A Survey of Coverage Issues in UAV networks

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***Abstract*— UAVs have been widely applied in military, public and civil applications based on their main characteristics of small volume, muscular mobility, flexibility, adaptive altitude and low communication overhead. One of the most active areas of research in UAV networks is that of area coverage problem, which is usually defined as a problem of how well the UAV networks can monitor the given space and how well the UAVs are inside a network can cooperate with each other. In this paper, we take a representative survey of the current work that has been done about this problem and made a general review of the coverage problems of UAVs so that we can give some inspiration to related researchers.**

***Keywords*— UAV network, Area coverage, Airborne base stations, Cooperation, FANET**

I. Introduction

The unmanned aerial vehicle(UAV) networks, also known as flying ad hoc network (FANET), is derived from the mobile ad hoc network(MANET) and the vehicle ad hoc network(VANET) and has the same network characteristics with them: each flight node has both the functions of a router and a terminal; these nodes can automatically complete the establishment of the entire network structure through various communication protocols and communication mechanisms, relying on the nodes themselves for organization, management, and configuration. The flying ad hoc network (FANET) also has its own unique characteristics, such as fast node movement, frequent topology changes, low node density, and limited energy [1].

Compared to traditional manned aerial vehicles, UAVs have been widely used in many aspects of military and civilian applications due to their small size, low cost, and ease of deployment. UAVs can perform missions such as environmental monitors, real-time surveillance, automated tracking, search, emergency rescue, and relay transmission [2].

The area coverage problem is a classic problem in wireless sensor networks. It is worthwhile mentioning that a lot of works so far have been focused on the area coverage problem because most mission-driven UAV communication technologies can eventually convert into the practical application under the area coverage problem. Hence, under the circumstance of cooperative UAV control coverage, missions such as investigation, communication, and mapping can be well accomplished, as shown in Fig. 1. UAVs can take along a wireless sensor while carrying out missions, so solutions of coverage problems in wireless sensor networks sometimes can also fit in UAV networks [3], [4]. However, a UAV network has its features, and that leads to many new solutions. First of all, due to the mobility characteristics of UAVs, the existing coverage algorithms are mostly static coverage which is difficult to apply. Secondly, when developing coverage algorithms, it is necessary to consider the constraints of limited energy and communication distance. Finally, the robustness and delay of the coverage algorithm are also factors that must be considered.

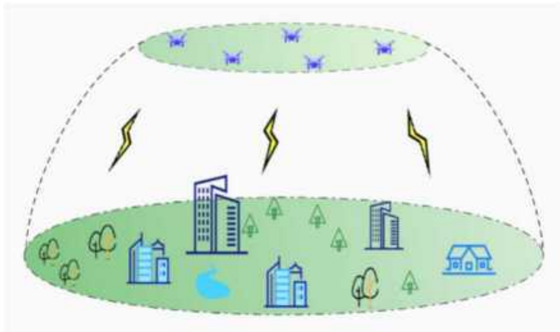

Figure 1. Scenes of UAV networks covering urban environments

The contributions of this article are as follows: First, we introduce the important factors that need to be considered for drone coverage. Second, classify the existing literature according to coverage types, scheduling deployment, node types, constraint restrictions, etc., and give a brief overview. And finally, we summarize and compare the existing coverage methods.

In section II, we made a detailed investigation on the classification of relevant literatures on UAV network coverage and evaluated some of them. In Section Ⅲ, we compared the existing literatures in a table form. In Section Ⅳ, we summarized the whole paper and pointed out the hot research directions in the future.

II. Related Work

The UAVs are autonomous and capable to fly freely or controlled by ground stations. The unmanned aerial vehicle communication networks (UAVCN) comprise of a collection of unmanned aerial vehicles (UAVs) to build a network that can be used for many applications. These nodes autonomously fly in free space in ad-hoc mode to carry out the mission. Usually, each UAV carries one sensor and the monitor range is limited. The area coverage problem is the vary base of many UAV applications, which is usually interpreted as the monitoring degree of a sensor network to a given area. So how to achieve monitoring the given area with a reasonable number of UAVs is a research highlight. Unfortunately, the UAVs face some challenging issues in the UAV coverage problem [5].

A. Considerations for coverage issues

There are a number of characteristics of drones that need to be considered when solving the problem of drone network coverage. We have briefly outlined the following five aspects: coverage ability, environment, mobility, connectivity and energy.

***1)Coverage Ability*:** The ratio of coverage area and given area is a measurement of the coverage ability of the UAV network. The goal of a coverage algorithm is to monitor and perceive environmental information, so the coverage ability is an important factor that must be considered. Because sometimes the coverage algorithms cannot achieve full coverage of a given area, sometimes the number of UAVs used in a coverage algorithms is not optimal even a full coverage is achieved[6].

