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Role of UAVs in Public Safety Communications: Energy Efficiency Perspective

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ABSTRACT Unmanned aerial vehicles (UAVs) have acquired remarkable popularity, thanks to their variety of applications in numerous domains spanning from surveillance, health to agriculture and smart cities. UAVs are also enabler in wireless communication that has potential features such as ubiquitous and reliable connectivity, fast and easy deployment, adaptive altitude, higher chance of line of sight (LOS) propagation path, higher mobility and flexibility. There are numerous surveys that summarized these advantages for different situations and scenarios. However, none of these surveys discussed the role of UAVs in public safety communications from the energy efficiency perspective. In this paper, we review the existing literature for UAV communication with taking into account the energy consumption criteria, and propose a multi-layered network architecture incorporating UAVs for public safety communication. Future research directions are also discussed.

INDEX TERMS UAV, multi-layered architecture, QoS, energy efficiency, public safety communications.

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) based communication is an emerging research area in next-generation wireless networks. It has numerous applications in the field such as health services, traffic monitoring, inspection, and public safety [1], [2]. The attractive features of UAVs and their promising on-demand applications has been a research focus for both industry and academia [3], [4]. Recent studies in the field of UAVs make it possible to broadly deploy UAVs, such as air balloons and aircraft, for wireless public safety applications [5].

In particular, when a UAV operates as a base station, it can provide a tremendous connectivity to the existing terrestrial base station (TBS) to enhance capacity, coverage and energy efficiency of wireless networks [6]. In comparison to TBS, UAVs provide a scalable and higher chance of obstruction-free wireless communications. The advanced technical capabilities of UAVs are also helpful in implementing the concept of UAV-to-everything (U2X) communications. In U2X communications, the UAVs move and collect important data from, for example, cars, machines, and pedestrians industry, etc. This has the benefits of gathering crucial information from the places where epidemic diseases spread out or an emergency situation occurs, as shown in Fig.1. Hence, in the future, UAVs with such capabilities will be an integral part of the next-generation wireless communications.

In recent years, UAVs have attracted significant attention of mobile operators to boost communications for cost effective, reliable, flexible and power efficient wireless networking applications for ground users as well as additional capacity in emergency and temporary event scenarios [7]–[9]. Natural disasters can result in failure of the existing TBSs [10]. Whilst it is impossible to build a new TBS at once, UAVs can swiftly be deployed to provide a fast and guaranteed quality-of-service (QoS) wireless connectivity [11], [12] in a rapid manner to meet the demand of public safety users during rescue operations [13]. Naturally, there is a need to place a UAV at unique point where it can cover the maximum

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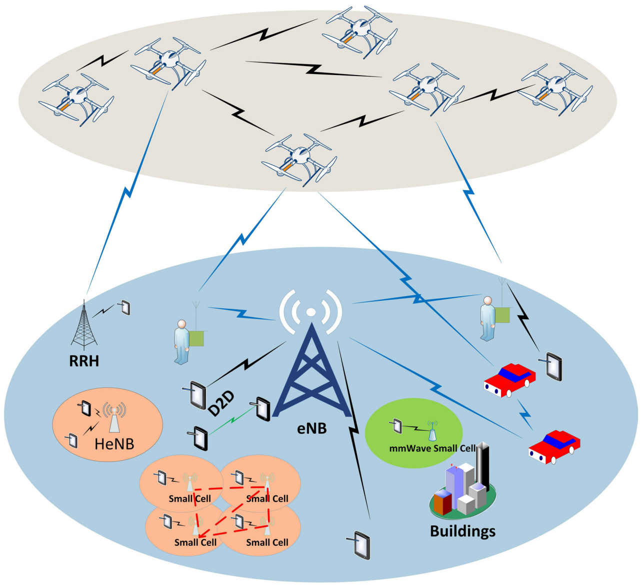


FIGURE 1. UAVs-to-everything (U2X) communications in next-generation systems.

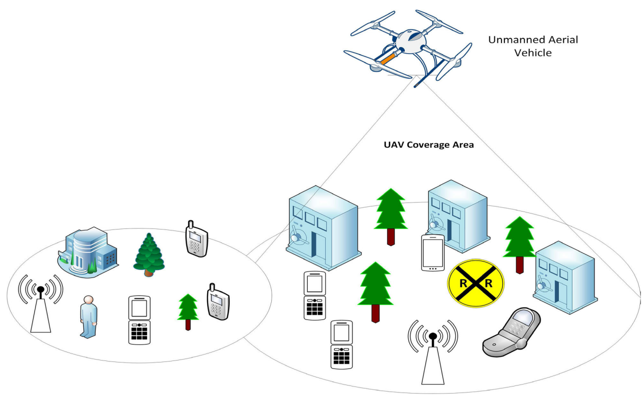


FIGURE 2. Public safety applications of UAVs.

number of users at minimum energy consumption, because the flight and communication time of the UAVs are also limited. In [1], the authors proposed a three-layered disaster-resilient architecture which also integrates UAVs deployed at the edge to provide communication during emergency situation. This architecture would be a good candidate to enable public safety applications.

UAVs' performance depends on various factors. For instance, high power batteries, robust motors, size and payload are well-known factors for the evolution of UAVs. UAVs rely on batteries to power its rotors during flight [14]. Energy is the main and important parameter for the performance and execution of UAV mission including flight time duration [15].

Propagation path loss model highly impacts the UAVs communication model. One of the most challenging tasks is to optimize the positioning of the UAVs [16], [17] taking into account the energy consumption. The deployment of UAVs in either line of sight (LOS) or non-line of sight (NLOS) plays a very important role in terms of energy consumption [18]. LOS communication does not face hurdles and will have direct link between the transmitter and receiver, which results in less energy consumption. The opposite of this is applied for NLOS communication.

In the literature, different types of UAVs exist based on the accompanied features, all of which have some limitations as well as advantages. Always there would be a trade-off between the features and better performance results. For example, higher altitude UAVs cover the maximum number of users and also provide a higher chance of maximum LOS propagation path between the transmitter and receiver, but their mission flight time is reduced due to the limited amount of energy [19]. Also, there exists a trade-off between resource management, flight time duration, and energy consumption. By efficiently using the bandwidth, the flight time is increased as a result of energy consumption being decreased.

