UAV Mesh Network Trajectory Planning for Age Optimal Data Collection in Infrastructureless Areas

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***Abstract*—Collection of environmental data from emergency sites where there is no or minimal cellular infrastructure exists is very critical for efficient response management. Unmanned aerial vehicles (UAV) can provide a tremendous support during that process thanks to their flexibility, agility and lower cost. A mesh network formed among the UAVs can facilitate the data collection process while also keeping the communication among them. However, as the age of the collected information (i.e., from the moment it is generated at the ground sensor node to the moment it is delivered to the emergency response center) defines the success of response tasks, the trajectory of the UAV mesh network should be determined carefully considering the timely delivery of the critical data. In this paper, we study the path planning problem for a UAV mesh network for AoI optimal data collection from the ground IoT devices in such emergency sites with minimal or no infrastructure. We explore different settings that could happen in such scenarios and develop an Integer Linear Programming (ILP) based model for each to optimize the UAV trajectories with the main goal of minimizing the maximum AoI from the collected data. In order to avoid the high complexity of ILP solutions, we also propose relaxed models. Through simulations, we compare the results in different scenarios in terms of the maximum AoI and UAV path lengths and discuss potential drawbacks in each.**

***Index Terms*—UAV mesh network, trajectory planning, age of information, Internet of Things, emergency and disaster sites.**

I. INTRODUCTION

In the aftermath of emergency and disaster scenarios, communication and environmental data collection has a significant role in efficient response management. In such situations, communication can be achieved in various ways including through a satellite communication, ad hoc communication or local base stations or a mixture of these solutions partially. UAVs have been considered as assistive vehicles during such scenarios as they can be deployed as flying base stations [1] that can provide a good line-of-sight (LoS) connection with low interference, or as relays among the ground users/devices or to connect them to the backhaul.

Previous works that consider deployment of UAVs in disaster or emergency situations study various problems including the optimal deployment of UAVs [2] to increase the coverage of the stranded users or the communication data rates among them, topology maintenance [3], and routing of packets efficiently [4]. In some studies, the energy constraints and charging schedules of UAVs as well as the management of the interference among UAVs and also the users have also been taken into account for more realistic solutions.

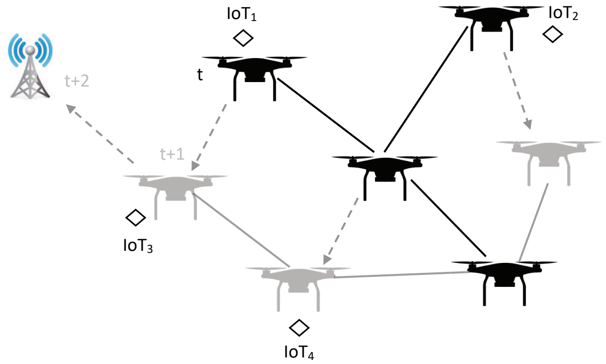


Fig. 1: A UAV mesh network of four UAVs collecting data from four ground IoT devices at time t (black) and $t+1$ (gray) and uploading their data to a base station at time $t+2$.

In this paper, we explore the problem of data collection from ground sensor nodes or IoT devices in emergency sites considering the age of information (AoI) of collected data. Previous works have extensively studied UAV path planning for efficient data collection from ground IoT devices [5]. Similarly, trajectory optimization for UAVs considering different aspects (e.g., energy, limited time, environmental constraints, connection outage [6], [7]) has also been studied extensively [8]. With the introduction of age of information [9] in this domain, several studies [10], [11] have also looked at the AoI optimal data delivery problem in UAV-assisted IoT networks. These studies assume that the data is generated before the UAV mission starts; however, in practice, each ground sensor data can be generated at different times, even during the mission of UAVs. Moreover, multi-UAV mesh network and connectivity maintenance has not been considered in any of these studies. Thus, our study is unique in comparison to existing work in terms of bringing all the aforementioned components together.

