Unmanned Aerial Vehicles for Package Delivery and Network Coverage

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***Abstract*—Unmanned aerial vehicles(UAVs) have become important in many application fields including last-mile deliveries, surveillance and monitoring, and wireless networks. This paper aims to design UAVs that simultaneously perform multiple tasks. We aim to design UAV trajectories that minimize package delivery time, and at the same time provide uniform coverage over a neighborhood area which is needed for applications such as network coverage or surveillance. First, we study multi task UAVs for a simplified scenario where the neighborhood area is a circular region with the post office located at its center and the houses are assumed to be uniformly distributed on the circle boundary. We propose a trajectory process such that if according to which the drones move, a uniform coverage can be achieved while the delivery efficiency (delivery time with respect to unconstrained case) tends to 1. Second, we consider a more practical scenario in which the delivery destinations are arbitrarily distributed in an arbitrarily-shaped region. We also do not assume any restrictions on the package arrivals. We show that simultaneous uniform coverage and efficient package delivery is possible for such realistic scenarios.**

***Index Terms*—Unmanned aerial vehicles, multi-purpose drones, package delivery, uniform network coverage.**

I. Introduction

Commercial unmanned aerial vehicles (UAVs), commonly known as drones, deployed in an unmanned aerial system (UAS), have recently drawn increased interest from private industry and academia, owing to their autonomy, flexibility, and broad range of application domains. With the on-going miniaturization of sensors and processors and ubiquitous wireless connectivity, drones are finding many new uses in enhancing our way of life. Applications of UAV technology exist in agriculture [1], surveying land or infrastructure [2], security [3], cinematography [4] and emergency operations [5].

An important emerging application of drones is on-demand delivery of goods and services which is shown to be cost-competitive compared to traditional ground-based delivery methods [4], [6]–[9]. The drones can provide on-demand, inexpensive, and convenient access to the goods and items already in or near an urban area, including consumer goods, fast-food, medicine, and even on-demand groceries. In the design and scheduling of on-demand delivery application, the goal usually is to minimize the overall delivery time/distance [4], [10].

Another important application of drones is their deployment in communications and surveillance [11]–[16]. In the former case, the drones are also referred to as aerial base stations (ABSs) [17]. In many cases, the ABS's are assumed to be moving along some pre-designed trajectories [18], [19]. The latter case, referred to as surveillance drones (SD) is usually associated to the drones that can carry video cameras and transmit video to provide new perspectives in visual surveillance [20]. Although these two applications may seem fundamentally different, they share a common requirement: they have to fly along trajectories so as to provide a relatively uniform coverage over the area in which they operate. Throughout this paper, such applications are referred to as uniform-coverage applications (UCAs).

Since drones can be used in many applications, an interesting idea is to design UAS's that simultaneously perform multiple tasks. This could significantly improve the efficiency of such systems. In this paper we aim to investigate this idea for the first time. As a first step, we consider a residential region where drones are used as the last-mile delivery tools within the area. Since these drones are already flying all over the area and providing some kind of aerial coverage, we may want to use them in a UCA framework. If this is the case, an important question would be whether the same mobility patterns can provide a uniform coverage in the area of interest. Alternatively, if we modify the patterns to achieve a uniform coverage, do we necessarily have to lose anything in terms of delivery efficiency?

To get an insight into the proposed question, we considered the 780-acre University of Massachusetts (UMASS) campus that contains about 170 buildings (Figure 1a) in which we assume that the last-mile delivery office is located in the lower-left corner of the figure with 10 operating drones at each mission. The drones start flying in straight lines with constant velocity to deliver the package to the building of interest and fly back to the post office. It is not difficult to see that this is the most efficient delivery profile. Now we investigate the coverage associated to this mobility pattern. To do so, we divide the maps into small regions and find the average number of drones on that region at an arbitrary time instant through a simulation setup. The results have been shown on a heat map in Figure 1b.

