B. Yilmaz, L. Xiang, and A. Klein, "UAV-Assisted Delay-Sensitive Communications with Uncertain User Locations: A Cost Minimization Approach," accepted for presentation in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Sep. 2022.

UAV-Assisted Delay-Sensitive Communications with Uncertain User Locations: A Cost Minimization Approach

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***Abstract*—In this paper, we consider optimal resource allocation for unmanned aerial vehicle (UAV)-assisted delay-sensitive communications, where a UAV flies to deliver time-critical messages to multiple ground users (GUs) as soon as possible. However, the GUs' locations cannot be perfectly known at the UAV, which may jeopardize the timeliness of message delivery to the GUs. To tackle this challenge, we consider a disk-based fixed-rate transmission scheme at the UAV, which can exploit the mobility of the UAV to facilitate timely communications despite uncertain user locations. Consequently, the system performance hinges on the UAV's flight trajectory and the scheduling of GUs, which are further optimized using a cost minimization approach. Thereby, a general class of delay-aware cost functions, referred to as the cost of delivery delay (CoDD), is defined taking into account the diverse delay-sensitivity requirements of the GUs, and we jointly optimize the user scheduling and the UAV's trajectory for minimization of the sum CoDD of all GUs incurred before the UAV's mission completes. The formulated optimization problem is a nonconvex mixed-integer nonlinear program. Exploiting the underlying structure of this problem, we further propose two novel low-complexity solutions based on approximate dynamic programming (DP). Simulation results show that the proposed schemes can flexibly adjust the UAV's flight trajectory and resource allocation according to the GUs' individual delivery delays, delay tolerance, and location uncertainty, which translates into significantly lower sum CoDD for the GUs than several benchmark schemes.**

I. Introduction

Recently, unmanned aerial vehicles (UAVs) have increasingly been exploited for delay-sensitive wireless communications [1]–[4], such as for emergency communications in aftermath of natural disasters, fires, and cyber/terror attacks, as well as industrial and vehicular communications. Thereby, UAVs with flexible mobility are sent to deliver delay-sensitive messages about e.g. situational awareness, contingency plans and decisions, etc. Due to the time-varying nature of the situations, information carried in the given examples is most valuable when promptly delivered to the destined users. To this end, the authors of [1]–[4] either considered delays as hard deadline constraints for resource allocation [1], [2] or investigated minimization of the maximum and average delays in UAV-assisted communications [3], [4]. However, in practical systems, delivery delays may cause different costs/penalties to individual users, which was not considered in [1]–[4]. Also, the resulting costs may be nonlinear functions of individual delivery delays, rather than being linear as in [1]–[4]. Therefore, a general framework for optimizing UAV-aided delay-sensitive communications is crucially needed.

On the other hand, joint optimization of the trajectory and communication for UAV-assisted communications has usually been considered as a key technique for e.g. maximization of communication throughput [5], [6], minimization of the mission completion time [7], or minimization of energy consumption [1], [8]; see also [9] and references therein. However, the existing literature [1], [5]–[7], [9] usually assumes that the users' locations are perfectly known at the UAV during optimization. In practice, users' locations may only be imperfectly known by the UAV due to localization errors, privacy concerns, and/or unpredictable movement of the users [8]. This can further incur communication outages and jeopardize the timeliness of UAV-assisted communication. Hence, for the considered UAV-assisted delay-sensitive communications, *(i) ensuring timely communications against uncertain user locations* is of paramount importance but has rarely been addressed in the literature. Moreover, *(ii) how to capture both the delay sensitivity and delivery delays of individual users and (iii) how to improve the timeliness of UAV-assisted communications via intelligent resource allocation* remain as new research challenges.

To address these challenges, in this paper, we propose a generic framework based on cost minimization for optimizing UAV-assisted delay-sensitive communications, where a UAV is sent to disseminate messages to multiple ground users (GUs) at uncertain locations. Our contributions are:

- We consider a disk-based fixed-rate transmission scheme for UAV-assisted delay-sensitive communications, which can exploit the mobility of the UAV to facilitate timely communications despite GUs' uncertain locations.
- We define a general class of delay-aware cost functions, referred to as the cost of delivery delay (CoDD), to characterize the impact of message delivery delay on individual GUs that may have varying demands and perceive different linear/nonlinear costs.
- We investigate the joint scheduling and trajectory optimization for minimization of the sum CoDD of all GUs. By deriving the optimality conditions and transforming the problem into joint serving order and delivery delay optimization, we further propose two low-complexity suboptimal solutions based on approximate dynamic programming (DP).
- Simulation results show that the proposed schemes can

This work has been funded by the LOEWE initiative (Hesse, Germany) within the emergenCITY center and has been supported by the BMBF project Open6GHub under grant 16KISKO14.