During large-scale natural disasters, UAVs placement can be able to provide a flexible and promising services as shown in Fig. 2. Despite vast advantages of UAVs, serious challenges are faced during the design process. The most important is the efficient utilization of energy because that affects the complete performance of the UAVs [20]. Environmental parameters, flight time duration, payload and real-time deployment altitude are the basic constraints that also affects the consumption of energy [21].

A. EXISTING SURVEYS AND TUTORIAL OVERVIEW

There have been a number of surveys on UAVs over the past few years, and a number of research papers on the characteristics, requirements, issues and challenges of UAV communication systems have been published. A brief summary of these has been summarized in Table 1 and discussed here to prove the uniqueness of this survey.

In [14], the authors presented UAVs' major challenges that are faced during its stable and reliable communications. A comprehensive survey in [22] elaborates the possibilities for flexible low altitude unmanned aerial vehicles (LAUs) communication. The work in [23] discussed literature related to next-generation wireless network on the location optimization of UAVs. Furthermore, future research directions on the fifth generation (5G) location optimization of UAVs is discussed.

In [7], the authors presented a small-scale UAV platform, its potential issues and an analysis of key features such as navigation sensors, communication modules, and on-board processing unit. The survey in [24] discussed the main design, challenges, routing protocols, and open research problems of flying Ad-Hoc network (FANET). A comprehensive survey on the inspection of automated building UAV system (UAS) was presented in [25]. The work in [26] reviewed UAV networks for civil applications and characteristics for the prospect of communication, and also presented experimental results from various projects.

The survey [27] discussed a UAV-enabled wireless network tutorial, mathematical tool and analytical frameworks that are used to solve the fundamental problems. In [28], the authors

TABLE 1. UAV Communication related existing surveys.

Reference	Brief Summary
[7]	A detailed overview of small-scale UAV platform and their challenges
[14]	A survey on the main challenges in UAV communication Networks
[20]	A survey on the characteristics and main issues of the cellular based communication system
[22]	A survey on Low altitude UAV-based IoT communication
[23]	An overview of location optimization of UAV base station
[24]	A comprehensive survey on UAV flying Ad-Hoc network communication
[25]	Review of automated building inspection procedure UAV system
[26]	A survey on civil application and challenges of the UAV communication
[27]	A comprehensive tutorial on the use and challenges of UAV wireless networks
[28]	A survey on small and low cost UAVs identification
[29]	A survey of computer based simulators for UAVs
[30]	A comprehensive survey on airborne communication network
[31]	A technical overview of Hybrid UAVs for dynamic modeling
[32]	A survey of the autopilot systems for small or micro UAVs
[33]	An overview of Imagery collection in UAVs for disaster management
[34]	A survey on Remote sensing of the environment with small UAVs
[35]	A survey of the measuring techniques proposed for UAV channel modeling
[36]	A tutorial on 3D terrain traversability techniques for UAVs
[37]	A survey of 3D optimal planning methods for UAV communication
[38]	A survey of inspection methods and requirement of UAVs
[39]	An overview of the characteristic of the rotatory UAVs
[40]	Overview of routing and energy efficient models for UAVs
[41]	A survey of 5G based UAV communication
[42]	A survey of charging on UAV communication
[43]	A review of routing protocols for UAVs
[44]	A survey on cyber-security for UAVs

provided a complete knowledge of categorization of current methods, practical implementation, full background information of the system identification and applications for small low cast UAVs. Moreover, the survey in [29] provided a UAV simulator for both commercial and open source use, as well as a wide spectrum for both micro size or full size of unmanned surface, subsurface and ground vehicles [45]. Furthermore in [30], the protocols and mechanisms for the design of LAUs, high altitude UAVs (HAUs) and integrated communication based networks for airborne communication were surveyed.

A brief survey in [31] focused on the theory, linearity, implementation and primary flight control mechanism of hybrid UAV systems. The work in [32] presented an open source autopilot systems for micro and small UAVs. In [33], a survey of disaster research and management for imagery acquisition of the usage of UAVs system was discussed. Furthermore, in [34] the authors presented the main challenges related to image-based methodologies for the purpose of remote sensing, for various types of UAVs. The channel modeling and air-to-ground channel propagation, and their characteristics were discussed in [35].

3D optimal planning mechanism and terrain traversability methods were discussed in [36], [37]. In [38], the authors provided famous low-cost platforms and application fields for vision and control method of inexpensive UAVs. In [39], the challenges and the possible opportunities where UAVs can be deployed in civil engineering applications were summarized. Another comprehensive survey was done in [20], where they provided full details about the requirements, problems, and practical model of UAV cellular communication system. In [40], the authors described the factors that affect the energy consumption of UAV and also discussed its energy consumption models.

The tutorial in [41] provided practical strategies, application and future trends of UAV communication with 5G technologies at physical layer, network layer, and for joint communication, caching and computing. A survey in [42] elaborated various frequent wireless charging techniques and classification based on non-electromagnetic and electromagnetic techniques that will be helpful for UAV flight time improvement. The routing protocols for UAVs and their performance were reviewed in [43]. The energy efficient clustering and routing framework for disaster affected areas were presented in [46]. Simulated and actual attacks for cyber-security were discussed in [44].

Hence, various surveys has been done on UAVs, but to our knowledge, there is still no survey that targets UAVs with energy efficiency perspective, specifically in public safety scenarios. In this paper, we aim to fill this gap, and in doing so, we also highlight the related challenges, suitable solutions, and future research directions.

