-W. Chin, "Joint trajectory and link scheduling optimization in UAV networks," *IEEE Access*, vol. 9, pp. 84756–84772, 2021.

[361] V. Kouhdaragh, F. Verde, G. Gelli, and J. Abouei, "On the application of machine learning to the design of UAV-based 5G radio access networks," *Electronics*, vol. 9, no. 4, p. 689, Apr. 2020.

[362] P. S. Bithas, V. Nikolaidis, A. G. Kanatas, and G. K. Karagiannidis, "UAV-to-ground communications: Channel modeling and UAV selection," *IEEE Trans. Commun.*, vol. 68, no. 8, pp. 5135–5144, Aug. 2020.

[363] R. Sun, D. W. Matolak, and W. Rayess, "Air-ground channel characterization for unmanned aircraft systems—Part IV: Airframe shadowing," *IEEE Trans. Veh. Technol.*, vol. 66, no. 9, pp. 7643–7652, Sep. 2017.

[364] D. W. Matolak, R. Sun, H. Jamal, and W. Rayess, "L- and C-band airframe shadowing measurements and statistics for a medium-sized aircraft," in *Proc. 11th Eur. Conf. Antennas Propag. (EUCAP)*, Mar. 2017, pp. 1429–1433.

[365] B. Han, D. Qin, P. Zheng, L. Ma, and M. B. Teklu, "Modeling and performance optimization of unmanned aerial vehicle channels in urban emergency management," *ISPRS Int. J. Geo-Inf.*, vol. 10, no. 7, p. 478, Jul. 2021.

[366] X. Wang, W. Feng, Y. Chen, and N. Ge, "Power allocation for UAV swarm-enabled secure networks using large-scale CSI," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2019, pp. 1–6.

[367] J. Boiko, I. Pyatin, L. Karpova, and O. Eromenko, "Study of the influence of changing signal propagation conditions in the communication channel on bit error rate," in *Data-Centric Business and Applications*, vol. 69. Cham, Switzerland: Springer, 2021, pp. 79–103.

[368] Y. Yang, T. Li, X. Chen, M. Wang, Q. Zhu, R. Feng, F. Duan, and T. Zhang, "Real-time ray-based channel generation and emulation for UAV communications," *Chin. J. Aeronaut.*, vol. 35, no. 9, pp. 106–116, Sep. 2022.

[369] H. Jiang, M. Mukherjee, J. Zhou, and J. Lloret, "Channel modeling and characteristics for 6G wireless communications," *IEEE Netw.*, vol. 35, no. 1, pp. 296–303, Jan. 2021.

[370] X. Cheng, Y. Li, C.-X. Wang, X. Yin, and D. W. Matolak, "A 3-D geometry-based stochastic model for unmanned aerial vehicle MIMO Ricean fading channels," *IEEE Internet Things J.*, vol. 7, no. 9, pp. 8674–8687, May 2020.

[371] H. Jiang, Z. Zhang, L. Wu, and J. Dang, "Three-dimensional geometry-based UAV-MIMO channel modeling for A2G communication environments," *IEEE Commun. Lett.*, vol. 22, no. 7, pp. 1438–1441, Jul. 2018.

[372] A. Giagkos, E. Tuci, M. S. Wilson, and P. B. Charlesworth, "UAV flight coordination for communication networks: Genetic algorithms versus game theory," *Soft Comput.*, vol. 25, no. 14, pp. 9483–9503, Jul. 2021.

[373] L. Zhou, Z. Yang, G. Zhao, S. Zhou, and C.-X. Wang, "Propagation characteristics of air-to-air channels in urban environments," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2018, pp. 1–6.

[374] Z. Ma, B. Ai, R. He, G. Wang, Y. Niu, and Z. Zhong, "A wideband non-stationary air-to-air channel model for UAV communications," *IEEE Trans. Veh. Technol.*, vol. 69, no. 2, pp. 1214–1226, Feb. 2020.

[375] J. Wen and W. Dargie, "Evaluation of the quality of aerial links in low-power wireless sensor networks," *IEEE Sensors J.*, vol. 21, no. 12, pp. 13924–13934, Jun. 2021.