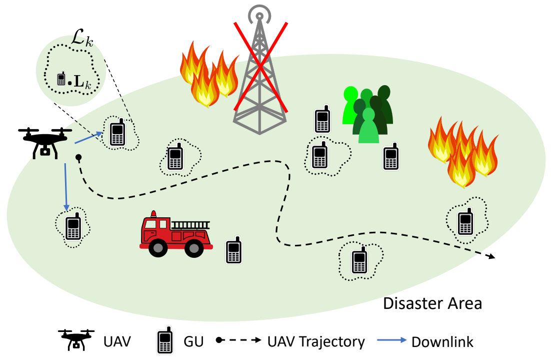


Fig. 1. System model for UAV-assisted delay-sensitive communications with uncertain user locations.

flexibly adjust the user scheduling and the flight trajectory according to the GUs' individual cost functions and location uncertainty, and hence, significantly lower the sum CoDD of all GUs than several benchmark schemes.

II. System Model

As shown in Fig. 1, we consider a UAV-enabled downlink communication system for information transmission to K GUs. The GUs, indexed by k with $k \in \mathcal{K} = \{1, \cdots, K\}$, cannot connect to the ground cellular networks due to e.g. network congestion, malfunction, or sabotage by natural or cyber attacks. Rather, time-critical information required by the GUs is delivered with the help of the UAV [10]. To this end, the UAV loaded with the required messages starts its mission from a given position $\mathbf{S} \in \mathbb{R}^{2\times 1}$ and flies toward the GUs while keeping at a fixed altitude H. The UAV's mission ends when all required messages are delivered.

We consider a continuous-time system, where the time is denoted by t. The horizontal location of GU k, $k \in \mathcal{K}$ is denoted as $\mathbf{L}_k \in \mathbb{R}^{2\times 1}$. However, the UAV can only know the region where GU k may lie in, denoted as $\mathcal{L}_k$, rather than its exact location $\mathbf{L}_k$. Note that $\mathcal{L}_k$ can be an arbitrary set in this work, cf. Fig. 1. On the other hand, the UAV's trajectory $\mathbf{U}(t) \in \mathbb{R}^{2\times 1}$, denotes the UAV's time-varying locations when projected on the ground and is a continuous function of time to be calculated before the mission starts.

A. UAV-to-GU Communication Model

We assume that each GU and the UAV are equipped with a single omnidirectional antenna. Moreover, the UAV serves the GUs via time-division multiple access, where the UAV completes serving the GUs one by one. Let $q_k(t) \in \{0, 1\}$ be a binary variable, where $q_k(t) = 1$ if GU k is scheduled for communication at time t and $q_k(t) = 0$ otherwise. In this paper, we consider fixed-rate transmission at the UAV to lower the signaling overhead and hardware cost of (de)modulation and (de)coding at the UAV and/or the GUs. Thereby, the UAV transmits to GU k with a fixed data rate R_k specified by the GU and a fixed transmit power P_{tx}.

The UAV may experience both line-of-sight (LoS) and non-LoS (NLoS) propagation during flight. By following [11], the pathloss over the UAV-to-GU k link at time t is expressed as $\mathrm{PL}_{k,t} = \left(\|\mathbf{U}(t) - \mathbf{L}_k\|^2 + H^2\right)\cdot \xi/\rho_0$, where $\|\cdot\|$ denotes the Euclidean norm and ρ_0 is the pathloss at the reference distance of 1 m. Here, $\left(\|\mathbf{U}(t) - \mathbf{L}_k\|^2 + H^2\right)/\rho_0$ denotes the attenuation due to free space propagation, and $\xi \in \{\xi_{\text{LoS}}, \xi_{\text{NLoS}}\}$ denotes the additional attenuation for LoS or NLoS propagation over the UAV-to-GU k link. ξ is a Bernoulli random variable with $\Pr(\xi = \xi_{\text{LoS}}) = \mathrm{P}^{\text{LoS}}_{k,t}$ and $\Pr(\xi = \xi_{\text{NLoS}}) = 1 - \mathrm{P}^{\text{LoS}}_{k,t}$ [11], where $\Pr(\cdot)$ is the probability operator. The value of $\mathrm{P}^{\text{LoS}}_{k,t}$ is usually modeled as $\mathrm{P}^{\text{LoS}}_{k,t} = \frac{1}{1+\alpha\ \exp(-\beta(\theta_{k,t}-\alpha))}$, where $\theta_{k,t} = \arctan(H/\|\mathbf{U}(t) - \mathbf{L}_k\|)$ is the elevation angle of the UAV with respect to GU k. α and β are constant coefficients specified for the given environment [11].

Consequently, when $q_k(t) = 1$, the ergodic channel capacity of the UAV-to-GU k link at time t is given as [12]

$$\overline{R}_{k,t} = \mathbb{E}[B \log_2(1 + \gamma_{k,t})], \tag{1}$$

where $\mathbb{E}[\cdot]$ is the expectation operator, B is the bandwidth of the communication signal, $\gamma_{k,t} = \frac{P_{\text{tx}}\rho_0}{B\sigma^2(\|\mathbf{U}(t)-\mathbf{L}_k\|^2+H^2)\xi}$ is the instantaneous receive signal-to-noise ratio (SNR) at GU k, and σ^2 is the power spectral density of additive white Gaussian noise at the GU. Moreover, rate R_k is achievable if and only if $R_k \le \overline{R}_{k,t}$; otherwise, communication outage occurs. However, as GU k's location is only imperfectly known at the UAV, the UAV is unaware of the potential communication outages before transmission starts, resulting in performance loss. To tackle this problem, we require $R_k \le \min_{\mathbf{L}_k \in \mathcal{L}_k} \overline{R}_{k,t}$ such that rate R_k is always achievable at GU k irrespective of its possible location in $\mathcal{L}_k$. As will be shown in Lemma 1 of Sec. IV, this requires the UAV to first fly into a suitably defined disk region and then communicate with GU k only from this disk region. Consequently, the flexible movement of the UAV is exploited to mitigate the impact of uncertain user locations.