B. CONTRIBUTIONS

While numerous surveys related to UAVs have been published in recent few years, to the best of our knowledge, there is no existing survey that gives an in-depth discussion on UAVs taking into account energy efficiency aspect. In this paper, we provide a comprehensive survey of UAVs in public safety environment with energy efficiency perspective. In particular, our contributions are as follows:

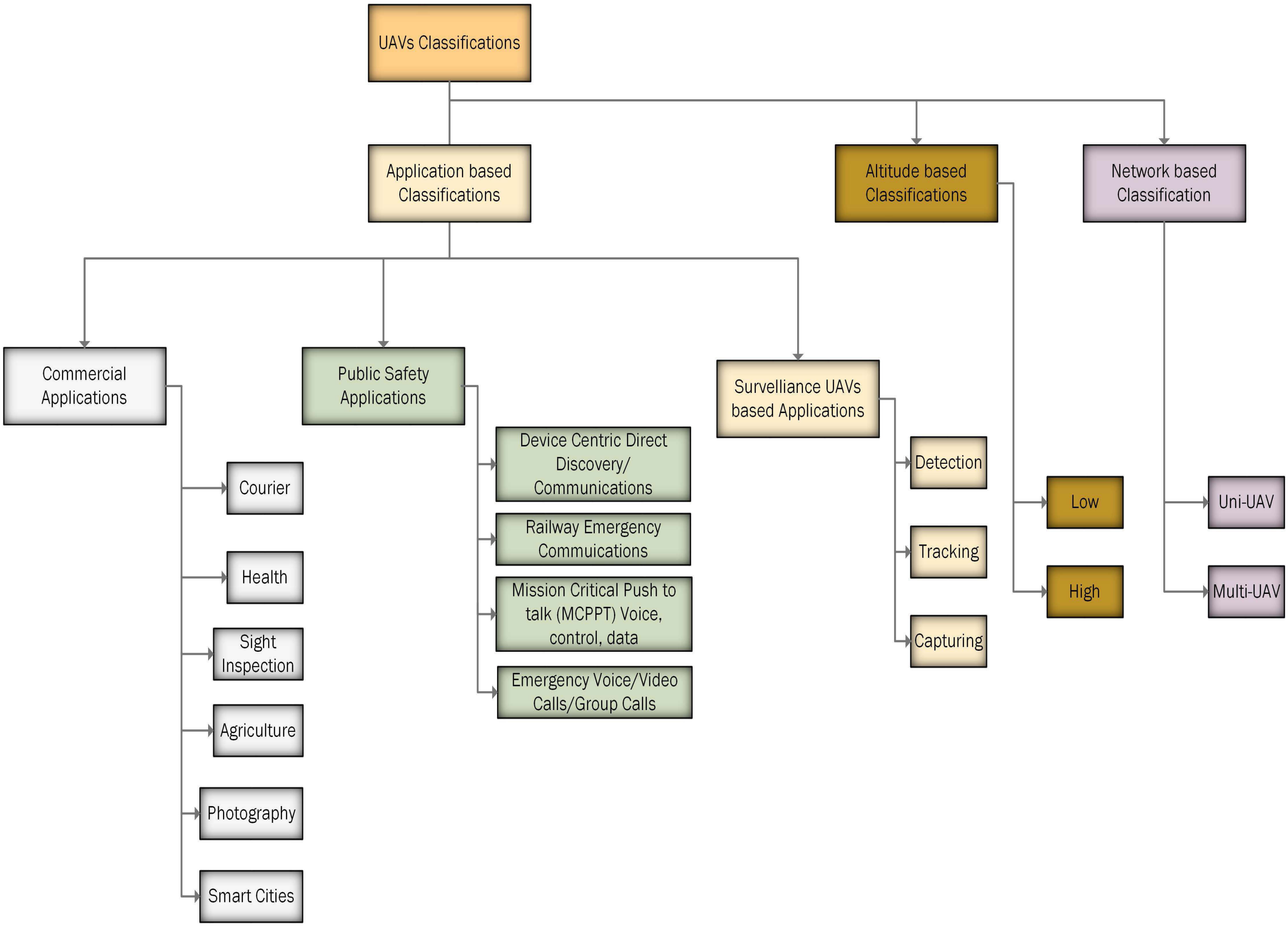


FIGURE 3. UAV classifications according to applications, altitude, and network infrastructure.

- We provide in-depth discussions on UAV-based communication systems, review the existing surveys in detail, and discuss UAVs classification based on the parameters such as altitude, network, and applications regarding UAV deployment with minimum energy consumption.
- We discuss existing architecture for safety communications, and proposed multi-layered architecture that can be utilized to enable emergency communications in the house basements by enabling wired and wireless communications paths.
- We discuss the key factors and challenges faced by UAVs during its placement and other important situations related to energy consumption in disaster situations.
- We summarize the open issues and future research directions for UAVs during emergency communications.

II. UAVs CLASSIFICATION

UAVs has numerous applications in almost every field. In this section, we group UAVs into three major broad categories: 1) altitude-based classification; 2) network-based classification; and 3) application-based classification.

A. ALTITUDE-BASED CLASSIFICATION SCHEMES

In aerial communication, the most challenging task is to select the type of UAVs that meets the required QoS, and energy requirements. Different UAV types are designed to cope with risky or affected areas. In the literature, some classifications have been proposed for service connectivity along with TBS to enhance the coverage, capacity, or to meet users' demands.

In fact, the energy-efficient use of UAVs also relates to UAVs' classification types as they take into account the flying altitude, speed, and flying time. UAVs classifications are shown in Fig. 3. Generally, in terms of altitude UAVs are classified into two main groups: HAUs and LAUs. Whereas, in terms of wing types they are categorized into rotary wings UAVs and fixed wings UAVs.

HAUs have a variety of opportunities for wireless communication that includes inexpensive wireless communication with maximum coverage area, less propagation delay, high data rate, and low transmission power. A lot of work has been done on HAUs but it is still in its infancy. The power control (PC) based schemes [47], [48] for HAUs have been discussed in [49]. In [50], a new technique was introduced for reducing the power in orbit. Power control scheme was investigated when the UAV was moving, and it achieved promising results.

HAUs cover a vast range and can stay much longer in the air [51]. However, HAUs' deployment is more costly, complex and they are basically used as a vehicle to supply Internet connectivity to a huge part of the world population. More significantly, HAUs used in wireless communications may cause higher power consumption due to immensely large inter-cell interference [52].

High altitude platforms are designed for longer endurance and for long term operation [15], [53]. Furthermore, larger range of services are done through HAUs. Interference, shadowing, multipath fading effect cause delay and higher amount of energy consumption. Energy consumption in HAUs is low due to high chance of LOS communication, lesser probability of shadowing, and multipath fading.