As can be seen, the coverage is quite far from uniform which suggests that the idea of multi-purpose UAS may not actually work. Surprisingly enough, we demonstrate that this is not the case. In this paper, we design efficient drone delivery systems that can simultaneously provide a fairly uniform coverage. This

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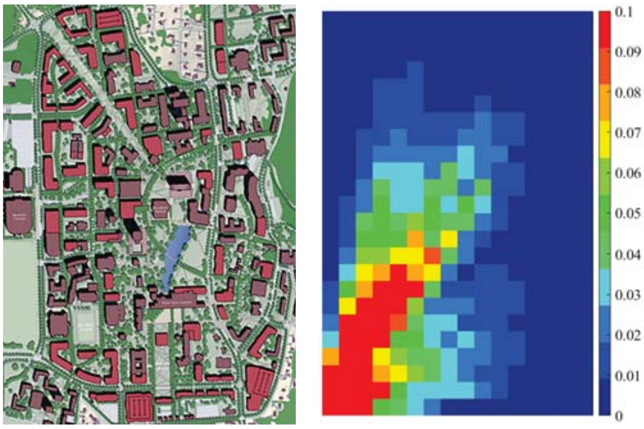

(A) University of Massachusetts (UMASS) campus

(B) Heat-map of average number of drones for the *fixed-speed-direct-line* algorithm

FIGURE 1: Multi-purpose drone algorithm for a residential area

is achieved through designing mobility trajectory on which the drones move with variable speeds. We first consider a simplified scenario where we assume a circular region with the post office located at its center (referred to as ideal case). The houses are assumed to be uniformly distributed on the circle boundary. Assuming the package arrivals are also uniform, we propose a trajectory process such that if according to which the drones move, a uniform coverage can be achieved while the delivery efficiency tends to 1. Next, we consider a more practical scenario in which the delivery destinations are arbitrarily distributed in an arbitrarily-shaped region. We also do not assume any restrictions on the package arrivals. In this case, we also show that simultaneous uniform coverage and efficient package delivery is practically possible.

The rest of the paper is organized as follows: in Section II, we introduce our system model, scenario, our proposed algorithm for ideal case (simplified scenario). In Section III, we present a practical scenario, then we describe the whole sequence of our proposed algorithm. Then in Section IV, provides simulation results, and Section V concludes our work.

II. Ideal case

A. Preliminary

If a fixed number of points are independently and identically distributed (i.i.d.) on a compact set $W \in R^d$, we say that these points can be modeled by general binomial point process (BPP) [21]. If these points are distributed uniformly within the same compact set, then we say the points are modeled according to a uniform BPP. In [18], authors obtain trajectories for UCAs.

We take a similar approach to [18] to formulate the uniform coverage problem. Specifically, we aim at designing trajectory processes for which, at any time the snapshot, the locations of drones are distributed according to a uniform BPP process over the neighborhood area.

B. System model

Figure 2 shows the neighborhood area in which we want to provide the uniform coverage. We assume that D drones deliver the arriving packages from the post office to the N destination houses and at the same time use them for UCA. There are N houses in the neighborhood area, which are destinations of the arrival packages. We assume packages are continuously arriving at the post office center. The $X_1, X_2, X_3, ...$ is a sequence of random variables that shows the sequence of incoming packages. We say that the i^{th} package must be delivered to the k^{th} house, if $X_i = k$, where $k \in \{1, 2, ..., N\}$.

FIGURE 2: Neighborhood area for Ideal case

To compare efficiency of different algorithms fairly, we assume that all the drones fly with the average velocity, i.e., V_{avg}. The time needed for one drone to reach the neighborhood edge from post office in a straight line by average velocity is denoted by τ, i.e., $\tau = \frac{\rho - \gamma}{V_{avg}}$ where γ is the radius of the post office center, and ρ is the radius of the entire neighborhood area. Before explaining the scenario and its algorithm, we obtain a lower bound of the total time to deliver m packages by D drones through Lemma 1, which is independent from the algorithm used. T_m indicates the total time to deliver m packages (note that $m >> D$). For simplicity, we ignore the down times such as night time and we just remove them from our analysis.

Lemma 1. The time to deliver m packages (T_m) by D drones must satisfy

$$\mathrm{T}_m \geq \frac{2m\tau}{D} \quad (1)$$

where τ and D are as defined above.

Using Equation 1, efficiency of the package delivery algorithm is defined as follows:

$$\eta = \frac{\left[\frac{2m\tau}{D}\right]}{\mathrm{T}_m}, 0 \leq \eta \leq 1 \quad (2)$$

If η is close to 1, it means that the algorithm is more efficient.

