Multi-Purpose UAVs: Towards Cost and Energy Efficient Aerial Networks

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***Abstract*—UAVs are expected to play an important role in next-generation networks due to their unique features and wide range of applications including last-mile delivery, communication relays, and aerial base stations (BSs). Motivated by the progress in communication technologies and advanced sensing systems, we investigate a new concept, multi-purpose UAVs, which act as communication relays and transportation simultaneously and aim to achieve a sustainable future aerial network. While delivering goods from warehouses to destinations (residential areas), UAVs can help in collecting data from multiple Internet-of-thing (IoT) clusters to terrestrial base stations (TBSs). We investigate data delivery efficiency as our main performance metric, defined as the ratio of collected data over the round trip time. Our simulation results show that multiple integrated features on single UAVs fully display their unique advantages, flexibility and mobility, and achieve cost and energy-efficient networks, using less drones to serve the network users.**

***Index Terms*—Multi-purpose UAV, package delivery, data collection, IoT devices**

I. Introduction

Unmanned aerial vehicles (UAVs), also known as drones, already play a key role in many industry verticals, and they might be indirectly influencing and helping citizens with everyday services. Drones are continuously developing with more features and capabilities added, which open a world full of possibilities and opportunities. Due to their airborne nature, UAVs can establish better communication channels with ground users than traditional fixed TBSs. They are more flexible and able to adjust their locations, as well as altitudes. Hence, they have a higher probability of establishing light-of-sight (LoS) links [1].

Generally, UAVs are designed to be dedicated to a single purpose, which may cause heavy traffic conflicts in future networks and it is not sustainable due to high cost and low energy efficient. This work aims to investigate the feasibility and flexibility of multi-purpose drones. While the authors in [2] consider UAVs delivering packages while providing cellular network coverage for a certain area, we extend our previous work [3] and consider muti-purpose UAVs to deliver packages and data for multiple IoT clusters, and design two algorithms to optimize the UAV trajectories from the perspective of data delivery and package delivery, respectively. Specifically, we use stochastic geometry and optimization tools to design UAVs' trajectories given the random locations of IoT clusters and TBSs and analyze the system performance on the sides of package delivery and data collection/delivery.

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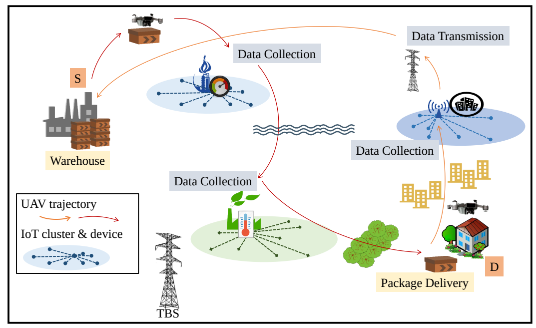

Fig. 1. Illustration of system model.

II. System Model

We consider a multi-purpose UAV delivering a package from a warehouse to a residential area while collecting data from nearby IoT clusters and forwarding it to nearby TBSs along the route, as shown in Fig. 1. Let Φ_b, $\Phi_{i,1}$ and $\Phi_{i,2}$ be the locations of TBSs, and two types of IoT clusters (considering IoT clusters have different priorities and data size), which are modeled by three independent PPPs. Worth mention that we consider UAV package delivery and IoT devices communication relay as our transportation and communication objectives, the proposed multi-purpose UAVs and stated results apply to different applications, such as providing coverage while monitoring, etc.

The power consumption of a rotary-wing UAV is sensitive to the payload and size. We consider an average weight of packages and UAVs use the optimal velocities to minimize the power consumption when traveling.

Definition 1 (Time Consumption)**.** *For a certain IoT cluster and UAV to TBS link, the total transmission time is*

$$T(R^{'}) \overset{(a)}{\approx} \mathbb{E}_{\rm G}\left[\frac{M_t}{b_w\log_2(1+{\rm SNR}|{\rm R}^{'})}\right], \quad (1)$$

where M_t is the transmitted data size, G is channel fading, the (a) follows from taking the expectation of R inside the logarithm operation, M_t is the collected/delivered data, b_w is the bandwidth, and R' is the distance between UAVs and IoT cluster centers/TBSs, ${\rm SNR}|{\rm R}^{'}$ is the conditional signal-to-noise (SNR) of these two links.

Let $\mathbf{h}_{\{e,t\}}$ and $\mathbf{s}$ be the possible UAV routes and decisions to travel to TBS(s), respectively, and $E_{\rm total}$ and $B_{\max}$ be the total energy consumption of a trajectory and UAV on-board battery capacity. We propose two trajectories: (i) minimize the round trip time on the side of package delivery, and (ii) maximize the transferred data on the side of communication.