Fig. 1 illustrates an example scenario, with a set of UAVs, connected in a mesh network, collecting data from several ground IoT devices. We show two different time moments of the same UAV mesh network. At time t the data from the first two IoT devices is collected while in the next time moment, the data of the other IoT devices are collected. Note that the UAVs maintain their connectivity among each other. This helps up-to-date communication among them, which is vital in

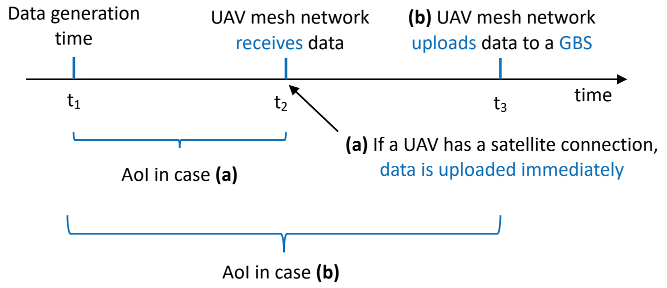


Fig. 2: Age of information in two different scenarios.

emergency sites, where there is no or minimal infrastructure. In this figure, we show that the UAVs also move and get into the range of a base station at a later time to upload the collected data to the backhaul, which makes it reach to the emergency response center to be processed.

Fig. 2 shows the AoI for the two different scenarios considered. If there is an undamaged ground base station (GBS) in the emergency site and the goal of the UAV mesh network is to delivery the collected data from the IoT devices to this GBS, the AoI will be from the moment the data is generated at t_1 until the moment it is delivered to the GBS at t_3. However, if there is a satellite connection possible from one of the UAVs, as soon as one UAV in the mesh network receives the data, it will be delivered to the backhaul through that satellite connection immediately (delay while exchanging data between connected UAVs is neglected assuming the data is very small).

Our goal in this paper is to plan the trajectory and connectivity of a UAV mesh network for AoI optimal data collection from IoT devices for a given scenario. There are other studies (e.g., [12]) that look at data collection from IoT devices with multiple UAVs considering the AoI in the design goals. However, none of these studies consider delivery of data to the backhaul through satellite or to a base station that is still active in an emergency site. The age of the data is defined by the time they are received by the UAV mainly, thus their AoI definition is different from how we define in this study (i.e., from the moment the data is generated till it is delivered to any backhaul entry point such as base stations or satellite connection). To the best of our knowledge, there are only two studies [13], [14] that define the AoI as it is considered in this study. However, these studies do not consider multiple UAVs that are connected within a mesh network and are deployed in an emergency site without any or minimal infrastructure.

The rest of the paper is organized as follows. We present an overview of the related work in Section II. In Section III, we describe our system model and assumptions. We also describe the problem and elaborate on the optimization models developed for different scenarios. We present our simulation results for different scenarios in Section IV. Finally, we conclude and discuss our future work in Section V.

II. RELATED WORK

Utilizing UAVs in disaster scenarios have been studied extensively [15], [16]. These works look at problems like trajectory planning for these UAVs [17], their topology management and energy efficiency [8]. Mesh network formation in the sky in emergency scenarios is indeed not just considered for UAVs but also between balloons [18] over a WiFi interface.

The path planning problem for UAVs has been studied extensively [6], [7], [19]–[21] under different objectives. Minimizing age of information has also been considered as one of the objectives especially when UAVs are utilized in assisting data collection efforts from ground IoT devices [5], [9], [10], [19], [22]–[24]. Despite the growing trend of these studies, the AoI is usually defined until the moment the data is collected by UAVs without considering the communication of the UAVs with the backhaul network. However, in emergency sites such as post-disaster areas, the data will not helpful until the data is delivered to the emergency response center by the UAVs. Moreover, these works do not take into account different data generation times at each ground IoT device. The recent works [13], [14] are the closest works to the work in this study, but they do not consider multiple UAVs and mesh network maintenance among UAVs. Thus, in this work, we address a unique problem which is critical in emergency sites.