***2)Energy*:** Energy is the weakness of UAVs. UAV nodes have required more energy for communication as compared to MANET and VANET nodes. It also depends upon the size and type of UAVs. It is a fact that the energy required to UAV for communication is considerably more significant than the energy needed in the MANET nodes for communication.

***3)Mobility*:** Mobility plays a vital role in the characteristics of UAV communications. UAV supports 2-dimension(2-D) and three-dimensional (3-D) mobility patterns for communication. On the one hand, mobility can improve the coverage of sensor networks; on the other hand, mobility makes the coverage of UAV networks more complicated, which is a significant challenge.

***4)Connectivity*:** Network connectivity is a critical issue for UAV networks. A UAV network is considered to be connected if each node pair can directly or indirectly communicate with other nodes. The aim of the coverage algorithm is information sensing and information conversion. Connectivity provides the roadmap for development and operational plan for a network, such as deployment patterns, processing algorithms, etc. But unfortunately, UAVs have a limited communication range, which creates difficulties for the connectivity of the entire UAV network. If an emergency occurs in a sub-region, it is essential to transmit this information to the console in the shortest possible time. Therefore, the connectivity strategy becomes another challenge.

***5)Environment*:** UAV nodes can fly in free space while MANET nodes can move close to the ground like VANET and WSN. However, there are many obstacles in the coverage area, such as buildings, trees, mountains, etc. These obstacles may affect the coverage results, so the free-space path loss model or another suitable model can be used for modeling the physical layer [3]. In addition, weather conditions, enormous obstacles (such as buildings, mountains, and ground reflections) can degrade the performance capabilities of the network, which in turn can lead to link failures. At present, there is not enough research on obstacle coverage algorithms in China.

B. Solutions to coverage issues

There are many factors that must be considered when developing a UAV coverage solution. Some researchers focus on only one aspect, and others give little consideration. In this section, different classifications and related algorithms are presented.

1)Cover Types

UAV has different types of motion, such as hover, stall, and flight. Different coverage types depend on different UA V motions. If the UAV remains hovering during the whole mission, we can consider it a static node, and the coverage problem is now called static coverage.

Zhou, L. et al. [7] considered a UAV-assisted cellular network in an urban environment and analyzed the coverage probability characteristics of the air-to-ground (AG) channel by modeling UAV as a uniform Poisson point process in the high and low SNR cases, revealing that the UA V height, PLE, and UA V density in the high and low SNR cases for both high and low SNRs and indicate some critical trends in the UA V height, PLE, and UA V density. The optimal height and density of the UAV are investigated to provide a basis for the static coverage deployment design of the UAV.

To study the effective coverage of UAV deployment, the authors of [8] considered drone small cells (DSCs) as airborne base stations to provide wireless services to ground users. In this article, the authors investigate the optimal height and minimum transmits power for UAVs to achieve static coverage of downlink in a given area, in both cases with and without interference, respectively.

The authors of [9] proposed a mathematical model based on statistical parameters of the urban subsurface environment to predict the optimal LAP height for static UAVs to maximize ground radio coverage. In addition, they proposed a closed formula for predicting the probability of a geometric line of sight between the LAP and the ground receiver. An important mediating parameter in this study is the probability of the line of sight from the LAP to the receiver, which is calculated as follows:

$$P(LOS,\theta) = \frac{1}{1 + a\exp(-b[\theta - a])}$$

Where θ is the ground elevation angle, and a and b are the 3D fitting parameters for the urban environment parameters. However, this paper does not consider the impact of multiple UAVs and UAV mobility on the coverage probability.

In [27], it is proposed to construct a UAV network for an urban environment using stochastic geometry in a scenario where a network of UAVs of a certain height provide wireless services within their coverage area. Their model considers parameters such as building density, height, and UAV antenna beam bandwidth, which are used to construct coverage probabilities for UAV networks and to demonstrate the performance tradeoffs that arise under different network conditions.

