Delay Optimal UAV Trajectory Planning for Secure Data Collection from Mobile IoT Networks

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***Abstract*—Unmanned aerial vehicles (UAVs) have recently been used in many applications from surveillance to communication. UAVs can also assist the process of data collection from ground Internet of Things (IoT) devices thanks to the low deployment cost and flexibility. Since the energy and flight time of UAVs is limited, the trajectory planning for the UAVs during this data collection process is vital. While there are several studies that look at this problem with varying objectives, there is still a need for finding the optimal UAV path for data collection from mobile IoT devices with both the delay and secure collection of data in mind as the main concern. In this *work-in-progress* paper, we study this problem where a UAV aims to minimize the average or maximum delay of the collected data from ground IoT devices within its flight duration while also staying away from potential eavesdroppers on its path. We model the problem using Integer Linear Programming (ILP) and present results for different scenarios. Our next goal is to develop a reinforcement learning based solution that can provide results that are close to optimal ILP based results but also applicable to real-life scenarios.**

***Index Terms*—UAV, delay, security, trajectory optimization, Internet of Things.**

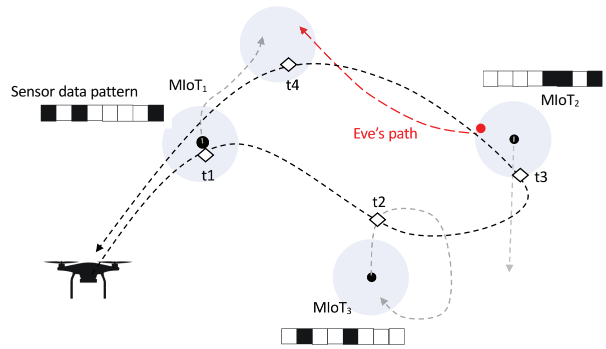

Fig. 1: An example scenario with a UAV and three ground mobile IoT devices where the UAV needs to travel over the area and collect data from each IoT device securely (i.e., while IoT-UAV communication is not eavesdropped) while optimizing the delay of the data collected.

I. Introduction

Thanks to their flexibility, enhanced functionalities and low-costs, UAVs have been considered recently in many application domains including but not limited to agriculture, smart-city, search and rescue and communication. With the growing number of IoT based applications supported by 5G networks [1], the data collection from massive number of IoT devices is also made possible by UAVs. Due to the heterogeneity of data generated by IoT devices, and also due to the various application requirements (e.g., minimizing delay for near real-time IoT services), environmental conditions (e.g., obstacles) or security attacks (e.g., eavesdropping) finding the best trajectory for the UAVs could be challenging.

An example scenario is illustrated in Fig. 1, with three mobile IoT devices and one eavesdropper that can also move around. Knowing the data patterns of the IoT devices, UAV travels over the area and collects data from IoT devices and goes to its final location. As the IoT devices move around, the data collection can happen at different times during the UAV's mission. During its flight, UAV avoids receiving of data from IoT when there is also an eavesdropper in the vicinity for security purposes. Thus, this can lead divergence of the path from the delay only optimal path and also can cause delays in the mission time. Our goal in this paper is to consider both the minimization of delay and maintaining the security during this data collection process within a dynamic network environment generated by the mobility of IoT devices and the eavesdroppers. Existing works that study UAV path optimization consider various constraints (e.g., delay) and goals (e.g., minimum path). However, to the best of our knowledge, the same constraints and joint objectives have not been considered in any other work.

The rest of the paper is organized as follows. We discuss the related work in Section II. In Section III, we provide the system model and provide the problem statement and optimization model. In Section IV, we provide numerical results regarding the performance of proposed solutions in various scenarios. Finally, we conclude and discuss future work in Section V.

II. Related Work

The limited flight time of UAVs has motivated many UAV trajectory planning studies with different goals [2]. These include minimizing the mission time [3], [4], maximizing the throughput [5], or maximizing the sweep coverage [6], and while considering different parameters such as antenna radiation pattern and backhaul constraint [7], and disconnectivity or outage constraint [8].

When UAVs are considered for data collection from ground IoT devices [9], several metrics like delay and Age of Information (AoI) have also been considered in the trajectory optimization of UAVs [10], [11]. This objective has also been