LAUs can be helpful for establishing a wireless communication based connection with modern wireless technologies like 3G, 4G LTE, GSM, WiFi, and WiMAX systems. Easy and fast deployment of LAUs makes them very attractive [51]. Moreover, LAPs deliver short-range LOS communication links that can notably enhance the performance and reduce energy consumption [53]–[55].

In [56] the authors adjusted the orientation of UAV base stations in vertical and horizontal directions to get the desirable positions where they can provide a maximum coverage with low transmit power. LAUs can freely fly up to 400 feet [57] and their positions changed based on users requirements. UAV mounted base stations can be a very suitable solution for delivering a rapid and ubiquitous service connectivity in public safety application scenarios.

UAVs' design also have significant effect on energy consumption as there exist UAVs in a lot of shapes and sizes. Each of these have their own individual advantages, limitations and challenges. Fixed wings are small size UAVs, that are further divided into low wing, mid wing, and high wing. All of these have unique pros, cons and critical challenges. Fixed wings have simple structure and provide fault repairing, maintenance, flight mission time with low cost and minimum energy [24]. Fixed wings UAVs move with high speed and are highly capable to carry out high payload for longer distance and with high energy efficiency [30].

Generic energy consumption model was designed for energy-efficient UAV communications in [15]. Here, energy efficient UAV communication system was investigated that maximizes given flight duration. In particular, analytical framework for fixed-wing UAV was designed in [58] that formulate suitable trajectory path that minimizes energy consumption.

Most of the real world communication applications are operated via rotatory wings UAVs. They can hover over specific area, allow vertical landing without long run way [59]. They can rapidly fly and capable to change their positions to deliver on-demand mobile communications to ground users in disaster situations such as during flood, earthquake and fire: when ground terrestrial base stations are temporarily destroyed. In this situation, it is completely impossible to put a new terrestrial station in very short period of time.

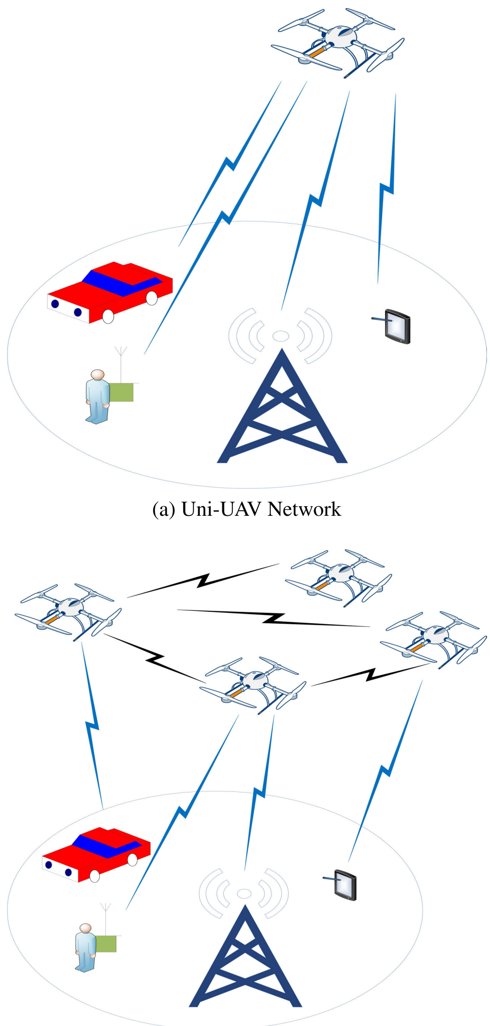
Energy-efficient UAV communication with rotary-wing UAVs was evaluated in [60], where minimum power utilization generic model was derived for rotary-wing UAVs. Rotatory-wing UAVs have complex structure. However, they are capable to hover in a desirable area with low speed and their flight duration of less than an hour, and at a low attitude. Such UAVs have finite mobility and utilize necessary power during their flight against gravity.

B. NETWORK-BASED CLASSIFICATION SCHEMES

It is important to categorize UAV networks in order to understand the associated advantages and constraints. For instance, these may include: structure and topology suitable for UAV networks, how fast network topology changes, the number and type of UAVs needed for good network performance, suitable architecture for UAV networks, whether a UAV network dynamically supports the removal or addition of a node, and whether a UAV network requires extra control. UAV Network classifications are shown in Fig. 3. The UAV network can be categorized mainly into two types: uni-UAV network and multi-UAV network. Multi-UAV networks are further divided into eight categories, namely cooperative networks, opportunity-based networks, UAV-aided routing and posting networks, task allocation based networks, cluster formation network, delay-tolerant network, self-organized networks, and heterogeneous network.

In uni-UAV type, it mainly consists of one aerial node and more than one ground node. Aerial node can be dynamic in controlling its altitude, and follow a pre-determined path, circular path or optimized path that helps the ground station to communicate through it. Uni-UAV networks a variety of applications in both civilian and military areas. In military, they can be used in surveillance, attack, reconnaissance, patrol, delivery and counter-terrorism, whereas in civilian area, they are used in disaster scenarios, agriculture, or healthcare services [14]. A Uni-UAV network is shown in Fig.4 (a). This type of architecture is more energy efficient, but is only suitable for military scenarios with low-level security threats with small coverage desired [61]–[64].

A multi-UAV network consists of more than one aerial UAVs and is connected with one or more base station nodes. The biggest advantage with multi-UAV networks is to have a reliable communication between the UAVs and among the ground station at acceptable energy consumption and higher data rate [24]. In this way, the chance of failure is reduced while maximum coverage is provided at low cost. In a multi-UAV system, the control system, server or base station just connect with one or two UAVs and these connected UAVs will feed the other UAVs that are present in network, as shown in Fig. 4 (b). The multi-UAV network allows users' access to make call, transfer video and data [58]. Their advantages also include the complex characteristics of communication networks, such as self-organization/self-healing,



(a) Uni-UAV Network

(b) Multi-UAVs Network

FIGURE 4. Representation of network-based classification architecture; a) Uni-UAV network architecture; b) Multi-UAV network architecture.

high survivability, scalability, and high mission speed at low cost and energy consumption.