B. Delivery Delay and Incurred Cost

For the considered communication scenario, we assume that the UAV will deliver one message for each GU. The message intended for GU $k \in \mathcal{K}$ has a size of M_k bits. Moreover, let Γ_k be the delivery delay of GU k, which is the time duration from the start of the UAV mission till GU k's message is successfully delivered. To capture the importance of delay-sensitive information encoded within the messages, we define the CoDD for serving GU k as

$$C_k = f_k(\Gamma_k). \tag{2}$$

Here, C_k represents the devaluation of the importance, i.e., the cost/penalty of the message intended for GU k or, equivalently, the dissatisfaction of GU k within the delivery delay. $f_k(\cdot)$ can be an arbitrary function satisfying the following properties:

i) (Non-negativity) $f_k(x) \ge 0$, as we focus on evaluating the adverse effects of delayed messages.
ii) (Monotonicity) $f_k(x_1) \ge f_k(x_2)$, $\forall x_1 \ge x_2$, as delayed messages become less valuable and relevant over time for the considered applications.
iii) (Convexity) $f_k(\alpha x_1 + (1-\alpha)x_2) \le \alpha f_k(x_1) + (1-\alpha) f_k(x_2)$, $\forall \alpha \in [0,1], \forall x_1, x_2 \ge 0$, i.e., the rate of

devaluation, or the marginal cost, of each message is non-decreasing with Γ_k.

We note that such CoDD functions are general enough to also model delay-intolerant and delay-insensitive message transmissions by assigning an infinite delivery cost for violating the deadline and a constant cost for any delivery delays, respectively. An example of the CoDD function is

$$C_k = \Gamma_k^{\lambda_k} \cdot \omega_k, \tag{3}$$

where $\omega_k > 0$ denotes a factor of preference of GU k to the incurred delay and $\lambda_k \geq 1$ represents the urgency of the carried information.

III. Problem Formulation

To improve the timeliness of the UAV-assisted fly-and-communicate systems, we further consider joint optimization of the UAV's flight trajectory and communication link scheduling for minimizing the sum CoDD of the GUs incurred before the UAV's mission completes. The resulting optimization problem is formulated as

$$\begin{aligned}
\mathrm{P}_1: &\underset{\mathbf{U}(t),q_k(t),\Gamma_k}{\text{minimize}} \sum\nolimits_{k\in\mathcal{K}} f_k(\Gamma_k) &(4)\\
&\text{s.t. } \mathrm{C1}: \mathbf{U}(0)=\mathbf{S}\\
&\mathrm{C2}: \|\mathbf{U}(t+\Delta)-\mathbf{U}(t)\|/\Delta \leq V_{\max}, \quad 0\leq t\leq T\\
&\mathrm{C3}: q_k(t)\in\{0,1\}, \quad \forall k\in\mathcal{K}, \quad 0\leq t\leq T\\
&\mathrm{C4}: \sum\nolimits_{k\in\mathcal{K}} q_k(t)\leq 1, \quad 0\leq t\leq T\\
&\mathrm{C5}: \int_0^{\Gamma_k} q_k(t)\cdot R_k\cdot \mathbb{I}_{\{R_k\leq \min_{\mathbf{L}_k\in\mathcal{L}_k}\overline{R}_{k,t}\}}dt = M_k, \forall k\in\mathcal{K}\\
&\mathrm{C6}: \Gamma_k\leq T, \quad \forall k\in\mathcal{K},
\end{aligned}$$

where $\mathbb{I}_{\{x\}}$ is the indicator function; we have $\mathbb{I}_{\{x\}}=1$ if x is true, and $\mathbb{I}_{\{x\}}=0$ otherwise. In problem P_1, constraints C1 and C2 specify the starting point and the maximum flying speed of the UAV to be $\mathbf{S}$ and $V_{\max}$, respectively, where Δ is an infinitesimal time difference. C3 and C4 indicate that the UAV transmits to at most one GU at a time. C5 ensures that the UAV can complete data transmission to each GU in the worst case, despite the uncertainty in GUs' locations. Finally, C6 ensures that all GUs are served within time T, due to the limited available energy of the UAV or the requirement of the overall mission.

Problem P_1 is a mixed-integer nonlinear program as it requires joint optimization of the trajectory $\mathbf{U}(t)$ of the UAV, which consists of continuous variables, and the GU link scheduling $q_k(t)$, which is a binary variable. Moreover, as the delivery delays Γ_k are also optimization variables, the trajectory $\mathbf{U}(t)$ is actually an unknown continuous-time function to be optimized over an infinite-dimensional functional space [10], [13]. Finally, due to the indicator function, C5 is a semi-infinite nonconvex constraint, which further complicates the problem solution. Therefore, it is generally difficult to optimally solve problem P_1 within polynomial time.