III. SYSTEM MODEL

A. Assumptions

We assume a system model with a set of UAVs, represented by U, and a set $\mathcal{I}$ of ground IoT devices. Each IoT device generates a data at some specific time based on the application running on them. In emergency sites, this could be as simple as air quality or temperature data (or another critical environment related information) from ground sensors deployed from the air. We assume that IoT device i is located at l_i and it has generated a data at t_i. Further, we assume that UAVs can start their mission from any location on the map, however, this is flexible and UAVs can be given a starting point. The goal for the UAVs is to collect all data from ground IoT devices within a given time constraint $T_{\max}$, which is defined as the maximum possible flight time for the UAVs defined by their specifications. The collection of data from an IoT device happens when UAV arrives in the vicinity of the IoT device. That is, when the distance between the UAV and an IoT device is less than a certain threshold (R_I) we assume that the data from IoT to UAV is transmitted. We also assume that UAV-to-UAV communication range is R_U. For the sake of simplicity, we skip the details of how to find R_I and R_U in a real scenario, however SNR based models as considered in previous works [6], [21] could be applied. We assume that UAVs have a maximum speed of V and fly at a fixed altitude (H), which can be relaxed in a more detailed study. In this study, we also consider only the LoS based communication between the IoT devices and UAVs and avoid the optimization regarding interference avoidance. Finally, we denote the location of the UAV u at time t by $L(u,t) = (x(u,t),\ y(u,t),\ H)$.

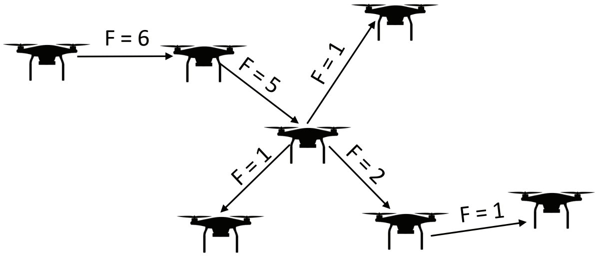


Fig. 3: Flow-based mesh network connectivity modeling.

B. Problem Statement and ILP Formulation

We start with the problem (P1) where UAVs need to collect data from all ground IoT devices while maintaining the connectivity among them and the data delivery happens through a satellite connection from one of the UAVs. We define a decision variable for the location of each UAV at each time moment, defined by a set $L = \{L_0, L_1, L_2, ..., L_T\}$. Our main goal is to minimize the maximum AoI during this data collection process:

$$\min A_{max}. \tag{1}$$

Under this objective we first divide the map into a grid and develop an ILP based model.

In order to make sure the UAVs do not move more than their max speed between two consecutive time frames, we use

$$\text{dist}_{L(u,t-1)}^{L(u,t)} \leq V, \forall t \in [1,T], \forall u \in \mathcal{U} \tag{2}$$

where, $\text{dist}_{L_i}^{L_j}$ represents the distance between two coordinates L_i and L_j.

Different UAVs are also not allowed to be in the same location at the same time by

$$\text{dist}_{L(u_i,t)}^{L(u_j,t)} > 0, \forall t \in [0,T], \forall u_i, u_j \in \mathcal{U}, i \neq j. \tag{3}$$

Since the data at each IoT may be generated any time, we also make sure that the UAV visits the IoT device's range and downloads or collects its data after its generation time (t_i):

$$V_i^D \geq t_i, \forall i \in \mathcal{I}, \tag{4}$$

where V_i^D denotes the time the UAV downloads the data of IoT i. Note that there could be multiple data generated by the same IoT and this formula applies to all such data.

We implement a flow-based connectivity management idea following the similar implementations in previous works that also consider full connectivity among graph nodes or UAVs [25]:

$$0 \leq F_{i,j}(t) \leq (|\mathcal{U}| - 1) \times A_{i,j}(t), \forall t \in T, \forall i,j \in \mathcal{U}, \tag{5}$$

where $F_{i,j}(t)$ denotes the virtual flow assumed to go from node (i.e., UAV) i to node j at time t. Here, we also use the connectivity information among the UAVs defined by

$$A_{i,j}(t) = \begin{cases} 1, & \text{if } \text{dist}_{L(u_i,t)}^{L(u_j,t)} \leq R_U \\ 0, & \text{otherwise.} \end{cases}, \quad \forall t \in T, \forall u_i, u_j \in \mathcal{U}, u_i \neq u_j. \tag{6}$$

We define the incoming flow to each UAV by

$$I_F(u,t) = \sum_{u!=u'}^{\mathcal{U}} F_{u',u}(t), \forall u \in \mathcal{U}, \forall t \in T. \tag{7}$$

Also, the outgoing flow from each UAV by

$$O_F(u,t) = \sum_{u!=u'}^{\mathcal{U}} F_{u,u'}(t), \forall u \in \mathcal{U}, \forall t \in T. \tag{8}$$