C. APPLICATIONS-BASED CLASSIFICATION SCHEMES

We have grouped UAVs into three sub-classifications according to their applications: 1) commercial, 2) public safety, and 3) surveillance UAVs. In this paper, our focus is on the public-safety applications, thus other applications are just briefly discussed.

To enable public-safety communications, UAVs can be used to enable device centric communications. That is, devices/users can directly communicate with the UAVs and among each other in disaster situations. UAVs are also used to enable emergency communication for railway users during emergency, as they gather information of the accident affected users in the train. Similarly, long-term evolution (LTE) has introduced numerous features for public-safety communications like mission critical push to talk (MCPTT) voice, control, and data services [65]. Moreover, LTE has also enabled emergency voice/video and group calls options, which can also be adopted for UAV-based public safety communications.

For commercial purposes, UAVs are almost adopted in courier service, health sector, civil works, agriculture, and smart cities.

III. PROPOSED MULTI-LAYERED ARCHITECTURE FOR PUBLIC SAFETY COMMUNICATIONS

UAVs plays a key role in providing conventional communication services and enabling public safety communications. During disaster situations, there is a possibility that the existing TBS is damaged and no alternate path is available for communications. In [66] the authors adopted UAV-assisted mobile architecture to enable energy-efficient uplink communications to collect data from internet-of-things (IoT) devices. Following proper clustering of IoT devices on the ground, the optimal trajectories of the UAVs is solved by using optimal transport theory to satisfy minimum energy constraints. Similarly, to resolve the issues of low latency and routing challenges in varying UAV network topology for safety communications, the concept of layered UAV swarm architecture and the latency reducing routing protocol were proposed in [67]. In this paper no solution has been provided to enable communications in the building basements during a disaster situation.

To overcome this, we propose a multi-layered architecture which has the capability pf providing an alternate communication path even if one path fails as shown in Fig. 5. The proposed architecture has three major layers: 1) underground (basement) layer; 2) ground layer; and 3) air layer. The underground layer has PS-LTE and UHF based TBS alongside with lifeline communication cable. Moreover, to enable communications in building basement, several repeaters and lifeline cables are also deployed to improve received signal quality. To avoid wireless communication failure in the basement, separate lifeline cable is also deployed to provide an alternate communication route, which is the unique feature of the proposed architecture. In the ground layer, three major types of TBS exist: commercial LTE TBS, PS-LTE TBS, ultra-high frequency or WiFi based TBS.

Finally, the air-layer has a swarm of UAVs interconnected with each other and also connected with the ground-layer users and base stations to ensure disaster site communication coverage even when the TBS is destroyed. To increase energy efficiency by decreasing latency, the UAV layer can also be used to enable edge/fog computing communications. Thus, the proposed architecture can be used in public safety communications.

IV. IMPORTANT FACTORS AFFECTING UAVs' ENERGY CONSUMPTION

Numerous factors affecting UAVs energy consumption includes UAV placement, resource management, user association, flight time optimization, and UAV mobility pattern optimization [30]. Besides these factors, UAVs' size and weight are key factors as well. Compared to small UAVs,

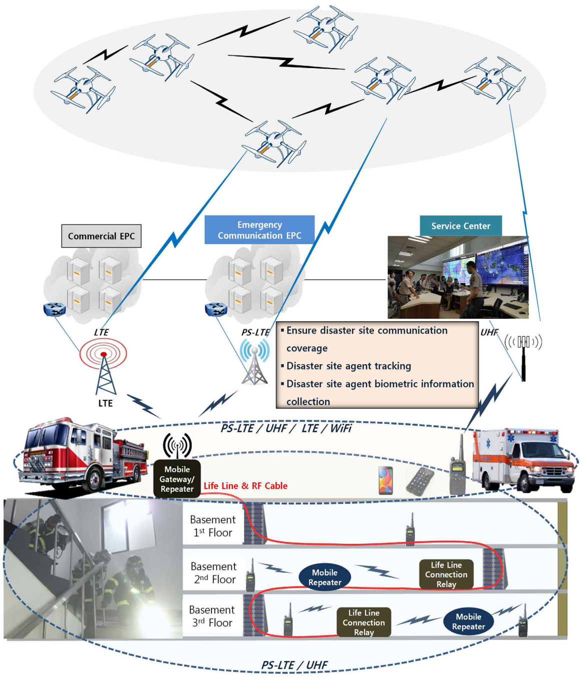


FIGURE 5. Multi-layered architecture for public safety communications.

large UAVs may carry higher payload and can complete the missions more quickly and effectively, but the maintenance expense of a small UAV is lower [30]. UAVs energy consumption is one of the most important parameters that need to be optimized specifically for public safety applications, because it will in turn save more lives. Therefore, UAV energy efficient deployment and transmission mechanisms should be considered in order to increase the lifetime of UAV-enabled wireless communication networks.

A. ENERGY-EFFICIENCY UAV PLACEMENT

UAV placement during a disaster situation is one of the key problems that need to be addressed [27], [30]. Its deployment is different for the conventional terrestrial base station (TBS) because of different constraints [68]. UAVs can be deployed at a different altitudes according to the situation and users' demands. However, by changing the altitude of the UAVs, the coverage area changes.

In the literature, various energy-efficient algorithms have been proposed to cope with the UAV placement problem. However, most studies were focused on the UAVs placement optimization that maximized the capacity or minimized the transmit power of the certain UAVs' present in affected areas to reduce the interference.

In particular, the 2D placement optimization problem was investigated in [69]. They proposed a k-means clustering algorithm to solve the optimization problem. In [70], the authors proposed the solution to minimize the number of UAVs needed to provide coverage for the users deployed in the vicinity. To achieve this, a polynomial-time algorithm was proposed that effectively covered all the users with low complexity. Hence, this algorithm could be a key to enable safety communications in disaster hit areas. Similarly, in [71], the authors found the UAV positions in an area using heuristic algorithm with different user densities. The main objective of UAV 3D placement was to meet the users' QoS requirements by placing the UAVs in appropriate location that can serve the maximum number of users with a minimum number of UAVs.

In [72], a UAVs' 3D placement mixed integer linear programming problem was investigated to obtain optimum location, altitude, and users in horizontal directions. For optimal placement, the authors adapted bisection search method that results in 95% covered users. Some recent studies in UAV optimal placement with the target of minimum energy consumption is summarized in Table 2.