Notations	Description
u	UAV traveling the map with specific starting and ending locations
$\mathcal{I}$	The set of IoT devices
$\mathcal{E}$	The set of eavesdroppers
L_{S}, L_{F}	Start and final location of UAV, respectively.
$u(t) = (x(t), y(t))$	Location of UAV in time slot t. Z coordinate is H for all times.
$i(t) = (x_i(t), y_i(t))$	Location of IoT device i in time slot t. Z coordinate is 0 for all times.
$e(t) = (e_x(t), e_y(t))$	Location of the eavesdropper e in time slot t. Z coordinate is 0 for all times.
S_i	The set of data generated by IoT device i.
$c_i(t)$	Connection status of the UAV to IoT device i at time t. It is equal to 1 if UAV can communicate to the IoT i and receive the data at time slot t; otherwise, it is 0.
$d_i^k(t)$	Collecting k^{th} data from IoT device i in time slot t. It is equal to 1 if the UAV collects the kth data from IoT device i in time slot t, otherwise 0.
t_i^k	The time of generating k^{th} data by IoT device i
R	Max distance/range for a IoT-UAV link to maintain required SNR level.
T_{max}	Maximum flight duration time of UAV to reach the destination.
V	Maximum speed of UAV
A_i	Sum (maximum) of delay for all data collected from IoT device i.

TABLE I: Notations and their descriptions.

considered together with some other objectives such as energy and service time allocations for packet transmissions [10]. Security of the data collection process in the presence of potential eavesdroppers has also been studied in some recent works. To this end, the secrecy rate for the IoT devices is also considered in the trajectory planning (e.g., maximizing the minimum average secrecy rate [12]). Despite the variety of these studies that consider several different criteria, however, to the best of our knowledge, none of them consider secure data collection process from mobile IoT devices with a goal of minimizing the delay.

III. System Model

A. Assumptions

We assume that there is a UAV and N ground IoT devices, represented by set $\mathcal{I}$, which generate data at some time slots. Note that this can depend on the application and the conditions set for data generation. The mission of the UAV is to start from a location, L_s and fly through the field where the IoT devices are deployed and collect information from them as it passes over them. We assume that all the data from an IoT device can be transmitted to the UAV when the distance between the UAV and an IoT device is less than R. Note that such an R can be found by considering the signal level modeling and the required bandwidth to transmit the application specific data [3], [7]. We assume that the UAV has a max speed V and flies at a fixed altitude, H which allows it to be able to communicate with the IoT devices in the Line-of-Sight (LoS) without having interference. We denote the location of the UAV at time t with $u(t) = (x(t), y(t), H)$, and $0 \leq t \leq T_{\max}$, where $T_{\max}$ is the maximum possible flight time of the UAV.

We assume that the IoT devices move in the field too. They can follow a pattern (e.g., back and forth between two points) or continuously move in one direction following a specific path (e.g., roads). The location of the i^{th} IoT device, I_i, at time slot t is represented with $(x_i(t), y_i(t))$. Each IoT device generates data at certain time slots and the set of these data from I_i is defined as $S_i = \{s_i^0, s_i^1, s_i^2, \dots s_i^{|S_i|}\}$. We also assume k^{th} data of device I_i is generated at time t_i^k.

B. Problem Statement

In the proposed scenario, the objective is to let the UAV travel in the field that consist of several ground IoT users such that the delay (i.e., time elapsed between the generation of data at the IoT device and the time it is delivered) of the collected data is optimized. For optimization, we consider two different objectives. In the first one, the objective is to minimize the average or total delay for all data collected. In the second one, the objective is to minimize the maximum delay of any data collected. At the end of the mission, the UAV should arrive to the final point (which can be same as the starting point) within the given maximum flight time, T_{max}.

We then define the optimization problem as follows:

$$\min \quad (A_{avg})\lambda + D_{sum} \tag{1}$$

$$\text{s.t.} \quad u(0) = (x_{\mathrm{S}}, y_{\mathrm{S}}, H) \tag{2}$$

$$u(T_{max}) = (x_{\mathrm{F}}, y_{\mathrm{F}}, H) \tag{3}$$

$$\mathrm{dist}_{u(t)}^{u(t+1)} \leq V, \forall t < T_{max} \tag{4}$$

$$c_i(t) = \begin{cases} 1, & \text{if } \mathrm{dist}_{i(t)}^{u(t)} \leq R \\ 0, & \text{otherwise.} \end{cases}, \forall t \leq T_{max}, \forall i \in \mathcal{I} \tag{5}$$

$$d_i^k(t) \begin{cases} = 0, & t \leq t_i^k \\ = 0, & \mathrm{dist}_{e(t)}^{i(t)} \leq R \\ \leq c_i(t), & \text{otherwise.} \end{cases}, \forall t \leq T_{max},$$
$$\forall i \in \mathcal{I}, \forall k \in S_i, \forall e \in \mathcal{E} \tag{6}$$

$$\sum_{t=0}^{T_{max}} d_i^k(t) = 1, \forall k \in S_i \tag{7}$$

$$A_i^{sum} = \sum_{k=0}^{|S_i|} \sum_{t=t_i^k}^{T_{max}} (d_i^k(t) \times (t - t_i^k)), \forall i \in \mathcal{I} \tag{8}$$

$$A_{avg} = \left(\sum_{i=1}^{|\mathcal{I}|} A_i^{sum} \right) / |\mathcal{I}| \tag{9}$$

$$D_{sum} = \sum_{t=1}^{T_{max}} \mathrm{dist}_{u(t)}^{u(t-1)} \tag{10}$$

where,

$$\mathrm{dist}_u^v = \sqrt{(u.x - v.x)^2 + (u.y - v.y)^2 + (u.z - v.z)^2}.$$

Here, in (1), we use scalarization method (by multiplying the first goal with a large constant λ) and aim to first minimize the average delay and then minimize the total path length of