Then, to make sure each UAV, except the initial UAV (i.e., u_0) that starts the flow, keeps one item in the flow before releasing it, we set

$$I_F(u,t) - O_F(u,t) = 1, \forall u \in \mathcal{U} \setminus \{u_0\}, \forall t \in T. \tag{9}$$

Note that we need at least one flow incoming to each UAV so that it is connected to the other UAVs. Moreover, the max incoming flow should be limited by maximum initial flow defined. To satisfy both, we have

$$1 \leq I_F(u,t) \leq |\mathcal{U}| - 1, \forall u \in \mathcal{U} \setminus \{u_0\}, \forall t \in T. \tag{10}$$

The outgoing flow from the initial UAV should be enough to reach all other UAVs, so we have

$$\begin{aligned} O_F(u_0,t) &= |\mathcal{U}| - 1, \forall t \in T & (11) \\ O_F(u_0,t) - I_F(u_0,t) &= |\mathcal{U}| - 1, \forall t \in T & (12) \end{aligned}$$

The outcome of this flow based approach is illustrated in Fig. 3. The so-called source UAV sends enough flow to reach all UAVs and each gets one flow and sends the rest to others.

The connectivity between the UAV and each IoT device is determined based on the distance between the IoT device and each UAV u at a given time t.

$$c_i(u,t) = \begin{cases} 1, & \text{if } \text{dist}_{l_i}^{L(u,t)} \leq R_I \\ 0, & \text{otherwise.} \end{cases}, \quad \forall t \in T, \forall i \in \mathcal{I}, \forall u \in \mathcal{U}$$

We then allow the collection of data by each UAV in range of IoT device in (13) and only one time as defined in (14).

$$d_i(u,t) \leq c_i(u,t), \forall t \in T, \forall i \in \mathcal{I}, \forall u \in \mathcal{U} \tag{13}$$

$$\sum_{u \in \mathcal{U}} \sum_{\forall t \in T} d_i(u,t) = 1, \forall i \in \mathcal{I} \tag{14}$$

In (15), we assign the UAV's IoT visit time to its pre-defined variable V_i^D by multiplying the value of $d_i(t)$ by t and then computing the sum. Since $d_i(t)$ is equal to 1 in only one of the ts, the value of V_i^D becomes equal to the IoT visit time.

$$V_i^D = \sum_{u \in \mathcal{U}} \sum_{\forall t \in T} (d_i(u,t) \times t)), \forall i \in \mathcal{I} \tag{15}$$

Finally, we compute max AoI for any data collected from all IoT devices using the following equation. AoI here is defined as the time elapsed from data generation time t_i to its delivery or upload time at V_i^U, which is equal to V_i^D in this case.

$$A_{max} = \max \left\{ (V_i^D - t_i) \right\}, \forall i \in \mathcal{I} \tag{16}$$

C. Relaxed Problem using Critical Times (P2)

The problem P1 defined in the previous section considers the computation of each UAV's location at each time moment. However, this can be very costly and may not be very critical as long as the data is delivered with the same maximum AoI. To this end, in this section, we introduce an alternative approach in which we maintain the mesh network, ensuring that all UAVs are connected, but only during critical times, which are defined as time instances when a UAV downloads data from an IoT device. Unlike the previous problem, where we divide the total timeline into unit time slots, in this relaxed scenario, the total number of variables on the timeline is equal to the number of IoT devices. By adopting this strategy, we reduce the number of decision variables in the ILP model, thereby calculating the results more rapidly as the time complexity decreases. The sole limitation in this approach is that we cannot ensure the connectivity for all UAVs between the critical times during their flights.

In this problem, the set of locations that we look for each UAV is defined by the number of IoT devices. Let $L = \{L_0, L_1, \dots, L_{|\mathcal{I}|}\}$ represent the set of locations we seek to determine along the UAV's route, and let $T = \{T_0, T_1, \dots, T_{|\mathcal{I}|}\}$ denote the respective time moments. Similar to the previous problem, our primary goal is to minimize the maximum AoI during the data collection process.

In comparison with the previous problem, other than the reduced size of T, we just update Equation 2 as follows:

$$\text{dist}_{L(u,t-1)}^{L(u,t)} \leq V \times (T_t - T_{t-1}), \quad \forall t \in T,\ \forall u \in \mathcal{U}. \tag{17}$$

That is, we just need to make sure the path for each UAV between the critical times is possible within the time difference of critical times considering their max speed.