IV. Proposed Solutions

In this section, we first characterize the properties of the optimal solution for problem P_1. Based on this, we then transform the problem and solve it using approximate DP.

A. Necessary Optimality Conditions

Lemma 1. *Let $g(\mathbf{x}) \triangleq \max_{\mathbf{y}\in\mathcal{L}_k}\|\mathbf{y}-\mathbf{x}\|$ be the maximum distance from point $\mathbf{x}$ to region $\mathcal{L}_k$, which is a convex function. Define the center of region $\mathcal{L}_k$ as $\mathbf{O}_k \in \arg\min_{\mathbf{x}\in\mathbb{R}^{2\times 1}} g(\mathbf{x})$, which minimizes the distance function $g(\mathbf{x})$, with $d_k = g(\mathbf{O}_k)$. Then, for minimization of the sum CoDD, the optimal user scheduling, denoted as $q_k^*(t)$, has to satisfy*

$$q_k^*(t)\cdot\|\mathbf{U}(t)^* - \mathbf{O}_k\| \leq D_k, \tag{5}$$

i.e., the UAV should serve GU k only when it is in a disk centered at $\mathbf{O}_k$ with radius D_k, such that

$$\mathbb{E}_\xi\left[B\log_2\left(1+\frac{P_{\mathrm{tx}}\rho_0}{B\sigma^2((D_k+d_k)^2+H^2)^{\alpha/2}}\right)\right] = R_k. \tag{6}$$

Proof: Note that $\overline{R}_{k,t}$ is a monotonically decreasing function of $\|\mathbf{U}(t)-\mathbf{L}_k\|$. Then, $R_k \leq \min_{\mathbf{L}_k\in\mathcal{L}_k}\overline{R}_{k,t}$ holds if and only if $\max_{\mathbf{L}_k\in\mathcal{L}_k}\|\mathbf{U}(t)-\mathbf{L}_k\| \leq D_k + d_k$. Hence, the UAV can only serve GU k within region $\mathcal{U}_k \triangleq \{\mathbf{U}(t) \mid \max_{\mathbf{L}_k\in\mathcal{L}_k}\|\mathbf{U}(t)-\mathbf{L}_k\| \leq D_k+d_k\}$, outside of which $q_k^*(t)=0$.

Let $\overline{\mathbf{U}}(t)$ be an arbitrary boundary point of $\mathcal{U}_k$, i.e., $\max_{\mathbf{L}_k\in\mathcal{L}_k}\|\overline{\mathbf{U}}(t)-\mathbf{L}_k\| = D_k+d_k$. Due to the triangle inequality, given any $\mathbf{x}\in\mathbb{R}^{2\times 1}$, we have $\max_{\mathbf{L}_k\in\mathcal{L}_k}\|\overline{\mathbf{U}}(t)-\mathbf{L}_k\| \leq \|\overline{\mathbf{U}}(t)-\mathbf{x}\| + g(\mathbf{x})$. This further implies

$$\begin{aligned}
\max_{\mathbf{L}_k\in\mathcal{L}_k}\|\overline{\mathbf{U}}(t)-\mathbf{L}_k\| &\leq \min_{\mathbf{x}}\|\overline{\mathbf{U}}(t)-\mathbf{x}\| + g(\mathbf{x})\\
&\overset{\text{(a)}}{\leq} \|\overline{\mathbf{U}}(t)-\mathbf{O}_k\| + d_k,
\end{aligned} \tag{7}$$

where (a) is due to $d_k = g(\mathbf{O}_k) = \min_{\mathbf{x}} g(\mathbf{x})$. Here, equality condition holds in both inequalities of (7) if and only if $\|\overline{\mathbf{U}}(t)-\mathbf{O}_k\| = D_k$ and $\mathbf{O}_k$ is collinear with $\overline{\mathbf{U}}(t)$ and $\overline{\mathbf{L}}_k \in \arg\max_{\mathbf{L}_k\in\mathcal{L}_k}\|\overline{\mathbf{U}}(t)-\mathbf{L}_k\|$. Therefore, we have $q_k^*(t)=0$ if $\|\mathbf{U}(t)-\mathbf{O}_k\| > D_k$, which implies (5). ■

Note that Lemma 1 still holds if the GUs' locations are perfectly known, i.e., if $\mathcal{L}_k = \{\mathbf{L}_k\}$ is a singleton, where we have $d_k = 0$ and $\mathbf{O}_k = \mathbf{L}_k$. The latter result is consistent with [7, Lemma 1].