[376] T. D. Dinh, D. T. Le, T. T. T. Tran, and R. Kirichek, "Flying ad-hoc network for emergency based on IEEE 802.11 p multichannel MAC protocol," in *Proc. Int. Conf. Distrib. Comput. Commun. Netw.* Cham, Switzerland: Springer, 2019, pp. 479–494.

[377] S. Khan, M. Zeeshan, and Y. Ayaz, "Implementation and analysis of MultiCode MultiCarrier code division multiple access (MC–MC CDMA) in IEEE 802.11 ah for UAV swarm communication," *Phys. Commun.*, vol. 42, Oct. 2020, Art. no. 101159.

[378] J. Supramongkonset, S. Duangsuwan, M. M. Maw, and S. Promwong, "Empirical path loss channel characterization based on air-to-air ground reflection channel modeling for UAV-enabled wireless communications," *Wireless Commun. Mobile Comput.*, vol. 2021, pp. 1–10, Jul. 2021.

[379] L. Shi, N. J. H. Marcano, and R. H. Jacobsen, "A review on communication protocols for autonomous unmanned aerial vehicles for inspection application," *Microprocessors Microsyst.*, vol. 86, Oct. 2021, Art. no. 104340.

[380] J. Kakar and V. Marojevic, "Waveform and spectrum management for unmanned aerial systems beyond 2025," in *Proc. IEEE 28th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Montreal, QC, Canada, Feb. 2018, pp. 1–5.

[381] A. Shamsoshoara, F. Afghah, A. Razi, S. Mousavi, J. Ashdown, and K. Turk, "An autonomous spectrum management scheme for unmanned aerial vehicle networks in disaster relief operations," *IEEE Access*, vol. 8, pp. 58064–58079, 2020.

[382] Z. Lv, "The security of Internet of Drones," *Comput. Commun.*, vol. 148, pp. 208–214, Dec. 2019.

[383] C. Bunse and S. Plotz, "Security analysis of drone communication protocols," in *Proc. Int. Symp. Eng. Secure Softw. Syst.* Paris, France: Springer, Jun. 2018, pp. 96–107.

[384] B. Ly and R. Ly, "Cybersecurity in unmanned aerial vehicles (UAVs)," *J. Cyber Secur. Technol.*, vol. 5, no. 2, pp. 120–137, Apr. 2021.

[385] Y. Zou, J. Zhu, X. Wang, and L. Hanzo, "A survey on wireless security: Technical challenges, recent advances, and future trends," *Proc. IEEE*, vol. 104, no. 9, pp. 1727–1765, Sep. 2016.

[386] K. Pelechrinis, M. Iliofotou, and S. Krishnamurthy, "Denial of service attacks in wireless networks: The case of jammers," *IEEE Commun. Surveys Tuts.*, vol. 13, no. 2, pp. 245–257, May 2011.

[387] Q. Wu, W. Mei, and R. Zhang, "Safeguarding wireless network with UAVs: A physical layer security perspective," *IEEE Wireless Commun.*, vol. 26, no. 5, pp. 12–18, Oct. 2019.

[388] D. Darsena, G. Gelli, I. Iudice, and F. Verde, "Detection and blind channel estimation for UAV-aided wireless sensor networks in smart cities under mobile jamming attack," *IEEE Internet Things J.*, vol. 9, no. 14, pp. 11932–11950, Jul. 2022.

[389] M. Gharibi, R. Boutaba, and S. L. Waslander, "Internet of Drones," *IEEE Access*, vol. 4, pp. 1148–1162, 2016.

[390] P. Boccadoro, D. Striccoli, and L. A. Grieco, "An extensive survey on the Internet of Drones," *Ad Hoc Netw.*, vol. 122, Nov. 2021, Art. no. 102600.

[391] A. Nayyar, B. L. Nguyen, and N. G. Nguyen, "The Internet of Drone Things (IoDT): Future envision of smart drones," in *Proc. Int. Conf. Sustain. Technol. Comput. Intell.*, vol. 1045. Singapore: Springer, Oct. 2019, pp. 563–580.