In [73], the authors used optimal trajectory optimization and facility location problems as a tool for finding the optimal 3D deployment by using four UAVs. A framework for flexible energy-efficient communication for IoT was proposed. As a result, this optimization mechanism provides a reliable communication with low uplink transmit power, and devices are able to send data to their associated UAVs. Results in this paper shows that the energy efficiency increases because uplink transmit power is reduced by around 78%.

Similarly, in [74], by using directional antennas having specific beamwidth with same frequency for multiple UAVs placed in a circular area, the study could offer a maximum service for downlink communications. In order to achieve the maximal coverage area with three UAVs, the authors used circular packing theory. The results clearly showed that by using a larger number of UAVs and decreasing the altitude for the purpose of interference avoidance, optimal wireless coverage can be obtained. They provided a comparison that as altitude decreased from 2000m to 1300m there was an increase in number of UAVs needed from three to six.

The authors in [75] discussed the joint UAV placement and IoT users association problem. Their target was to maximize the users' connectivity with minimum UAVs. They proved that their proposed heuristic scheme performs well and have less complexity, which in turn will reduce the energy consumption as well. Thus, this scheme is one of the potential candidates for energy-efficient UAV placement.

Recently, machine/deep learning has been introduced as an emerging area in wireless communications [76], [77]. Motivated by this, in [78] the authors adapted reinforcement learning to obtain the best possible position of UAVs during emergency situations. The proposed solution maximized the number of users covered by UAVs after satisfying backhaul and radio access network constraints. The results proved that Q-learning solution performed much better than other approaches. Hence, intelligent UAVs placement is an attractive solution for public safety communications network. Similarly, in [79] the authors proposed machine learning framework for efficient and predictive UAVs deployment that would assist in meeting users' wireless connectivity demands. They adopted a Gaussian mixture model and

TABLE 2. UAVs' optimal placement with energy efficiency for safety communications.

Reference	Scenario	Deployment	Objective	Problem Type	Solution	Energy Reduction
[15]	Downlink	3D	Jointly constrained and unconstrained trajectory with transmit power optimization	Constrained & Unconstrained Optimization	Optimal Transport Theory	20.25% for constrained & 60% for unconstrained
[56]	Downlink	3D	UAV Optimal Placement with Maximum Coverage	MINLP (mixed integer non linear programming)	Circular Packing Theory	48%
[72]	Downlink	3D	Maximize Network Revenue	MINLP	Combination of Interior Point Optimizer and Bisection Search Algorithm	51%
[73]	Uplink	3D	Achieve Low Transmit Power for IoT	Non-Convex Optimization	Trajectory Optimization, Facility Location Theory	78%
[74]	Downlink	3D	Avoid Interference and Achieve Maximal Coverage Radius	Constrained Optimization	Circular Packing Theory	Very Less Power Consumption
[79]	Downlink	3D	UAV Optimal Placement for Maximum Connectivity	Centralized Machine Learning Approach	Machine learning	20-80%
[80]	Downlink	3D	Find Optimal Trajectory to increase Coverage Radius	——	Joint Trajectory Optimization	74%
[81]	Downlink	3D	Efficiently Consume Energy by Reducing Flight Time	Convex Optimization	Transport Theory	53%
[82]	Downlink	2D	Find Optimal Altitude to Achieve Maximum Coverage	—-	Facility location theory	53%
[83]	Downlink	3D	Minimum Energy Consumption	—	Circular Packing Theory	5.7dBm, 8.6dBm,11.1dBm (dense urban, urban, sub urban)
[84]	Downlink	3D	Minimize UAVs Flight Time	Non-convex Optimization	Particle Swarm Optimization Algorithm	73%
[85]	Downlink	3D	UAVs Optimal Placement	———	Q-learning	——
[86]	Downlink	3D	UAVs Secure Communication with Minimum Transmit Power	Non-Convex Optimization	Joint Trajectory Optimization	82%

weighted expectation maximization algorithm for machine learning for network congestion prediction. The results showed that this can save over 20% and 80% power for downlink transmission and mobility, respectively.

Mathematical tools and approaches that have been adopted to solve the UAV placement problem discussed here are depicted in Fig. 6.

B. UAV-USER ASSOCIATION IN EMERGENCY COMMUNICATIONS

User association during emergency situations has an important role as compared with the normal operating conditions. During a disaster, the conventional TBS is not usually working, so there is a need of UAV deployment in the vicinity. Alongside UAV deployment, enabling device-to-device (D2D) communications could also be helpful to enhance coverage. The main problem after this deployment is the user association for multiple types of base stations. To solve this challenge, the authors in [87] discussed the user association problem for UAV-enabled networks via D2D connections by maximizing the weighted sum rate of the users served by UAVs and total D2D users. This complex problem is solved by proposing learning-based clustering algorithm, which in turn achieved a sub-optimal performance and with much lower complexity. As a result, this algorithm can be adapted for future public safety communications.

To have a user association with minimum handoffs is necessary to avoid spectrum wastage and energy consumption in UAV networks. To solve this issue, in [88], a smart user association algorithm termed as reinforcement learning handoff (RLH) is proposed to reduce the handoffs frequency in UAV networks and also mobility control algorithms are adopted together with the proposed RLH to have an optimized system throughput.

In [89], a novel framework for UAVs association by using mathematical theory of optimal transport theory

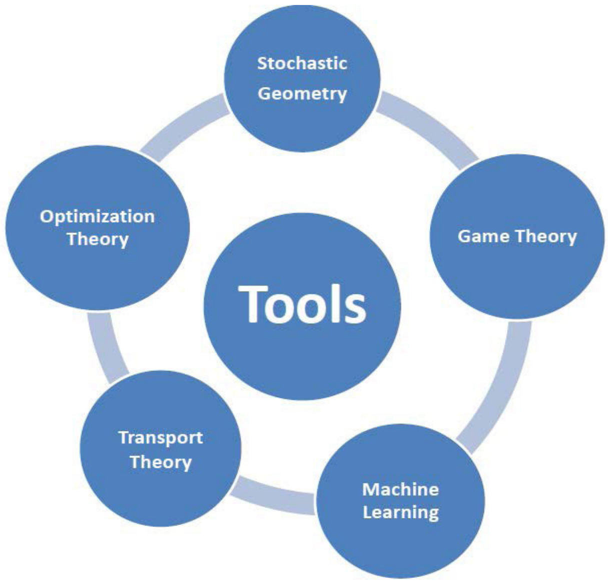


FIGURE 6. Mathematical tools for solving UAV placement problem.

was proposed. This scheme targeted to achieve user association with less delay which in turn could be a suitable candidate for public safety communications.