Lemma 2. *For minimization of the sum CoDD, the UAV has to fly over straight line segments at the maximum speed between serving any two consecutive GUs.*

Proof: A similar proof has been given in [14] for minimizing the completion time of UAV communications. It can be extended to our considered CoDD minimization problem in a straightforward manner, due to the monotonicity of CoDD functions with respect to (w.r.t.) delivery delay. ■

B. Problem Transformation

As the UAV completes serving the GUs one by one, the whole trajectory can be partitioned into K segments, where each GU is served in exactly one segment. Based on Lemma 2, finding the optimal trajectory reduces to determining the starting and ending points of each segment. In particular, let $\mathbf{u} = [u(1)\ldots, u(K)]$ be the order of the GUs for message delivery, where $\mathbf{u}(\cdot) : \mathcal{K} \to \mathcal{K}$ is a permutation of the GU indices and $u(i) = k$ indicates that GU k is served in the ith place, $i \in \mathcal{K}$. Moreover, let $\mathbf{s}_{u(i)}, \mathbf{e}_{u(i)} \in \mathbb{R}^{2\times 1}$ be the starting and ending points of the UAV's trajectory segment during serving GU $u(i)$. Based on Lemma 1, $\mathbf{s}_{u(i)}$ and $\mathbf{e}_{u(i)}$ have to be within the disk region of GU $u(i)$ specified in (5). Using this notion, the delivery delays for serving two consecutive GUs, $\Gamma_{u(i)}$ and $\Gamma_{u(i-1)}$, satisfy

$$\mathrm{C7} : \Gamma_{u(i)} \geq \Gamma_{u(i-1)} + \frac{\|\mathbf{s}_{u(i)} - \mathbf{e}_{u(i-1)}\|}{V_{\max}} + \frac{M_{u(i)}}{R_{u(i)}}, \quad (8)$$

where $\Gamma_{u(0)} = 0$. In (8), the second and the third terms on the right-hand side denote the time for flying from $\mathbf{e}_{u(i-1)}$ to $\mathbf{s}_{u(i)}$ and communicating with GU $u(i)$, respectively. Moreover, we can reformulate problem P_1 as

$$\begin{aligned}
\mathrm{P}_2 : &\underset{\mathbf{u},\mathbf{s}_{u(i)},\mathbf{e}_{u(i)},\Gamma_{u(i)}}{\text{minimize}} \sum\nolimits_{i=1}^{K} f_{u(i)}\left(\Gamma_{u(i)}\right) \quad (9)\\
&\text{s.t. } \mathrm{C7},\ \overline{\mathrm{C6}} : \Gamma_{u(i)} \leq T, \quad \forall i \in \mathcal{K}\\
&\mathrm{C8} : \|\mathbf{s}_{u(i)} - \mathbf{O}_{u(i)}\| \leq D_{u(i)},\ \forall i \in \mathcal{K}\\
&\mathrm{C9} : \|\mathbf{e}_{u(i)} - \mathbf{O}_{u(i)}\| \leq D_{u(i)},\ \forall i \in \mathcal{K}\\
&\mathrm{C10} : \|\mathbf{s}_{u(i)} - \mathbf{e}_{u(i)}\| \leq M_{u(i)} V_{\max}/R_{u(i)},\ \forall i \in \mathcal{K}.
\end{aligned}$$

In problem P_2, constraints C8 and C9 follow from (5). C10 ensures that the UAV flight satisfies the speed limit, cf. C2, when serving a GU.

Note that for given $\mathbf{u}$, $f_{u(i)}(\cdot)$ is a convex and monotonically increasing function and that $\Gamma_{u(i)}$ is a convex function of $\mathbf{s}_{u(i)}$ and $\mathbf{e}_{u(i)}$. Hence, the objective function is jointly convex w.r.t. $\mathbf{s}_{u(i)}$ and $\mathbf{e}_{u(i)}$ [15]. Moreover, constraints $\overline{\mathrm{C6}}$, C7–10 are also convex. Therefore, problem P_2 is convex when $\mathbf{u}$ is given, and can be efficiently solved using off-the-shelf solvers. However, due to the combinatorial nature of order optimization, a brute-force solution of problem P_2 using exhaustive search has to enumerate over $K!$ visiting orders and solve a convex problem for each order. As each latter step incurs a computational complexity of $\mathcal{O}(K^{3.5})$, where $\mathcal{O}(\cdot)$ is the big-O notation, the resulting overall computational complexity is $\mathcal{O}(K! \times K^{3.5})$. To lower the computational complexity, we propose below two approximate DP-based algorithms to solve problem P_2.

C. DP based Joint Serving Order and Delivery Delay Optimization

We first reformulate problem P_2 as a K-stage DP, where the stages are indexed by $i \in \mathcal{K}$. For this purpose, let us define the state, action, and cost of the DP as follows.

- **State:** We define a state by $(\mathcal{S}^i, k)$, which represents the GUs having been visited, where $\mathcal{S}^i$ is a subset of the GUs with $|\mathcal{S}^i| = i$. Moreover, index k denotes the lastly visited GU in $\mathcal{S}^i$. Using this notion, the initial state is given by $(\varnothing^0, 0)$, where the UAV is at the starting point $\mathbf{S}$ with no GUs served yet. Moreover, there are K terminal states as given by $(\mathcal{S}^K, k)$, $k \in \mathcal{K}$ with $\mathcal{S}^K \equiv \mathcal{K}$, where the UAV finishes serving all GUs with GU $k \in \mathcal{K}$ being lastly served.
- **Action:** At state $(\mathcal{S}^i, j)$, the UAV selects a GU from $\mathcal{K} \setminus \mathcal{S}^i$ to serve in the next stage.
- **Cost:** Assume that GU $k \in \mathcal{K} \setminus \mathcal{S}^i$ is selected as action at state $(\mathcal{S}^i, j)$. The system then transits to a new state $(\mathcal{S}^{i+1}, k)$, where $\mathcal{S}^{i+1} = \mathcal{S}^i \cup \{k\}$ and $j \neq k$. This transition incurs a cost of a^i_{jk}, for $j, k \in \mathcal{K} \cup \{0\}$, which accumulates over stages. Let $\Gamma^{\mathcal{S}_i}_j$ be the delivery delay of GU j in state $(\mathcal{S}^i, j)$. Moreover, let t_{jk} be the time difference between the completion of serving GU j and GU k, where $t_{jk} = \Gamma^{\mathcal{S}^{i+1}}_k - \Gamma^{\mathcal{S}^i}_j = \frac{\|\mathbf{s}_k - \mathbf{e}_j\|}{V_{\max}} + \frac{M_k}{R_k}$. Then, according to problem P_2, we can define the cost as