D. Delivery to Ground Base Stations (P3)

In the third problem, we explore the scenario where the data delivery happens to a ground base station or GBS that is still functioning in the emergency site (no satellite connection from a UAV). In this scenario, we assume there are several GBSs across the map. The UAVs' mission now extends beyond merely downloading data from IoT devices. They must also upload this data to the GBSs. Given this expanded role, we revise the definition of the age of information as the time interval starting when the data is generated by an IoT device and ending when the UAV delivers the data to a GBS. As with the previous problems, our objective remains to maintain the mesh network and ensure connectivity among the UAVs while minimizing the maximum AoI.

Here, we consider an approach similar to previous problem (P2) using variables for only time critical moments. Compared to P2, however, we need to double the number of critical times. This adjustment is necessary because, in this scenario, the UAVs are required to perform two tasks for each data from the IoT devices: first, to download the data from the IoT device, and then to upload it to one of the GBSs. Let $L = \{L_0, L_1, \dots, L_{2|\mathcal{I}|}\}$ denote the set of locations we aim to identify along the UAV's route, and let $T = \{T_0, T_1, \dots, T_{2|\mathcal{I}|}\}$ represent the corresponding set of times. We also define the location of GBSs $\mathcal{G} = \{g_1, g_2, \dots, g_n\}$. Our primary objective remains to minimize the maximum AoI throughout the data collection and delivery process.

In addition to constraint (4), the UAV must deliver the downloaded data to one of the GBSs, and this delivery must occur after one of the UAVs captures the data (all other UAVs get the same data due to mesh network based connectivity among UAVs). Therefore, we add the following constraint to our model:

$$V_i^U \geq V_i^D, \quad \forall i \in \mathcal{I} \tag{18}$$

This ensures that the visit to upload data at a GBS (V_i^U) occurs on or after the visit to download data from an IoT device (V_i^D) for each IoT device i in the set $\mathcal{I}$.

Next, in addition to the connectivity constraint between a UAV and an IoT device for downloading of data as given in (13), we check out the connectivity between the UAV and GBS based on the distance between the GBS and each UAV u at a given time t.

$$g_i(u,t) \quad = \quad \begin{cases} 1, & \text{if } \text{dist}_{l_g}^{L(u,t)} \leq R_G \\ 0, & \text{otherwise.} \end{cases}, \\ \forall t \in T, \forall g \in \mathcal{G}, \forall u \in \mathcal{U}$$

Given that our network is a mesh network and we operate under the assumption that UAVs are always connected, if one of the UAVs is within the range of a GBS, it can upload or deliver the data. This remains valid even if the UAV performing the upload is not the same one that initially downloaded the data. Equation (19) verifies whether at least one of the UAVs is within the range of a GBS. Furthermore, (20) indicates that uploading is feasible if any UAV is within the range of a GBS. To ensure that data from all IoT devices are uploaded to the GBSs, we integrate (21) into our model. We also keep the times for delivering each IoT's data by adding Equation (22) to our model.

$$G(t) = min(1, \sum_{u \in \mathcal{U}} \sum_{\forall i \in \mathcal{G}} g_i(t)), \forall t \in T \tag{19}$$

$$u_i(t) \leq G(t), \forall i \in \mathcal{I}, \forall t \in T \tag{20}$$

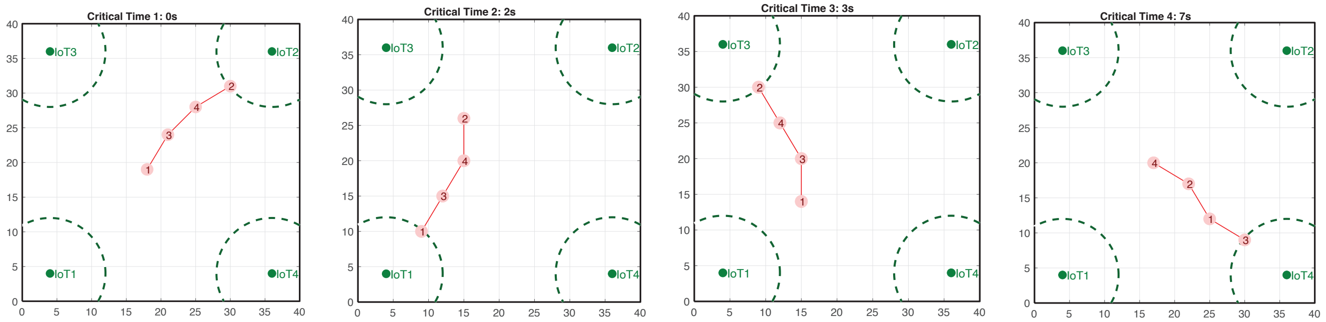
$$\sum_{\forall t \in T} u_i(t) = 1, \forall i \in \mathcal{I} \tag{21}$$