C. Scenario

We assume that D drones deliver the arriving packages from the post office in a circular neighborhood area. Figure 3 shows the parameters of this scenario. θ_i $(0 \leq \theta_i \leq \theta_{max})$ is the angle of the i^{th} house on the perimeter of the circle sector. In the case it is a full circle, then θ_{max} is equal to 2π which is shown in Fig. 2. We show the whole neighborhood area A by Equation 3. We assume houses are distributed uniformly over the neighborhood edge. We also assume package destinations are uniformly distributed over $1, 2, ..., N$.

$$A = \{(r, \theta) : \gamma \leq r \leq \rho; 0 \leq \theta \leq \theta_{max}\} \quad (3)$$

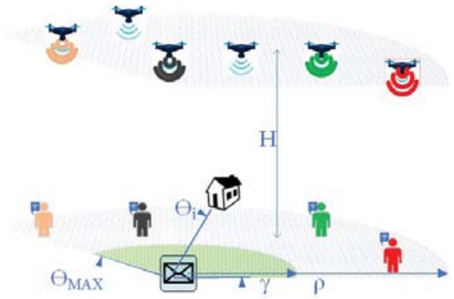

FIGURE 3: Parameters of our system model

D. Algorithm

In this algorithm, first, we choose the take off times of drones, $T_1, T_2, ..., T_D$, independently and uniformly from $(0, \tau)$. A package $X_i = k (1 \leq k \leq N, i = 1, 2, ...)$ is assigned to a free drone to be delivered. Each drone first flies to a predetermined altitude of H, then flies in a straight line with angle θ_k, which is uniform over $(0, \theta_{max})$, towards the neighborhood edge. When the drone reaches the neighborhood edge and delivers its assigned package, it returns to the origin on the same angle to complete the first cycle and this action repeats continuously. Figure 4 shows this trajectory process.

Algorithm 1 Algorithm corresponding to the ideal case

function DELIVERYCOST(D, m, X)
  Inputs:
  D drones with average speed V
  m number-of package to deliver
  X arrival packages which are distributed over $1, 2, ..., N$
  Output:
  Total time to deliver m packages(T_m)
  for `<i=1; i<=`D`>` **do**
    Generate random variable T_i uniform over $(0, \tau)$.
    Assign i^{th} package to i^{th} drone
    i^{th} drone flies at T_i and fly in a straight line with $V_d(t)$ at angle θ_i
  end for
  j=D+1;
  while `j<=m` **do**
    Assign j^{th} package to a free drone (say i^{th} drone)
    i^{th} drone flies right away and fly in a straight line with $V_d(t)$ at angle θ_j
  end while
end function

In Section IV simulation results confirm that if d_{th} drone flies with speed $V_d(t)$ at time t given by Equation 4, the drones will provide a uniform coverage over the area A.

$$V_d(t) = \begin{cases} \frac{(\rho^2-\gamma^2)}{2\sqrt{\tau((\rho^2-\gamma^2)(t-T_d)+\tau\gamma^2)}}, & \text{if } T_d \leq t \leq T_d + \tau. \\ \frac{-(\rho^2-\gamma^2)}{2\sqrt{\tau((\rho^2-\gamma^2)(2\tau+T_d-t)+\tau\gamma^2)}}, & \text{if } T_d + \tau \leq t \leq T_d + 2\tau. \end{cases} \quad (4)$$

In the next section, we move to the practical scenario and explain an algorithm in which D drones provide uniform network coverage, and at the same time, they can deliver the packages with high efficiency in a real community.

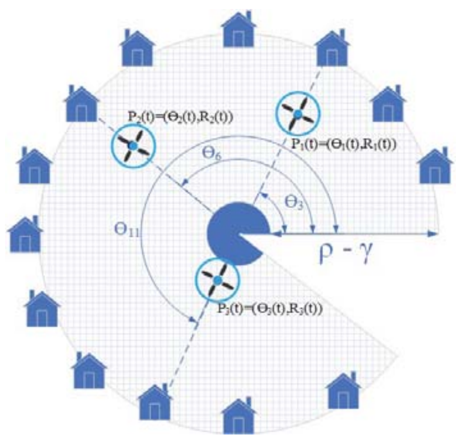

FIGURE 4: First process trajectory

III. PRACTICAL (GENERAL) CASE

In this section, first, we review the system model and scenario for the general case. For this case, we do not consider any assumptions on the density or location of houses or the distribution of arrival packages. Therefore, this case can be applied to any neighborhood area. In last part of this section, we propose our algorithm which delivers the packages efficiently and provides uniform coverage over the area.