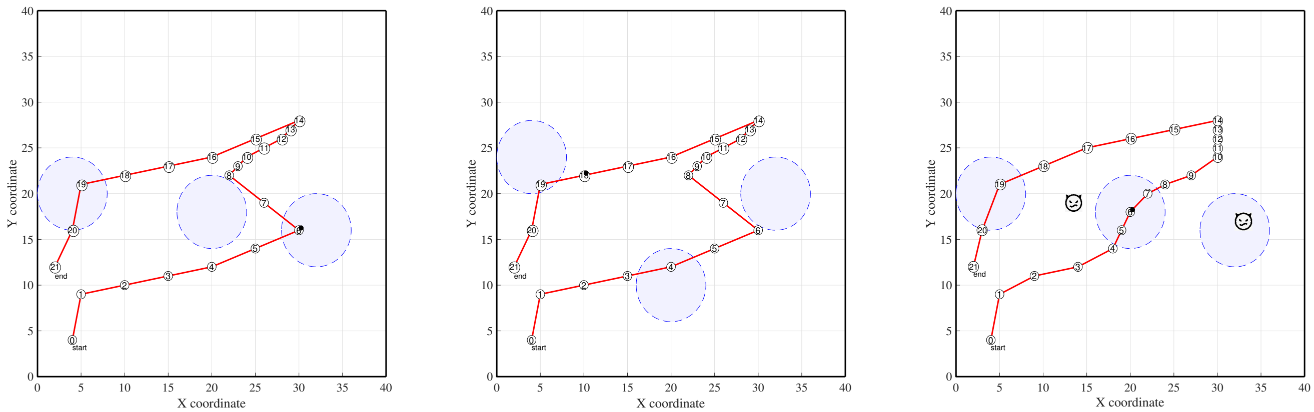

Fig. 2: The UAV path when the objective function is to minimize the average delay of data collected. (a-b) UAV and MIoT locations at time slot 6 and 18, respectively, when there is no eavesdroppers. (c) UAV, MIoT and eavesdropper locations at time 6 when UAV is restricted to communicate with IoT devices when the eavesdroppers are not around.

the UAV with this minimum delay. In (2) and (3), we make sure the UAV is at the start and end point at the beginning and at the end, respectively. In (4), the UAV is constrained to move not more than what its maximum speed allows between the consecutive time slots. In (5), the connectivity between the UAV and each IoT device is set based on the distance between the position of the IoT device and the UAV at that time slot. We then allow collection of data by the UAV only after its generation and when there is no eavesdropper in range of IoT device in (6) and only one time as defined in (7). In (8) and (9), we then compute sum and average of the delay for all data collected from all IoT devices. Finally, in (10), we calculate the total path travelled by UAV which is considered in the objective function as well as a second priority.

Note that these constraints and the objective are defined for minimization of the average delay as main goal (while also minimizing the UAV path length). However, when the goal is minimizing the maximum delay from any data received at the UAV, we define

$$A_{max} = \max\{(d_i^k(t) \times (t - t_i^k))\}, \forall i \in \mathcal{I}, \forall s_i^k \in S_i, \forall t \leq T_{max}$$

and aim

$$\min\left((A_{max})\lambda + D_{sum}\right)$$

.

IV. Numerical Results

In this section, we provide our initial results for the studied system model. We consider a 40 by 40 grid map and assume that there are three IoT devices, with data generation times and mobility behaviors as described in Table I. We also consider two eavesdroppers that are mobile as well. For both objectives, we obtained the ILP results using CPLEX both with and without eavesdroppers.

In Fig. 2, we show the results with the first objective of minimizing the average delay (and also minimizing path length after that). When there is an eavesdropper, as the last figure shows, the UAV changes its delay-optimal path and considers receiving data from IoT devices when the eavesdroppers are not in the vicinity.