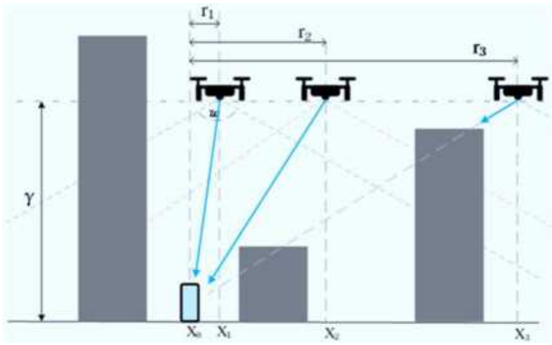

Figure 2. Side view showing UAVs in an urban environment

The experimental scenario is shown in Fig. 2 with UAVs X1, X2, X3 of height γ. The user signal is served by the UAV with the strongest signal, and the remaining UAVs generate LOS and NLOS interference. The experimental results demonstrate that the effect of buildings on the coverage probability depends on the UAV network density and signal interference to noise ratio (SINR), and furthermore, for a given UAV antenna beamwidth, UAV density and SINR, there exists an optimal height to maximize the coverage probability.

As mentioned before, mobility is the most crucial characteristic of UAVs. If a UAV keeps flying during a mission, we call it dynamic coverage. On a battlefield of the same size, dynamic coverage requires fewer UAVs, but the coverage accuracy is significantly lower than static coverage.

In [10], the authors proposed that the dynamic UAV coverage problem can be divided into two parts: region decomposition and path planning within a subregion, based on a polygonal region decomposition algorithm. This article [11] explores and analyzes existing research in the literature on different approaches involving dynamic coverage path planning problems, in particular the use of UAVs to solve simple geometric flight patterns and more complex mesh-based solutions. This review also considers different shapes of the region of interest, such as rectangles, concave polygons, and convex polygons.

In [12], the authors focus on the rapid deployment of UAVs for dynamic coverage of UAV networks. The authors prove that both problems with objectives of min-max and min-sum deployment delay are NP-complete in general. Subsequently, the problem is further transformed into dynamic programming, and a pseudo-polynomial implementation algorithm is proposed to solve the problem optimally. In this work [6], the authors develop a game-theoretic formulation of cooperative search and surveillance for multiple UAVs. Binary log-linear learning is used for motion control to ensure optimal coverage. Lyu J. et al. [13] propose a spiral placement algorithm that is considered as a stochastic layout scheme for solving the general geometric disk coverage (GDC) problem.

2)Deployment

The architecture of the UAV network can be either autonomous or inter-user architecture. Autonomous architecture networks can perform their tasks alone without external help, which is usually suitable for simple, straightforward environments with no high-performance requirements. If the task is very complex, an inter-user architecture is required.

i）AUTONOMOUS ARCHITECTURE

In this work [14], the authors investigate the coverage performance of reference user equipment (UE) in a limited network of multiple three-dimensional (3D) mobile unmanned aerial vehicles (UAVs). The authors propose a hybrid mobility (MM) model and then invoke the random waypoint movement (RWPM) and uniform movement (UM) models to represent the UAV motion in vertical and spatial directions, respectively, and subsequently analyze the coverage probability of the reference UE in a finite network of multiple UAVs under a uniform UAV association and closest UAV association policy.

Zhang J. et al. [15] introduces a novel tractable antenna gain model, which is a nonlinear function of the elevation angle and the directivity factor for directional antenna-based UAV communication. The authors derive the connectivity, association probability, and coverage probability of multi-layer UAV networks for both line-of-sight (LOS) and non-line-of-sight (NLOS) propagation scenarios and suggest the application of high-gain directional antennas to improve downlink transmission.

The work in [12] proposes an optimized 3D placement algorithm for unmanned aerial vehicle base stations (UAV-BSs) that uses the minimum transmit power to maximize the number of covered users. They decouple the problem of deploying UAV-BSs in the vertical and horizontal dimensions without any loss of optimality. In addition, the authors show that the deployment of UAV-BS in the horizontal dimension can be modeled as a circle placement problem and a smallest outer circle problem. Similarly, the authors in [16] modeled the UAV-BSs layout problem as a multi-circle layout problem and proposed an optimal layout algorithm based on one-dimensional parametric exhaustive search (ES) in the closed region. The authors also proposed a low-complexity algorithm, namely, the maximum weighted area (MWA) algorithm to reduce the complexity of the algorithm. The letter [13] proposes a new MBS placement algorithm by placing the UAV-BSs sequentially, starting from the perimeter of the area boundary in an inward spiral manner until all ground terminals (GTs) are covered. In the proposed spiral placement algorithm, each UAV-BS is first positioned to cover at least one uncovered GT near the area boundary, and then its position is adjusted inwards toward the area center to cover as many additional uncovered GTs as possible. This localized strategy has low complexity and does not partition the coverage area into independent regions, hence overcoming the limitations of the strip-based algorithm.