A. System model

Figure 5 shows a typical neighborhood area over which we want to provide a uniform coverage. In this case, the geometric shape of neighborhood area can be any arbitrary 2D shape. In addition, the houses are distributed in the neighborhood area, and the distances from the post office to the houses can be any arbitrary value. We assume that D drones deliver the arriving packages from the post office to the N destination houses and at the same time use them for UCA framework. We assume packages are continuously arriving at the post office center.

FIGURE 5: A typical neighborhood area for practical case

B. Scenario

In our practical scenario, we assume D drones delivering packages to houses, are distributed over any arbitrary geometrical shape, and the packages may be sent to them non-uniformly, too. This assumption is more practical because in reality, the packages are sent to some houses more than others. The density of houses in the different location of neighborhood area could also be non-uniform. The location of h^{th} house is defined in a three-dimensional (3D) Cartesian coordinate system by $(x_h, y_h, 0)$, where $1 \leq h \leq N$. Drones fly at a constant altitude H above the ground and the location of d^{th} drone at time t is shown by $(X_d(t), Y_d(t), H)$, where $1 \leq d \leq D$.

C. Algorithm

In this algorithm first, we divide the neighborhood area into small regions or cells in which the drones are used as UAS and last-mile delivery tools. We use A_l to refer to these regions where $1 \leq l \leq S$ and S is the number of cells. We assume that A_l is small so that at most one drone can fly over the cell at any time. This assumption is compatible with the safety concern of drones as well.

Algorithm 2 Algorithm corresponding to the practical case

1: **function** DeliveryCost(A, D, m, X)
2: **Inputs:**
A the area should be covered
D drones with average speed V
m number-of packages to deliver
X arrival packages which are not uniformly distributed over $1, 2, ..., N$
3: **Output:**
Total time to deliver m packages(T_m)
4: Define V_{MAX} and V_{MIN}
5: Divide A into small cells; called these cells $A_1, A_2, ..., A_S$
6: for each small cells consider coverage probability p_r , $1 < r < S$ and initialize it with 0
7: **for** *h=1; $h <= N$* **do**
8: Generate the straight trajectory between the post office and h^{th} house and called it PT_h
9: **end for**
10: **for** *l=1; $l <= S$* **do**
11: **if** None of PT does not pass through A_l **then**
12: Select PT_h which is the closest trajectory to A_l
13: Change PT_h in such a way that it passes through A_l
14: **end if**
15: **end for**
16: **for** *j=1; $j <= \frac{m}{D}$* **do**
17: **for** *i=1; $i <= D$* **do**
18: Assign $((j-1) * D + i)^{th}$ package to i^{th} drone
19: Assume h is the destination of $((j-1) * D + i)^{th}$ package
20: foreach region l which PT_h passes through
21: **if** $p_l < p^*$ **then**
22: Set velocity of i^{th} drone to $MAX(V_{MIN}, \frac{H_1(PT_h, A_l)}{p^* - p_l}(1 - p^*))$
23: **else**
24: Set velocity of i^{th} drone to V_{MAX}
25: **end if**
26: Update p_l
27: **end for**
28: **end for**
29: **end function**

Then, we should define the trajectory paths, $PT_h : 1 \leq h \leq N$, between the post office and the houses in order to deliver the package with high efficiency and simultaneously provide the uniform coverage. In order to achieve these goals, we change the straight line between the post office and the houses in a way that all defined small regions are crossed by at least one trajectory. It means that we want to make sure $((\cup_{h=1}^{N} PT_h) \cap A_l \neq \varnothing)$ for region l where $1 \leq l \leq S$.

Because we do not have any information about the arrival packages, we adjust the velocity of drones when they enter the regions in order to preserve the uniformity in all cells. So, we should keep the coverage probability for each region(A_l) at any time and call it $p_l(t)$ where $1 \leq l \leq S$. In order to compute p_l, we use $f_l(t)$ as the total time that drones fly over each cell(A_l) during interval $[0, t]$ and $p_l(t) = \frac{f_l(t)}{t}$. Intuitively, if the coverage probability is less than the expected coverage probability (p^*), we should increase the velocity of the drone and if it is more than the expected coverage probability, the drone should pass this region faster. Lines 21 to 25 of Algorithm 2 show this adjustment, where H_1 is Hausdorff measure.