[392] B. B. Zarpelão, R. S Miani, C. T. Kawakani, and S. C. de Alvarenga, "A survey of intrusion detection in Internet of Things," *J. Netw. Comput. Appl.*, vol. 84, pp. 25–37, Apr. 2017.

[393] C. Lin, D. He, N. Kumar, K.-K. R. Choo, A. Vinel, and X. Huang, "Security and privacy for the Internet of Drones: Challenges and solutions," *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 64–69, Jan. 2018.

[394] A. Allouch, A. Koubaa, M. Khalgui, and T. Abbes, "Qualitative and quantitative risk analysis and safety assessment of unmanned aerial vehicles missions over the internet," *IEEE Access*, vol. 7, pp. 53392–53410, 2019.

[395] S. Liao, J. Wu, J. Li, A. K. Bashir, and W. Yang, "Securing collaborative environment monitoring in smart cities using blockchain enabled software-defined Internet of Drones," *IEEE Internet Things Mag.*, vol. 4, no. 1, pp. 12–18, Mar. 2021.

[396] N. A. Khan, N. Z. Jhanjhi, S. N. Brohi, and A. Nayyar, "Emerging use of UAV's: Secure communication protocol issues and challenges," in *Drones in Smart-Cities*. Amsterdam, The Netherlands: Elsevier, 2020, pp. 37–55.

[397] F. Al-Turjman, M. Abujubbeh, A. Malekloo, and L. Mostarda, "UAVs assessment in software-defined IoT networks: An overview," *Comput. Commun.*, vol. 150, pp. 519–536, Jan. 2020.

[398] D. B. Rawat and S. R. Reddy, "Software defined networking architecture, security and energy efficiency: A survey," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 325–346, Jan. 2017.

[399] J. McCoy and D. B. Rawat, "Software-defined networking for unmanned aerial vehicular networking and security: A survey," *Electronics*, vol. 8, no. 12, p. 1468, Dec. 2019.

[400] D. Kreutz, F. M. V. Ramos, P. Verissimo, C. E. Rothenberg, S. Azodolmolky, and S. Uhlig, "Software-defined networking: A comprehensive survey," *Proc. IEEE*, vol. 103, no. 1, pp. 14–76, Dec. 2015.

[401] Z. Latif, K. Sharif, F. Li, M. M. Karim, S. Biswas, and Y. Wang, "A comprehensive survey of interface protocols for software defined networks," *J. Netw. Comput. Appl.*, vol. 156, Apr. 2020, Art. no. 102563.

[402] S. A. Mehdi, J. Khalid, and S. A. Khayam, "Revisiting traffic anomaly detection using software defined networking," in *Proc. Int. Workshop Recent Adv. Intrusion Detection*, in Lecture Notes in Computer Science, vol. 6961. Berlin, Germany: Springer, 2011, pp. 161–180.

[403] H.-M. Chuang, F. Liu, and C.-H. Tsai, "Early detection of abnormal attacks in software-defined networking using machine learning approaches," *Symmetry*, vol. 14, no. 6, p. 1178, Jun. 2022.

[404] T. Xing, Z. Xiong, D. Huang, and D. Medhi, "SDNIPS: Enabling software-defined networking based intrusion prevention system in clouds," in *Proc. 10th Int. Conf. Netw. Service Manage. (CNSM)*, Nov. 2014, pp. 308–311.

[405] T. Girdler and V. G. Vassilakis, "Implementing an intrusion detection and prevention system using software-defined networking: Defending against ARP spoofing attacks and blacklisted MAC addresses," *Comput. Electr. Eng.*, vol. 90, Mar. 2021, Art. no. 106990.

[406] A. Shaghaghi, M. A. Kaafar, and S. Jha, "WedgeTail: An intrusion prevention system for the data plane of software defined networks," in *Proc. ACM Asia Conf. Comput. Commun. Secur.*, Apr. 2017, pp. 849–861.

[407] S. Rout, K. S. Sahoo, S. S. Patra, B. Sahoo, and D. Puthal, "Energy efficiency in software defined networking: A survey," *Social Netw. Comput. Sci.*, vol. 2, no. 4, pp. 1–15, May 2021.