ii）INTER-USER ARCHITECTURE

With the development of technology, autonomous distributed UAV networks may be realized in the near future, but the primary architecture used in practice today is a centralized inter-user network. In [17], the authors introduce an inter-user UAV network. They include user intervention in sub-area path planning, which results in better performance. In [18], it has been demonstrated that an effective UAV can only be improved by the use of energy-efficient components. The authors suggest optimizing the maximum operating range and frequency band for data transmission to ground stations. In addition, complex tasks are assigned to multiple UAVs working as a fleet. The authors of [8] study optimal coverage and rate performance of UAV-based wireless communication in the presence of underlaid device-to-device (D2D) communication links. Both a static and a mobile UAV scenario are considered, and the UAV altitude along with D2D user density influence the overall measured performance. For the mobile case, the optimal stopping number is computed to ensure coverage for the downlink users.

3)Node types

Different types of UAVs are flourishing worldwide, and there is a wide variety of small UAVs. In most cases, a mission is performed by the same type of drone, but in some cases, different types of drones may be assigned to the same mission. These situations include lack of required UAVs, damage or battery failure of the initially used UAV, and mission assignments. In this context, UAV networks can be divided into homogeneous and heterogeneous networks. A homogeneous network is one in which there is only one type of UAV, and a heterogeneous network is one in which there are different types of UAVs within the network. Homogeneous coverage is simpler than heterogeneous coverage, and research on homogeneous coverage has focused on its performance, which is discussed below. With the increasing complexity of heterogeneous overlays, the importance of algorithms and structures is becoming more prominent.

For low-altitude platforms, such as urban surveillance, terrain survey, and emergency rescue, single-layer homogeneous UAV clusters are used to perform these tasks. In [19], the authors investigated the optimal altitude to ensure maximum downlink ground coverage while minimizing the launch power of individual UAVs. They then studied two UAV scenarios and calculated the optimal height for each UAV as well as the separation distance to ensure maximum coverage in both free and fully jammed scenarios. The authors of [8] investigate the optimal coverage and rate performance of UAV-based wireless communication in the presence of an underlying device-to-device (D2D) communication link. Both static and mobile UAV scenarios are considered, where UAV height and D2D user density affect the overall measurement performance. In [20], the authors use an ITU model to describe the urban environment and then apply ray-tracing simulations to describe the path loss for LOS and non-line-of-sight (NLOS) components.

Multi-layer UAV communication prefers the use of heterogeneous UAV networks, where UAVs of different heights perform different jobs and work together to accomplish tasks. The performance of dynamic packet multi-layer heterogeneous networks with asynchronous time slots is studied in [21]. Two traffic models, time slot asynchronous and exponentially spaced, are proposed to derive the coverage probabilities of uplink and downlink under multipath channels, compare the uplink (DL) and downlink (UL) coverage probabilities of synchronous dynamic packet systems with asynchronous peer-to-peer systems, and demonstrate that synchronous systems outperform asynchronous systems at the cost of computational complexity. Moreover, when the UL time slots and DL link time slots are aligned and synchronized, the coverage probabilities are improved for both UL and DL link cases.

Naghshin, V et al. [22] investigate the downlink coverage probability of a two-tier heterogeneous cellular network based on time slots using a stochastic geometry aurbanpproach. Two traffic patterns, time slot asynchronous and exponential interval, are introduced to capture user activities and derive downlink coverage probabilities based on the maximum SINR correlation. In contrast to the existing literature, the transmission time slots of the base stations are asynchronous. This results in packets transmitted in a one-time slot experiencing different levels of interference during the time slot interval. To illustrate the impact of asynchrony on downlink performance, a comparison between asynchronous and conventional synchronous hybrid coded networks is provided. In [23], the coverage probability of a two-layer dynamic time-division duplex heterogeneous network is investigated, where both macro and small cell layers run dynamic time-division duplex and use orthogonal frequency bands to eliminate cross-layer interference. A realistic load-aware network model is proposed and the coverage probabilities are derived for each layer and network-wide. The authors also investigate the impact of association policies on coverage and derive UL/DL link configurations, base station densities, and deviation factors that maximize per-layer or network-wide coverage probabilities.

This article [15] proposes a directional antenna-based antenna gain model for UAV communication, which is based on a nonlinear function of pitch angle and directivity factor. The communication connectivity, association probability, and coverage probability of a multi-layer UAV network are calculated for both line-of-sight (LoS) and non-line-of-sight (NLoS) propagation scenarios. The analysis results show that for UAV networks using directional antennas, there is a necessary tradeoff between connectivity and coverage probability. Thus, low-flying UAVs require a large elevation angle to serve ground user equipment (UEs) successfully. In addition, the coverage probability of a multi-layer UAV network can be maximized using directional antennas to obtain an optimal directional factor.