$$\begin{aligned}
a^i_{jk} = &\min_{\mathbf{s}_k, \mathbf{e}_j} \sum\nolimits_{m \in \mathcal{K}\setminus\mathcal{S}^i} \Big(f_m(\Gamma^{\mathcal{S}_i}_j + t_{jk}) - f_m(\Gamma^{\mathcal{S}_i}_j) \Big) \quad (10)\\
&\text{s.t. } \|\mathbf{s}_k - \mathbf{O}_k\| \leq D_k,\ \|\mathbf{e}_j - \mathbf{O}_j\| \leq D_j,
\end{aligned}$$

which is the sum CoDD accumulated by GU k and the unvisited GUs during the time t_{jk}. The cost incurred when transiting from initial state to stage 1 is given as $a^0_{0k} = \sum_{m\in\mathcal{K}} f_m(t_{0k})$. Note that the optimization problem in (10) is convex. If this optimization problem is infeasible, e.g. when the lastly visited GU k does not meet C6, we let $a^i_{jk} = \infty$.

Now, let us introduce the value function of state $(\mathcal{S}^i, k)$, denoted as $J(\mathcal{S}^i, k)$, which gives the minimum accumulated CoDD, incurred from the starting point till the completion of serving each GU in $\mathcal{S}^i \subset \mathcal{K}$, with GU k served in stage i. The value function is defined recursively as [16]

$$J(\mathcal{S}^i, k) = \min\nolimits_{j\in\mathcal{S}^{i-1}} [J(\mathcal{S}^{i-1}, j) + a^{i-1}_{jk}]. \quad (11)$$

By convention, the value function of the initial state is just zero, i.e., $J(\varnothing^0, 0) = 0$, where the UAV has not started its movement. The value function of a terminal state ending at GU k, i.e., $J(\mathcal{S}^K, k)$, gives the minimum sum CoDD accumulated by all users starting from the initial state till every GU has been served, with GU k being lastly served. Therefore, problem P_2 is reduced to minimizing the value functions over all possible terminal states in the DP problem.

The value function $J(\mathcal{S}^i, k)$ can be calculated iteratively using the forward DP algorithm [16]. The overall procedure for solving the formulated DP problem is summarized in Algorithm 1. We note that when GU k is selected to be visited next, all states $(\mathcal{S}^{i-1}, j)$, $j \in \mathcal{S}^{i-1}$, which only differ in the lastly visited GU, will transit to state $(\mathcal{S}^{i-1} \cup \{k\}, k)$. While calculating $J(\mathcal{S}^{i-1} \cup \{k\}, k)$ in (11), let β^k_i, $k \in \mathcal{K}$, $i \in \mathcal{K}$ be the optimal solution of the right-hand side problem of (11), i.e.,

$$\beta^k_i \in \arg\min\nolimits_{j\in\mathcal{S}^{i-1}} [J(\mathcal{S}^{i-1}, j) + a^{i-1}_{jk}]. \quad (12)$$

Here, β^k_i gives the visited GU in stage $i-1$ before visiting GU k in stage i, where $\beta^0_0 = 0$ since there is no previous GU. The side information encoded in β^k_i can be exploited to determine the optimal visiting order after knowing the value function of the state.

Let us define one DP iteration for stage $i \in \mathcal{K}$, cf. lines 4–10, as follows. First, let Ξ_i be the set of states $(\mathcal{S}^i, k)$ in stage i.