Similarly, in Fig. 3, we show the results with the second objective of minimizing the maximum delay (and also minimizing path length after that). When there is an eavesdropper, as the last figure shows, the UAV follows a different path and schedule in its communication with IoT devices but this comes with an increased delay for the data collected. It is worth noting that the UAV sometimes can hover at a specific position (i.e., between time slots 11-15 in Fig. 3c) and wait for the IoT devices to arrive that location to collect their data. This can also generate a shorter path for the UAV in the case of eavesdroppers compared to its path when there is no

	Mobile IoT devices		
Parameter	**MIoT$_1$**	**MIoT$_2$**	**MIoT$_3$**
Time slots with data generated	1,13,18	0,4,7	1,3,14
Moving pattern per time slot	2 unit to north	2 unit to north	2 unit to north
Objective 1: Minimize average delay			
Time slots UAV receives data	1,19,19	4,4,8	6,6,14
Delay for each data	0,6,1	4,0,1	5,3,0
Overall average delay	2.22		
Objective 1: Minimize average delay (with Eavesdroppers)			
Time slots UAV receives data	1,19,19	4,4,7	10,10,14
Delay for each data	0,6,1	4,0,0	9,7,0
Overall average delay	3		
Objective 2: Minimize maximum delay			
Time slots UAV receives data	1,13,23	4,4,9	6,6,18
Delay for each data	0,0,5	4,0,2	5,3,4
Overall maximum delay	5		
Objective 2: Minimize maximum delay (with Eavesdroppers)			
Time slots UAV receives data	1,22,22	6,7,7	10,10,15
Delay for each data	0,9,4	6,3,0	9,7,1
Overall maximum delay	9		

TABLE II: Simulation parameters and values together with numerical results for both scenarios.

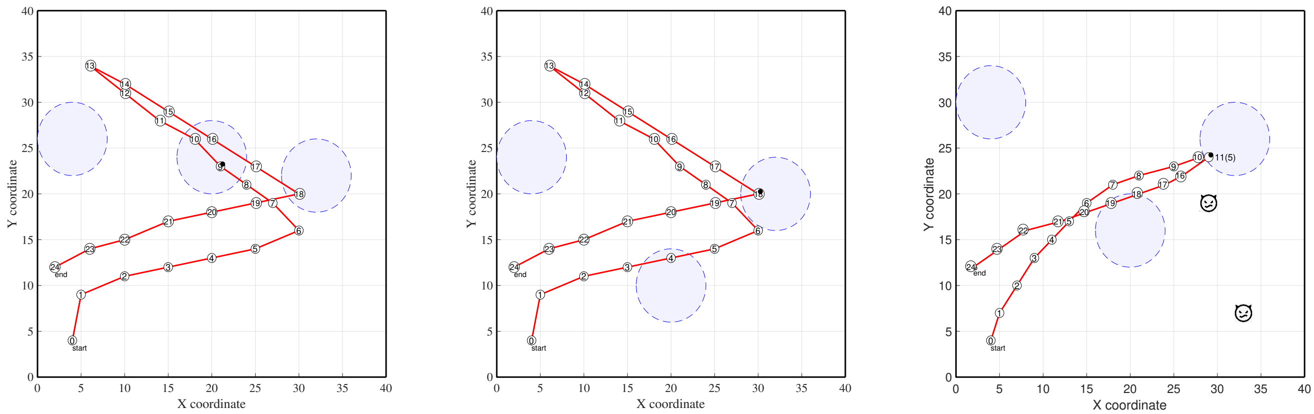

Fig. 3: The UAV path when the objective function is to minimize the maximum delay of any data collected. (a-b) UAV and MIoT locations at time slot 9 and 18, respectively, when there is no eavesdroppers. (c) UAV, MIoT and eavesdropper locations at time 15 when UAV is restricted to communicate with IoT devices when the eavesdroppers are not around.

eavesdroppers.

Results in both scenarios are also detailed with the associated information provided in Table II. We show the actual data generation times from each IoT device, and the time slots that UAV receives these data from them. Eavesdroppers increase the average delay from 2.22 to 3 time slots in the first scenario, while they also cause an increase in the maximum delay in the second scenario, i.e., from 5 to 9 time slots. However, in both scenarios our model can provide the optimal solutions within the defined constraints.

V. Conclusion

In this paper, we have investigated UAV trajectory optimization problem for a mission of data collection from ground IoT devices which are also mobile. We targeted two different delay objectives, namely, minimization of the average delay and the minimization of the maximum delay from any data. We also considered presence of eavesdroppers and restricted the UAV to receive data from IoT devices only when there is no eavesdropper around, and optimized the UAV path accordingly.

Both objectives are formalized using ILP and solved by CPLEX. The results show that the optimal paths are correctly obtained and achieve the targeted objectives. The presence of eavesdroppers however causes changes in the path and data communication schedule of the UAV with MIoT devices, and increases the delay. As the subject of our future work, we will look for cost efficient solutions that run faster than ILP based solution while providing closer to optimal results. We will also consider real-time path calculations; thus, we will study a reinforcement learning based model integration to the current design. We will also consider multiple UAVs and different numbers of MIoT devices and eavesdroppers together with varying mobility patterns for both.

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