TABLE 1. ISSUES DISCUSSED IN EACH RESEARCH PAPER

	Mobility	Coverage type	Coverage method	Network architecture	Deployment	Energy efficient	Obstacles	Connectivity
[7]	No	Static	Centralized	Single layer	Autonomous	No	No	Yes
[8]	Yes	Dynamic	Centralized	Single layer	Autonomous	Yes	No	Yes
[9]	No	Static	-	Single UAV	-	-	Yes	No
[10]	Yes	Dynamic	Distributed	Single layer	Autonomous	No	No	Yes
[12]	Yes	Dynamic	Distributed	Single layer	Autonomous	Yes	No	Yes
[13]	No	Dynamic	Distributed	Single layer	Autonomous	No	No	Yes
[14]	Yes	Dynamic	Centralized	Single layer	Autonomous	No	No	Yes
[15]	No	Static	Centralized	Multi tiers	Autonomous	No	No	Yes
[16]	Yes	Dynamic	Distributed	Single layer	Autonomous	No	Yes	Yes
[19]	No	Static	Distributed	Single layer	Autonomous	No	Yes	No
[20]	No	Static	Distributed	Single layer	Autonomous	No	Yes	Yes
[21]	No	Static	Centralized	Multi tiers	Autonomous	No	No	Yes
[22]	No	Static	-	Two tiers	User-inter	No	No	Yes
[23]	No	Static	-	Two tiers	User-inter	No	No	Yes
[24]	Yes	Dynamic	Distributed	Single layer	Autonomous	Yes	No	No
[25]	No	Dynamic	Centralized	Single layer	Autonomous	Yes	No	No
[27]	No	Static	Distributed	Single layer	Autonomous	No	No	Yes
[28]	Yes	Dynamic	Distributed	Multi tiers	Autonomous	No	No	Yes

4)Constrains

UAV networks play a significant role in military and civilian domains, but there are many constraints, such as energy, obstacle avoidance capability, communication range limitations, exposed locations, etc. Therefore, these issues must be taken into account when designing coverage algorithms.

This paper [24] proposes a multi-UAV coverage model based on energy-efficient communication by studying the existing UA V coverage problem. The model is decomposed into two steps of coverage maximization and power control, and it is shown that both actions are exact potential games (EPGs) with Nash equilibrium values (NEs). Then the multi-UAV energy-efficient coverage deployment spatially adaptive play (MUECD-SAP) is used for coverage maximization and power control to ensure the optimal energy-efficient coverage deployment. Optimal beacon control for infectious disease routing in energy-efficient tolerant networks based on energy efficiency is proposed in [25]. The authors propose a continuous Markov and derive a threshold beaconing strategy that maximizes the delivery ratio at energy constraints. Another factor that must be considered is connectivity. In [26], the location and movement of UAVs are optimized to improve wireless network connectivity. The authors formulate the UAV deployment and movement problem and develop adaptive algorithms to improve the network's performance in terms of global message connectivity. They show that adding drones to the network can improve network parity and k-connectivity. For the layered UAV network [28], the optimal number of UAVs in the upper layers under closed coverage boundaries is theoretically analysed, based on which a low latency routing algorithm (LLRA) is designed to provide high quality of service (QoS) for mobile users using partial information on UAV locations and network connectivity.

III. DISCUSSION

In this survey, we summarize the different classifications of UAV network coverage problems. In fact, many studies have considered several factors. In the classification, we present only some of them, so we can just provide a reference for the reader. In Table 1, we can see the issue summary. The columns represent the factors considered and the considered rows represent the papers cited. From the table, it can be seen that due to the mobility of UAVs, coverage schemes are mostly dynamic, but inter-user coverage has not been studied enough. Fewer papers have been reported on multi-layer UAV coverage than on single layer. Different constraints (energy, obstacles, connectivity, interference) are considered in various articles, and the connectivity constraint is considered more than other constraints, but the environment with obstacles is less studied. In fact, the research on the UAV network coverage problem is not systematic enough and needs more good ideas and more in-depth analysis.

This paper provides a more comprehensive understanding of the coverage problem of UAV networks. The coverage problem of UAV networks refers to the ability of the UAV network to monitor a given area. This paper provides an overview of this issue by categorization. The classifications include static or dynamic coverage, autonomous or inter-user coverage, homogeneous or heterogeneous coverage, and different constraints (energy, obstacles, connectivity, threats). Many factors must be considered when developing an overlay solution. We believe that the study of heterogeneous and barrier avoidance UAV coverage will be a hot issue in the future.

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