[408] M. F. Tuysuz, Z. K. Ankarali, and D. Gözüpek, "A survey on energy efficiency in software defined networks," *Comput. Netw.*, vol. 113, pp. 188–204, Feb. 2017.

[409] A. Mairaj, A. I. Baba, and A. Y. Javaid, "Application specific drone simulators: Recent advances and challenges," *Simul. Model. Pract. Theory*, vol. 94, pp. 100–117, Jan. 2019.

[410] A. I. Hentati, L. Krichen, M. Fourati, and L. C. Fourati, "Simulation tools, environments and frameworks for UAV systems performance analysis," in *Proc. 14th Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Limassol, Cyprus, Jun. 2018, pp. 1495–1500.

[411] A. Mohini, "CDSSim: Multi UAV communication and control simulation framework," M.S. thesis, Dept. Elect. Eng. Comput. Sci. College Eng. Appl. Sci., Univ. Cincinnati, Cincinnati, OH, USA, 2019.

[412] E. Ebeid, M. Skriver, K. H. Terkildsen, K. Jensen, and U. P. Schultz, "A survey of open-source UAV flight controllers and flight simulators," *Microprocessors Microsyst.*, vol. 61, pp. 11–20, Sep. 2018.

[413] A. R. Perry, "The FlightGear flight simulator," in *Proc. USENIX Annu. Tech. Conf.*, Boston, MA, USA, Jun. 2004, pp. 1–13.

[414] J. S. Berndt, "JSBSim: An open source flight dynamics model in C++," in *Proc. AIAA Modeling Simulation Technol. Conf.*, vol. 1, Aug. 2004, pp. 261–287.

[415] T. Vogeltanz and R. Jašek, "FlightGear application for flight simulation of a mini-UAV," in *Proc. AIP Conf.*, Rhodes, Greece, 2015, pp. 1–5.

[416] N. P. Koenig and A. Howard, "Design and use paradigms for Gazebo, an open-source multi-robot simulator," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Sendai, Japan, vol. 3, Sep. 2004, pp. 2149–2154.

[417] H. R. M. Sardinha, M. Dragone, and P. A. Vargas, "Closing the gap in swarm robotics simulations: An extended ardupilot/gazebo plugin," 2018, *arXiv:1811.06948*.

[418] C. Bernardeschi, A. Fagiolini, M. Palmieri, G. Scrima, and F. Sofia, "ROS/Gazebo based simulation of co-operative UAVs," in *Proc. Int. Conf. Modeling Simulation Auto. Syst.*, in Lecture Notes in Computer Science, vol. 11472. Prague, Czech Republic: Springer, Oct. 2018, pp. 321–334.

[419] M. Calvo-Fullana, A. Pyattaev, D. Mox, S. Andreev, and A. Ribeiro, "Communications and robotics simulation in UAVs: A case study on aerial synthetic aperture antennas," *IEEE Commun. Mag.*, vol. 59, no. 1, pp. 22–27, Jan. 2021.

[420] F. C. Souza, S. R. B. D. Santos, A. M. D. Oliveira, and S. N. Givigi, "Influence of network topology on UAVs formation control based on distributed consensus," in *Proc. IEEE Int. Syst. Conf. (SysCon)*, Apr. 2022, pp. 1–8.

[421] S. Shah, D. Dey, C. Lovett, and A. Kapoor, "AirSim: High-fidelity visual and physical simulation for autonomous vehicles," in *Field and Service Robotics* (Springer Proceedings in Advanced Robotics), vol. 5. Cham, Switzerland: Springer, 2018, pp. 621–635.

[422] J. S. Gill, M. S. Velashani, J. Wolf, J. Kenney, M. R. Manesh, and N. Kaabouch, "Simulation testbeds and frameworks for UAV performance evaluation," in *Proc. IEEE Int. Conf. Electro Inf. Technol. (EIT)*, Mount Pleasant, SC, USA, May 2021, pp. 335–341.

[423] S. Baidya, Z. Shaikh, and M. Levorato, "FlyNetSim: An open source synchronized UAV network simulator based on ns-3 and ArduPilot," in *Proc. 21st ACM Int. Conf. Modeling, Anal. Simulation Wireless Mobile Syst.*, Oct. 2018, pp. 37–45.