Algorithm 1 Proposed approximate DP algorithm for solving problem P_2

1: **Input:** Given $V_{\max}, \{\mathcal{L}_k, R_k, M_k\}_{k=1}^K$
2: **Initialization:** Set $\Xi_0 \triangleq \{(\varnothing^0, 0)\}$, $J(\varnothing^0, 0)=0$, $\beta_0^0=0$, $\Gamma_0^0=0$; Calculate $\{\mathbf{O}_k, D_k\}_{k=1}^K$ ▷ Eq. (6)
3: **for** $i = 1 : K$ **do** ▷ For each stage i
4: Set $\Xi_i = \varnothing$
5: **for** $(\mathcal{S}^{i-1}, j) \in \Xi_{i-1}$ **do**
6: Calculate costs a_{jk}^{i-1}, $k \in \mathcal{K} \setminus \mathcal{S}^{i-1}$ ▷ Eq. (10)
7: Calculate $J(\mathcal{S}^{i-1} \cup \{k\}, k), k \in \mathcal{K} \setminus \mathcal{S}^{i-1}$ ▷ Eq. (11)
8: Collect side information: β_i^k, $\Gamma_k^{\mathcal{S}_i}$ ▷ Eq.(12)
9: Update $\Xi_i = \Xi_i \cup (\mathcal{S}^{i-1} \cup \{k\}, k)$
10: **end for**
11: **end for**
12: Calculate $u(K) = \arg\min_{k \in \mathcal{K}} J(\mathcal{S}^K, k)$
13: **for** $i = K-1 : 1$ **do** Calculate $u(i) = \beta_{i+1}^{u(i+1)}$
14: **end for**
15: **Output:** $\mathbf{u} = [u(1), \ldots, u(K)]$

Ξ_i is initialized to be an empty set, $\varnothing$, in line 4. For each state $(\mathcal{S}^{i-1}, j) \in \Xi_{i-1}$ with $j \in \mathcal{S}^{i-1}$, we then identify all possible new states that can be reached in stage i and associated costs, cf. line 6. Meanwhile, for each obtained new state, denoted as $(\mathcal{S}^{i-1} \cup \{k\}, k)$, we calculate the value function $J(\mathcal{S}^{i-1} \cup \{k\}, k)$ in line 7 based on $J(\mathcal{S}^{i-1}, j)$ and a_{jk}^{i-1}. Additionally, we collect the side information for the obtained state, cf. line 8. Finally, these new states are stored in Ξ_i, cf. line 9.

The DP iteration continues until the terminal states are reached, cf. lines 3-11, where Ξ_K has K terminal states and the minimum costs needed to reach each of them, i.e., $J(\mathcal{S}^K, k)$, are known. Hence, we can now find an approximate optimal visiting order by selecting the terminal state $(\mathcal{S}^K, k)$ with the lowest cost among all terminal states, cf. line 12, and tracking β_K^ks backwards from Ξ_K to Ξ_1, cf. line 13–14. After obtaining the visiting order, P_2 can be further solved to compute the exact user scheduling and the UAV's trajectory.

The proposed DP algorithm finds an approximate optimal visiting order for problem P_2 with a computational complexity of $\mathcal{O}(K^2 \times 2^K \times K^{3.5})$ [16], which is much lower than $\mathcal{O}(K! \times K^{3.5})$. For example, when $K = 16$, we can reduce the computational complexity by $\frac{K!}{K^2 \times 2^K} > 10^6$ times. Note that the proposed DP algorithm becomes the exact DP algorithm when the state definition is altered such that, the subset representing GUs have been visited $\mathcal{S}^i$ is replaced by a vector which represents GUs having been visited with exact order, i.e. $[u(1), \ldots, u(i)]$. In this case, the optimal solution of problem P_2 can be obtained, but the resulting computational complexity is similar to that of exhaustive search.

D. Joint Serving Order and Delivery Delay Optimization with Problem Approximation

Algorithm 1 may become computationally intensive when K is large, as it requires solving an optimization problem for calculating cost of each state in (10). To further lower the computational complexity, in this section, we provide another DP algorithm to solve an approximate problem of P_2.

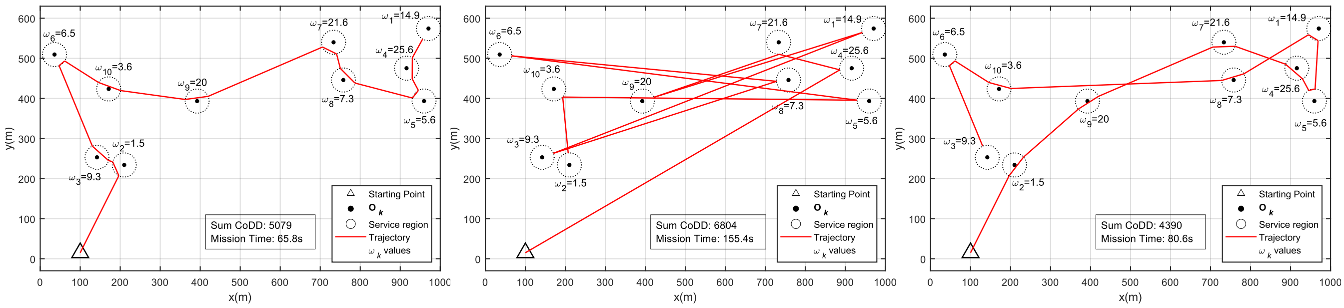
In particular, assume that the UAV has to hover over $\mathbf{O}_k$ till completing the information transmission to GU k, $k \in \mathcal{K}$. In this case, based on Lemma 2, the optimal trajectory is given by the line segments connecting the GUs according to the optimal serving order, where the starting and ending points of each trajectory segment coincide with the hovering points of the UAV. Consequently, problem P2 reduces to finding only the visiting order of the GUs that minimizes the sum CoDD within time T, which can be solved in two steps.