Definition 2 (Minimal Time Path and Maximal Data Path)**.** *Let T^*_{total} be the minimal time of finishing a round trip given the locations of IoT clusters and TBSs,*

$$T^*_{\text{total}|\Phi_{\mathrm{i},1},\Phi_{\mathrm{i},2},\Phi_{\mathrm{b}}} = \min_{\mathbf{h_t},\mathbf{s}} T_{\text{total}},$$
$$\text{s.t.} \quad E_{\text{total}} \leq B_{\max}, \quad \mathbf{s} \in \{0,1\}. \tag{2}$$

Let D^*_{total} be the maximal transferred data while consuming all the energy given the locations of IoT clusters and TBSs,

$$M^*_{\text{total}|\Phi_{\mathrm{i},1},\Phi_{\mathrm{i},2},\Phi_{\mathrm{b}}} = \max_{\mathbf{h_e},\mathbf{s}} M_{\text{total}},$$
$$\text{s.t.} \quad E_{\text{total}} \leq B_{\max}, \quad \mathbf{s} \in \{0,1\}. \tag{3}$$

Definition 3 (Data Delivery Efficiency)**.** *Data delivery efficiency, which characterizes the system average data collection performance (average over the locations), is defined as*

$$\xi = \mathbb{E}_{\Phi_{i,1},\Phi_{i,2},\Phi_b}\left[\frac{M'_{\text{total}|\Phi_{\mathrm{i},1},\Phi_{\mathrm{i},2},\Phi_{\mathrm{b}}}}{T'_{\text{total}|\Phi_{\mathrm{i},1},\Phi_{\mathrm{i},2},\Phi_{\mathrm{b}}}}\right], \tag{4}$$

in which $M'_{\text{total}|\Phi_{\mathrm{i},1},\Phi_{\mathrm{i},2},\Phi_{\mathrm{b}}}$ and $T'_{\text{total}|\Phi_{\mathrm{i},1},\Phi_{\mathrm{i},2},\Phi_{\mathrm{b}}}$ is the delivered data and total time of an optimal trajectory obtained in Def. 2.

The higher ξ, the higher system energy efficiency, and this performance metric is upper-bounded by the average of the maximum achievable data rates of I2U and U2B channels.

III. Numerical Results

In Fig. 2 (a) we plot the data delivery efficiency of the proposed two trajectories and L is the distance between the source (warehouse) and destination (S to D distances). Clearly, the maximal data path has high efficiency under different L. Interestingly, we observe that while the values of ξ_d (data delivery efficiency for maximal data path) are continuous, the values of ξ_t (data delivery efficiency for minimal time path) have several peaks, which means that they are not continuous and have some gaps. This is because of the velocity. UAVs use the optimal velocities, which minimize the energy consumption, and the optimal velocities with/without packages are different However, we are not saying that the maximal data path is better than the minimum time path. The minimal time path is more practical if the required transferred data is limited and UAVs can forward all of the data to TBSs and the minimal time path is more efficient from the perspective of package delivery: shorter round trip time, hence, more packages can be delivered.

We then simplify our system model by considering only one IoT cluster and obtain the upper bound of the data delivery capacity (maximal delivered data) given L. Besides, we combine the aforementioned trajectories: if the reference UAV is able to deliver all the required data, we minimize the round trip time. If not, we maximize the transmitted data. Fig. 2 (b) plots the simulation results of the data delivery efficiency and capacity under different required data of IoT

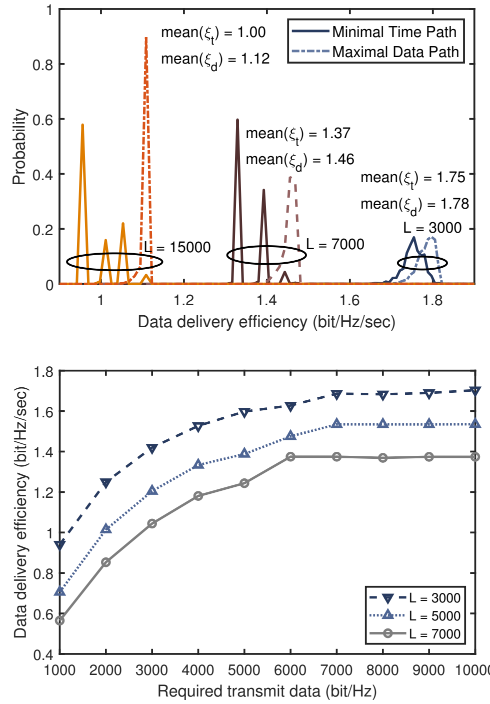

Fig. 2. **(a)** PDF of the data delivery efficiency of the minimal time path and maximal data path and L is the distance between S to D. **(b)** Simulation results of data delivery efficiency vs required collected/delivered data from IoT devices under different L.

clusters and different L. Data delivery capacity decreases with the increase of L. It is worth mentioning that shorter L does not always result in a shorter traveling distance owing to a lower probability of having a closer IoT cluster. Data delivery efficiency increases with the increase of required transmitted data since a longer time UAVs spend on data transmission. However, with the further increasing of the required data size, the data delivery efficiency reaches the maximum achievable value, which is limited the UAV battery and channel data rate.

IV. Conclusion

UAVs have drawn great attention due to their unique features and wide range of applications. Considering the growing industry demands for UAVs and motivated by the idea of infrastructure sharing, we capture a new aspect of the application, multi-purpose UAVs. Instead of dedicated drones for a single purpose, they can be designed more flexibly for multiple features. Our simulation results show that integrating multiple features on single UAVs is energy and spatial efficient, and hence, sustainable since it reduces the number of flying UAVs in the sky while guaranteeing the quality of service.

References

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