[424] M. Basharat, M. Naeem, Z. Qadir, and A. Anpalagan, "Resource optimization in UAV-assisted wireless networks—A comprehensive survey," *Trans. Emerg. Telecommun. Technol.*, vol. 33, no. 7, Jul. 2022.

[425] R. Masroor, M. Naeem, and W. Ejaz, "Resource management in UAV-assisted wireless networks: An optimization perspective," *Ad Hoc Netw.*, vol. 121, Oct. 2021, Art. no. 102596.

[426] H. Nawaz, H. M. Ali, and A. A. Laghari, "UAV communication networks issues: A review," *Arch. Comput. Methods Eng.*, vol. 28, no. 3, pp. 1349–1369, May 2021.

[427] M. Y. Arafat and S. Moh, "A Q-learning-based topology-aware routing protocol for flying ad hoc networks," *IEEE Internet Things J.*, vol. 9, no. 3, pp. 1985–2000, Feb. 2022.

[428] M. A. Khan, I. U. Khan, A. Safi, and I. M. Quershi, "Dynamic routing in flying ad-hoc networks using topology-based routing protocols," *Drones*, vol. 2, no. 3, p. 27, Aug. 2018.

[429] D. K. Sah and T. Amgoth, "Parametric survey on cross-layer designs for wireless sensor networks," *Comput. Sci. Rev.*, vol. 27, pp. 112–134, Feb. 2018.

[430] P. Sarwesh and A. Mathew, "Cross layer design with weighted sum approach for extending device sustainability in smart cities," *Sustain. Cities Soc.*, vol. 77, Feb. 2022, Art. no. 103478.

[431] M. Y. Arafat and S. Moh, "Localization and clustering based on swarm intelligence in UAV networks for emergency communications," *IEEE Internet Things J.*, vol. 6, no. 5, pp. 8958–8976, Oct. 2019.

[432] H. Nawaz and H. M. Ali, "Implementation of cross layer design for efficient power and routing in UAV communication networks," *Stud. Informat. Control*, vol. 29, no. 1, pp. 111–120, Mar. 2020.

[433] K.-Y. Tsao, T. Girdler, and V. G. Vassilakis, "A survey of cyber security threats and solutions for UAV communications and flying ad-hoc networks," *Ad Hoc Netw.*, vol. 133, Aug. 2022, Art. no. 102894.

[434] L. Wang, Y. Chen, P. Wang, and Z. Yan, "Security threats and countermeasures of unmanned aerial vehicle communications," *IEEE Commun. Standards Mag.*, vol. 5, no. 4, pp. 41–47, Dec. 2021.

[435] D. S. Lakew, U. Sa'ad, N.-N. Dao, W. Na, and S. Cho, "Routing in flying ad hoc networks: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 2, pp. 1071–1120, Apr. 2020.

[436] J. V. Ananthi and P. S. H. Jose, "A review on various routing protocol designing features for flying ad hoc networks," in *Mobile Computing and Sustainable Informatics*, vol. 68. Barcelona, Spain: Springer, 2022, pp. 315–325.

[437] J.-J. Wang, C.-X. Jiang, Z. Han, Y. Ren, R. G. Maunder, and L. Hanzo, "Taking drones to the next level: Cooperative distributed unmanned-aerial-vehicular networks for small and mini drones," *IEEE Veh. Technol. Mag.*, vol. 12, no. 3, pp. 73–82, Sep. 2017.