$$V_i^U = \sum_{\forall t \in T} (u_i(t) \times t), \forall i \in \mathcal{I} \tag{22}$$

Finally, in this problem, we compute the maximum AoI for all IoT devices' data using the following equation. In this formula, the AoI for each IoT device is the time elapsed from the data generation time t_i to its delivery time (upload time) to a GBS at time slot V_i^U.

$$A_{max} = \max\left\{(V_i^U - t_i)\right\}, \quad \forall i \in \mathcal{I}. \tag{23}$$

Multiple Objectives: In all problems, our primary objective is to minimize the max AoI. Then, we also set other objectives such as minimizing the average AoI and then minimizing the total path length of UAVs. These objectives are targeted in a



(a) (b) (c) (d)

Fig. 4: The snapshots of the UAV mesh network at four critical times (e.g., data collected from each of the four IoT devices) when backhaul connection is assumed to be made with a satellite connection from one of the UAVs. Data generation times for IoT devices 1 to 4 are 0, 0, 3 and 5, respectively. The resulting optimal maximum AoI is 2.

prioritized manner using scalarization. However, to expedite solution time in ILP solver, we also consider hierarchical solution. That is, we initially just minimize the max AoI and find an optimized answer. In a subsequent step, we add the max AoI as a constraint in our model and aim to reduce the total AoI across all IoT devices. In the third stage, we additionally impose the total AoI as a constraint and focus on minimizing the overall travel distance of the UAVs.

IV. SIMULATION RESULTS

In this section, we present the simulation results for the problems studied using 4 UAVs. Our simulation map is a 40x40 unit grid. For all simulations, the IoT-UAV communication range is set as $R_I = 2$ units, and the UAV-UAV communication range is set as $R_U = 6$ units. In Problems P1 and P2, we look at scenarios with 4 IoT devices positioned at each corner of the map, specifically at coordinates (4,4), (4,36), (36,4), and (36,36). The data from these IoT devices is generated at time slots 0, 0, 3, and 5.

Fig. 4 illustrates the critical moments (t = 0, 2, 3, and 7) in the mission of UAVs as obtained by P2 model. From these results, it is clear that the UAV first collects data from IoT devices 2 and 1 (which start generating data at time 0) at time slots 0 and 2, respectively. It then proceeds to gather data from IoT devices 3 and 4 at time slots 3 and 7. The results show that the AoI for each IoT device is 2, 0, 0, and 2, with a maximum AoI of 2. Note that the results obtained with P1 has the same max AoI but the solution is obtained in a much longer time as it requires a connectivity among the UAVs at all times.

In Fig. 5, we see CPLEX's output for P3. This scenario involves 3 IoT devices and 1 GBS. The UAV-GBS communication range is set as $R_G = 2$ units. The UAV's mission is to collect data from the IoT devices and deliver it to the GBS. The results show that the UAV prioritizes data collection from IoT devices 1 and 3, which start generating data at time 0. After delivering this data to the GBS, the UAV then collects data from IoT device 2, yielding a maximum AoI of 4.

Fig. 6 presents heatmap of the UAV mesh network coverage during their paths. Comparing Fig. 6a and Fig. 6b, we observe that our strategy in P2 enhances UAV movement efficiency. The UAVs tend to position themselves near the map's center, enabling quicker data collection from each IoT device. This demonstrates the advantage of the *critical time* concept introduced in P2 over P1. On the other hand, in P3, the UAVs prioritize collecting data from IoT devices 1 and 3, which have earlier data generation times, before delivering this data to the GBS and then collecting data from the remaining device.