Edge computing brings a paradigm shift in public safety communications. By deploying edge computing center in UAVs, tasks processing latency could be reduced significantly, which in turn will be able to decrease the response time to users and save their lives. This type of approach was presented in [90], where the authors jointly optimize user association, UAV trajectory, and user power in order to maximize offloaded bits from user to UAV, by considering energy constraint of UAV and users' QoS constraint.

C. UAV SCHEDULING OPTIMIZATION

In a disaster situation, the optimal resource allocation is of utmost importance to maintain users' connection. To address this challenge, in [86] the authors presented a framework for UAV-assisted emergency networks. Their contributions are three-fold: firstly with the functional TBS, UAV trajectory and scheduling have been jointly optimized to enable communications for the users. Secondly, multi-hop D2D establishment and the UAV transceiver design is studied to extend the UAV coverage. Finally, a multi-hop relaying scheme has been discussed to share information among the disaster area and outside where UAVs' hovering positions are optimized.

Similarly, in [91] UAVs are used as relays to assist the D2D wireless information and power transfer systems. The major limitation in UAVs is the limited energy and flight time, thus to mitigate this, energy consumption is managed in a real-time by jointly optimizing the energy harvesting time and power control. In [92], specifically for safety scenarios, a context-aware resource allocation scheme was proposed. This scheme considers users context information during resource allocation which in turn is more energy efficient as compared with the schemes that do not.

D. UAV FLIGHT-TIME OPTIMIZATION

In [81], a framework is proposed to optimize the UAV performance in terms of average number of transmitted bits to users and flight time (hover) duration. The authors introduced two schemes. The first one is fair resource allocation scheme, which was based on the maximum possible hover time to supply the maximum average data service. In the second scenario, under the given user requirement, minimum average flying time required to complete this service was derived. Simulation results proved that with the proposed scheme around 64% of the flying time can be saved.

To minimize the data collection time from the start till the end is the main target of the safety communications. A flight time optimization scheme was proposed in [93] to cope with this challenge, where they collected data from various sensor nodes by not violating the energy constraint. The main objective was to minimize the UAVs' flight time from start till destination. The complete trajectory was divided into three non-overlapping intervals that were jointly optimized, where during each interval one sensor was served by a UAV. These intervals are: 1) data collection intervals, 2) UAV speed, and 3) the sensors' powers. Similarly, to timely gather the data from various nodes in IoT networks during a disaster situation, efficient optimization methods with relay-assisted UAVs in WSNs were proposed [94]. The proposed algorithms has low computational complexity and execution time. Thus, the schemes are the potential candidates for enabling safety communications.

E. UAVs MOBILITY AND TRAJECTORY OPTIMIZATION

UAVs' optimal path planning is very crucial for public safety scenarios [95]. Different factors such as energy, flight time and user demands remarkably affect the UAV trajectory.

In [96], fixed-wing UAVs are deployed to gather important information from the users in their coverage. To meet the users' QoS and scheduling requirements, energy efficiency is maximized by optimizing the UAVs' flight trajectory. The problem formulated was a mixed integer and non-convex, which was solved using standard linear programming and successive convex optimization techniques. The authors further proposed an efficient iterative algorithm to jointly optimize user scheduling and UAV trajectory.

In [15], energy-efficient UAV communication schemes with trajectory optimization was proposed. The authors optimized the UAVs' trajectory by jointly considering throughput and the UAV energy consumption. A theoretical model based on the propulsion energy consumption as a function of the various constraints like UAV flying speed, direction, and acceleration was derived. The results proved that the proposed scheme achieved higher efficiency as compared with other schemes. Similarly, in [97], the authors maximized users' throughput by jointly optimizing UAV trajectory and transmit power and considering various constraints

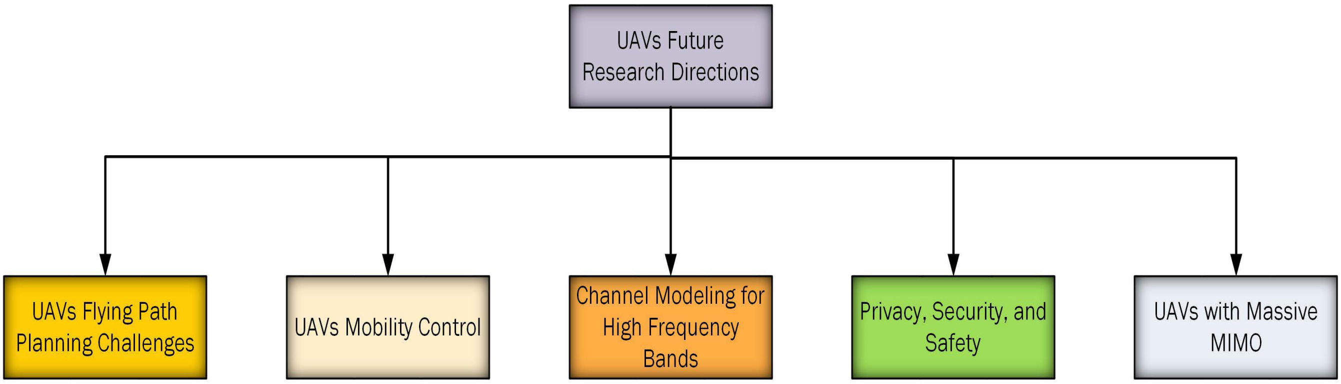


FIGURE 7. Future research directions for UAVs in public safety communications.

like mobility, collision avoidance, the information causality constraints, and the average and peak transmit power constraints of the source and UAVs acting relays.