IV. Simulation Results

We run simulation for ideal and practical cases to verify our claim for uniformity coverage and delivery efficiency. To investigate the coverage associated to each trajectory, we divide the neighborhood area into small cells and measure the average number of drones over the regions through a simulation. We compare the performance of our proposed algorithms with the benchmark algorithm in which drones fly in straight lines with constant velocity to deliver the packages to the houses.

For ideal case, we consider 10 disjoint equal cells within $\frac{5}{8}$ of a circular area with radius $\rho = 5km$ as shown in Fig 6. We set the radius of the post office center to 100, i.e., $\gamma = 100m$, and the number of houses to 100, i.e., $N = 100$. We run the simulation with two different number of drones $D = 5$ and $D = 10$.

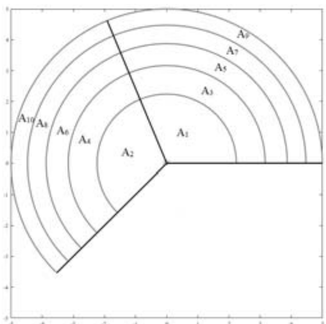

FIGURE 6: Circular area with radius 5 km is divided to 10 disjoint regions

Figure 7 shows the average number of drones flying over each of the ten regions for the benchmark and Algorithm 1. As can be seen, the benchmark algorithm provides more coverage in the regions which are closer to the post office and our algorithm provides the uniform coverage over the neighborhood area in both configurations. In other words, providing uniform coverage is independent of number of drones used in the algorithm.

For the practical case, we proposed the algorithm to deliver the packages and provide the uniform coverage simultaneously which can be applied to any neighborhood area with any distribution of arrival packages and position of houses. We consider University of Massachusetts Amherst to verify our claim about uniformity in coverage and investigate the efficiency of our algorithm to deliver the packages. We introduced University of Massachusetts Amherst community in Section I. Figure 1a and

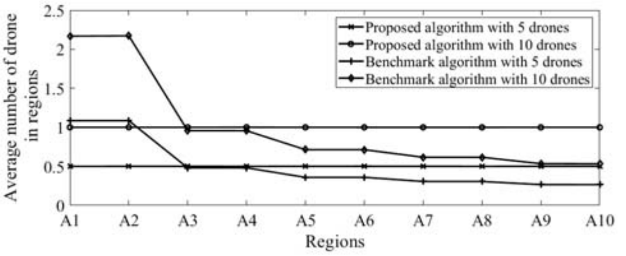

FIGURE 7: Average number of the drones over the regions for 5, 10 drones

1b show the neighborhood map and the heat-map of average number of drones for the benchmark algorithm, respectively. Figure 8 shows the heat-map of the average number of drones for the proposed algorithm which is simulated by 10 drones. As can be seen, our algorithm provides uniform coverage over the neighborhood area.

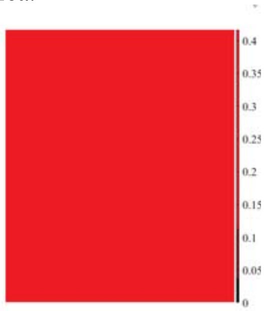

FIGURE 8: 10 drones are used to simulate our proposed multi-purpose drone algorithm for University of Massachusetts (UMASS) community

So far, we showed that our proposed algorithm provides uniform coverage over the neighborhood area. Here, we want to show that this algorithm delivers the packages efficiently. Therefore, we measure the average delivery time of 1000 packages through simulation and show the efficiency in Table I. Our proposed algorithms is able to deliver the packages over the community efficiently. To show that our algorithm provides fast deliveries for all packages, we report the average number of packages with delivery time more than 30 minutes in Table I. As reported in this table, the number of these packages is very small.

TABLE I: Average time to deliver 1000 packages with 10 drones

	Efficiency	# of packages(average) with delivery time >30 mins
Algorithm 1	1	0.000
Algorithm 2	1	0.006

V. Conclusion

In this paper, we proposed UAVs that simultaneously perform multiple tasks, uniform-coverage applications (UCAs) and last-mile delivery. We investigated the multi task UAVs for two scenarios: i) a simplified scenario where the neighborhood area is a circular region, and ii) a practical scenario where the neighborhood area is an arbitrarily-shaped region. For each scenario, we proposed an algorithm for UCA and last-mile delivery. Simulation results confirmed that our algorithms provide a uniform coverage over the neighborhood area, and at the same time provide package delivery with high efficiency.

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