[438] A. Hardy, M. Makame, D. Cross, S. Majambere, and M. Msellem, "Using low-cost drones to map malaria vector habitats," *Parasites Vectors*, vol. 10, no. 1, pp. 1–13, Jan. 2017.
[439] S. Isaac, A. Conrad, T. Rezaei, D. Sanchez-Rosales, R. Cochran, A. Gutha, D. Gauthier, and P. Kwiat, "Drone-based quantum key distribution," in *Proc. Conf. Lasers Electro-Opt.*, 2021, p. 6784.
[440] A. Conrad, S. Isaac, R. Cochran, D. Sanchez-Rosales, B. Wilens, A. Gutha, T. Rezaei, D. J. Gauthier, and P. Kwiat, "Drone-based quantum key distribution (QKD)," *Proc. SPIE*, vol. 11678, pp. 177–184, Mar. 2021.
[441] C. Quintana, P. Sibson, G. Erry, Y. Thueux, E. Kingston, T. Ismail, G. Faulkner, J. Kennard, K. N. Gebremicael, C. Clark, C. Erven, S. Chuard, M. Watson, J. Rarity, and D. O'Brien, "Low size, weight and power quantum key distribution system for small form unmanned aerial vehicles," *Proc. SPIE*, vol. 10910, pp. 240–246, Mar. 2019.
[442] X. Liu, Y. Liu, Y. Chen, and L. Hanzo, "Trajectory design and power control for multi-UAV assisted wireless networks: A machine learning approach," *IEEE Trans. Veh. Technol.*, vol. 68, no. 8, pp. 7957–7969, Aug. 2019.
[443] H. V. Abeywickrama, B. A. Jayawickrama, Y. He, and E. Dutkiewicz, "Comprehensive energy consumption model for unmanned aerial vehicles, based on empirical studies of battery performance," *IEEE Access*, vol. 6, pp. 58383–58394, 2018.
[444] Z. Yang, W. Xu, and M. Shikh-Bahaei, "Energy efficient UAV communication with energy harvesting," *IEEE Trans. Veh. Technol.*, vol. 69, no. 2, pp. 1913–1927, Feb. 2020.
[445] Q. Liu, M. Li, J. Yang, J. Lv, K. Hwang, M. S. Hossain, and G. Muhammad, "Joint power and time allocation in energy harvesting of UAV operating system," *Comput. Commun.*, vol. 150, pp. 811–817, Jan. 2020.
[446] H. Yan, Y. Chen, and S.-H. Yang, "UAV-enabled wireless power transfer with base station charging and UAV power consumption," *IEEE Trans. Veh. Technol.*, vol. 69, no. 11, pp. 12883–12896, Nov. 2020.
[447] H. Ren, Z. Zhang, Z. Peng, L. Li, and C. Pan, "Energy minimization in RIS-assisted UAV-enabled wireless power transfer systems," *IEEE Internet Things J.*, early access, Feb. 9, 2022, doi: 10.1109/JIOT.2022.3150178.
[448] Y. Yao, Z. Zhu, S. Huang, X. Yue, C. Pan, and X. Li, "Energy efficiency characterization in heterogeneous IoT system with UAV swarms based on wireless power transfer," *IEEE Access*, vol. 8, pp. 967–979, 2020.
[449] P. Luong, F. Gagnon, L.-N. Tran, and F. Labeau, "Deep reinforcement learning-based resource allocation in cooperative UAV-assisted wireless networks," *IEEE Trans. Wireless Commun.*, vol. 20, no. 11, pp. 7610–7625, Nov. 2021.
[450] S. Fu, M. Zhang, M. Liu, C. Chen, and F. R. Yu, "Towards energy-efficient UAV-assisted wireless networks using an artificial intelligence approach," *IEEE Wireless Commun.*, early access, May 9, 2022, doi: 10.1109/MWC.105.2100389.
[451] L. Wang, K. Wang, C. Pan, W. Xu, N. Aslam, and L. Hanzo, "Multi-agent deep reinforcement learning-based trajectory planning for multi-UAV assisted mobile edge computing," *IEEE Trans. Cognit. Commun. Netw.*, vol. 7, no. 1, pp. 73–84, Mar. 2021.
[452] S. Zhou, Y. Cheng, X. Lei, and H. Duan, "Multi-agent few-shot meta reinforcement learning for trajectory design and channel selection in UAV-assisted networks," *China Commun.*, vol. 19, no. 4, pp. 166–176, Apr. 2022.

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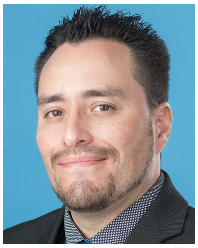

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