V. CONCLUSION

We have explored the path planning problem for a UAV mesh network that collects data from ground IoT devices considering the minimization of the maximum age of information. We have studied several scenarios where the data delivery to the backhaul happens through satellite connection as well as through a few existing base stations in the area. Depending on the scenario and the associated AoI definition which is determined by the data delivery time to the backhaul, we formulated the problem using ILP to find the optimal path and mesh topology of UAVs towards minimizing the max AoI. We have considered relaxed ILP solutions as well to reduce the time complexity of the solutions. Through simulations, we have shown that the results in different scenarios are optimal and they have pros and cons to one another. In our future work, we will consider more realistic communication models and also study heuristic based solutions which can provide close to optimal ILP results with a much faster running time.

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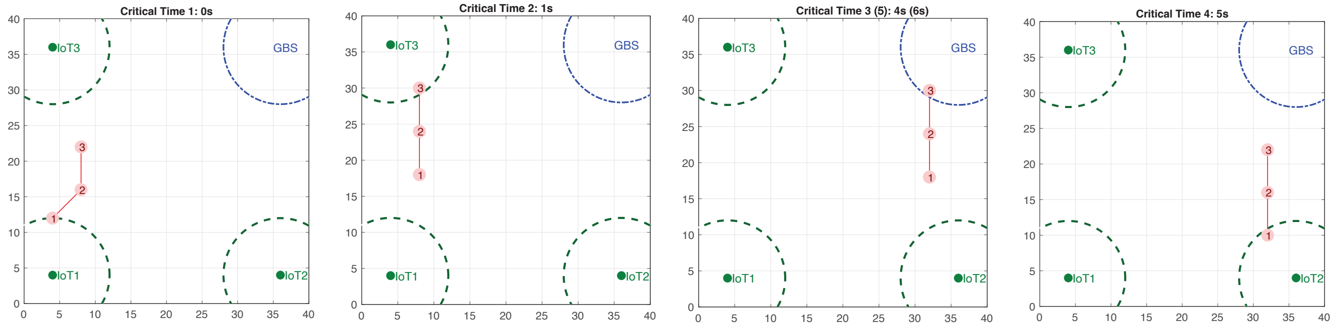
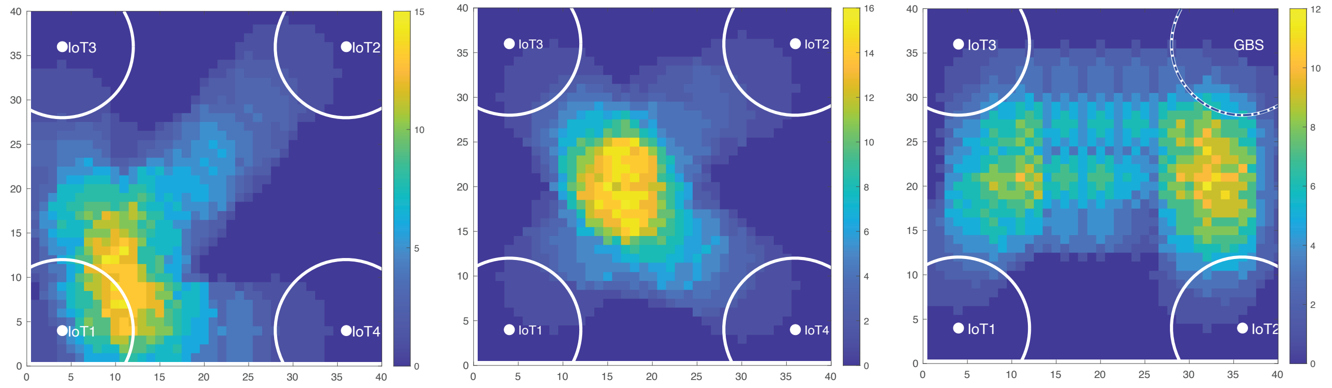


(a) (b) (c) (d)

Fig. 5: The snapshots of the UAV mesh network at five critical times (e.g., data collected from each of the four IoT devices) when the data is delivered to an undamaged base station in the emergency site by one of the UAVs. Data generation times for IoT devices 1 to 3 are 0, 2, and 0, respectively. The resulting optimal maximum AoI is 4.



(a) (b) (c)

Fig. 6: Coverage heatmap of UAV mesh networks during their paths in P1, P2 and P3, respectively.

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