In [98], the optimal UAV trajectory problem was solved by considering the mission duration constraint, that is the optimized trajectory of UAV should be achieved within a desired time to save important lives during disaster situation. For an interference limited scenario, the authors aimed to maximize the cellular system data rate and adopted dynamic programming to find the optimum UAV trajectory. These approaches with optimal trajectory were proved to be best in a sense of improving per user capacity and provisioning of high coverage probability.

F. MINIMIZING THE UAV's COMMUNICATION AND MECHANICAL ENERGY

Limited battery is a challenge in the UAV-based communication systems. Therefore, it is necessary to increase the battery life to increase or fulfill the operation done by UAVs. Communication and mobility (Mechanical) both consume huge battery in UAV [20]. A lot of works has been done but still this challenge has not been well addressed.

Minimizing the transmission power of the UAVs system can reduce the communication energy. UAV deployment at optimal location results in maximum coverage area with minimum transmission power [99].

To reduce the UAVs mechanical energy, energy consumption model is needed. An Energy consumption model is defined in [100] where UAVs energy utilization is varied according to their altitude. According to the model in [101], the mechanical energy is calculated for specific altitude, if height changes then their performance decreases. Higher altitude may cause maximum coverage area and high energy consumption. Different kinds of UAVs have different constraints regarding energy consumption. These features define the energy storage capacity and flying time of the UAV in a particular route. UAVs' consumed energy is determined by balancing the parameters according to energy consumption models.

Therefore, there is a trade-off present between the constraints such as energy consumption, UAVs' altitude, flight time, resource management, and coverage area.

V. OPEN ISSUES, CHALLENGES AND FUTURE RESEARCH DIRECTIONS

In this section, we introduce various open issues, challenges, and future research directions. Fig.7 depicts the future research directions for UAVs, with an emphasis on public safety communications.

A. UAVs FLYING PATH PLANNING CHALLENGES

UAVs' path planning problem has many constraints such as collision avoidance, energy consumption, trajectory cost, mission cost, communication cost, and flight cost. Mathematical optimization theory is faced with lots of challenges due to the abrupt increase in the variable dimensions while solving UAVs' path planning problem.

Nature inspired intelligent optimization algorithms can be used in future research to solve this problem. Multiple UAVs or swarms of UAVs for cooperative mission execution by using nature inspired swarm intelligence model is a very interesting topic for upcoming research. Furthermore, the deep/machine learning for UAV movement control is also one of the hot spots in future research. Machine learning is a very useful technique for the design and optimization of the UAV communication system [102], [103]. UAVs are expected to be able to adjust their position and motion controls according to the ground users and direction of the flight by using reinforcement learning algorithms. They should easily predict the behavior of ground users by using neural networks technique and can easily deploy the UAVs at optimal place.

B. PRIVACY, SECURITY, AND SAFETY CHALLENGES

When UAVs provide services then privacy security and trust plays a significant role in the system because of the technology become hazardous if the information is leaked or misused. In addition, power consumption increases because a sophisticated mechanisms of security and privacy usually require an amount of computational power and memory. It is challenging to combine privacy and security with interoperability, but there is a need to discover a trade off between energy consumption and security.

From the safety point of view, it is essential to design a mechanism for safe and targeted landing for public safety applications. There is a need to introduce a multiple schemes that provide promising safe landing of the device in emergency situations, to avoid breakage in communication links, avoid collisions, and engine failures. Artificial intelligence techniques provide promising solutions to address the security in UAV cellular connected applications [104].

C. UAVs RECHARGING AUTOMATION

Limited fuel is the greatest challenge in UAV communication scenarios. There is a significant need to dissociate the UAV intermittently from relay network for charging and replacing purpose. However, this is very expensive and difficult. In [105], the authors introduced the macro base stations to handle the battery recharging or replacing issues.

Latest research proposed the use of the energy harvesting techniques by using solar energy, but they have less efficiency as compared to fuel and stored energy batteries because solar techniques depend on light intensity. Distributed multipoint wireless power techniques, novel energy delivering techniques are useful to enhance the performance of energy efficiency.

D. UAVs SWARMS MANAGEMENT

It is a very critical challenge to control the multiple UAVs simultaneously, because each UAV may provide their services to more than one user. Simultaneously, control and handling of many devices on board may cause synchronization, communications, and latency issues. UAVs swarm coordination is also one of the most important challenge, that needs proper attention. To solve these challenges, game theory, contract theory, optimal transport theory, machine learning, and optimization theory can be adopted. Thus, efficient mechanism and algorithms are required to validate and realize the situation and then manage them properly.

E. CHANNEL MODELING FOR HIGH FREQUENCY BANDS

Due to the recent introduction of mmWave bands utilization for UAVs and other communication devices, more accurate air-to-ground or air-to-air channel models for high frequency are required that properly consider wind, temperature, foliage, urban environments, near sea environments, and other factors [106], [107]. Hence, there are many open research challenges in this area such as fast beam-forming training and tracking requirements, directional and range communications, rapid channel variations, blockage and multi-user access. For instance, transceiver beam alignment for attaining high antenna gain is one of the challenge of utmost importance. Hierarchical beam search techniques are an efficient beamforming training and tracking approaches that can be used to reduce the beam search complexity and overhead in mmWave bands.

F. MASSIVE MIMO FOR UAVs

The existing wireless technologies have the problem of short ranges and low-mobility situations. They also face the challenges of connectivity with the swarm of UAVs. Thus, existing scheme cannot easily meet the requirements in public safety situations. Massive MIMO has the potential to meet these demands and hence can be adapted for public safety situations [108].

VI. CONCLUSION

UAVs have notable applications in every field of wireless communications. To effectively utilize UAVs by targeting specific applications, different challenges need to be addressed. In this paper, we summarized the role of UAVs in public safety communications from energy efficiency perspective. To justify the uniqueness of this review, we first summarized the existing surveys in the literature. We also proposed the multi-layered architecture to enable public safety communications, which has the capacity of enabling the communications in basements with the help of wired as well as wireless communications. Moreover, we also highlighted that how UAVs can be placed, communicate, plan their trajectory, etc. in an energy efficient way. Finally, we highlighted the future research directions for the researchers working in this area.

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