In the first step, we optimize the order of visiting GUs by solving the approximate problem of P_2, where $q_k(t) \cdot \|\mathbf{U}(t) - \mathbf{O}_k\| = 0$, $\forall k \in \mathcal{K}$. To this end, Algorithm 1 can be applied by replacing starting and ending points of line segments with $\mathbf{O}_k$, $k \in \mathcal{K}$. Therefore, instead of an optimization in (10), t_{jk} could be calculated as $\frac{\|\mathbf{O}_k - \mathbf{O}_j\|}{V_{\max}} + \frac{M_k}{R_k}$. In the second step, we optimize the exact user scheduling and the UAV's trajectory by solving P_2 for given serving order, which is a convex optimization problem. The resulting overall computational complexity reduces to $\mathcal{O}(K^2 \times 2^K)$ as no optimization is needed in each state, which is several orders lower than that of Algorithm 1 when $K \gg 1$. Note that both algorithms in Section IV-C and Section IV-D are based on joint serving order and delivery delay optimization, which necessarily incur an exponential computational complexity of $\mathcal{O}(2^K)$. This complexity hurdle may be further overcome by heuristic solutions based on e.g. greedy search; however, our simulation results in Section V indicate that this may result in a non-negligible performance loss.

V. Performance Evaluation

In this section, we evaluate the performance of the proposed schemes via simulation. The considered UAV flies at an altitude $H = 50$ m to communicate with K GUs in an area of 1000 m $\times$ 600 m. Note that the location region of GU k, $\mathcal{L}_k$, can be an arbitrary set provided its center, $\mathbf{O}_k$, and maximum distance to the center, d_k, are given, cf. Lemma 1. In the simulation, for given d_ks, $\mathbf{O}_k$s are randomly and uniformly placed in the considered area. In the special case of $d_k = 0$, we assume $\mathbf{L}_k = \mathbf{O}_k$. The starting location of the UAV is fixed at $(100, 15)$. The maximum speed and mission completion time of the UAV are $V_{\max} = 50$ m/s and $T = 200$ sec, respectively. Message sizes M_k are randomly and uniformly selected from set $\{0.3, 0.6, 0.9, 1.2, 1.5\}$ MBytes. For transmission to the GUs, the UAV is allocated a bandwidth $B = 0.1$ MHz and employs a transmit power of $P_{\text{tx}} = 10$ mW, where channel power gain $\rho_0 = 1$. We consider air-to-ground communication in an urban area, where the channel parameters are given as $\sigma^2 = -137$ dBm/Hz, $\xi_{\text{LoS}} = 1.12$, $\xi_{\text{NLoS}} = 10$, $\alpha = 12.08$, and $\beta = 0.11$ [11]. The data rate R_k of the UAV-to-GU k link is set according to (6), where we set $D_k \equiv D$ and $d_k \equiv d$; the values of D and d are later specified. In the simulations we consider the CoDD function stated in (3), with tolerance paramaters $\gamma = 1$ and $\omega_k = \frac{M_k}{R_k} \cdot m$, for m being randomly and uniformly chosen from the interval $[1, 10]$.

Fig. 2 shows the trajectories obtained by approach proposed in Section IV-C, referred to as Proposed Scheme 1, and



(a)

(b)

(c)

Fig. 2. Trajectories obtained by (a) Baseline Scheme 1, (b) Baseline Scheme 2, and (c) Proposed Scheme 1.

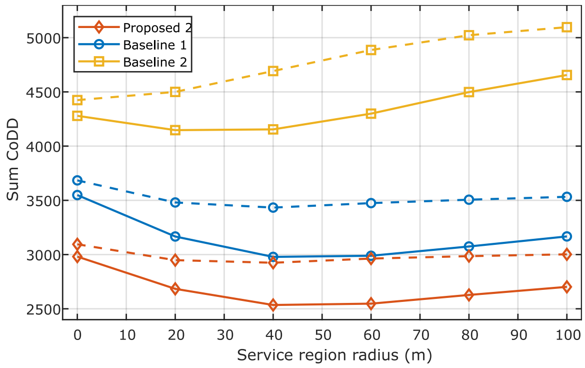


Fig. 3. Sum CoDD of the considered schemes versus radius of service disk, D, considering 12 GUs. Cases of certain ($d = 0$ m) and uncertain ($d = 30$ m) GU location knowledge shown with solid and dashed lines respectively.

benchmarks for the same scenario setting with $K = 10$ GUs and $d = D = 30$ m. The values of individual delay preference factors, i.e. ω_ks, are also shown next to each GU location. The Baseline Scheme 1 minimizes the length of the flight path and, hence, completes the mission in the shortest amount of time; however, by ignoring the GUs' individual tolerance to stale information, it leads to a higher sum CoDD than the Proposed Scheme 1. On the contrary, Baseline Scheme 2 determines the visiting order solely based on the tolerance of GUs', i.e. ω_k, but ignores the distances between the GUs. As a result, Baseline Scheme 2 leads to the longest traveling distances and delivery delays, which severely penalizes the sum CoDD. On the other hand, we note that with the Proposed Scheme 1, the UAV starts with serving the GUs located at the right top of the area, similar to Baseline Scheme 2, since these GUs have larger preference factors, i.e. higher costs caused by delivery delay. However, unlike Baseline Scheme 2, Proposed Scheme 1 also serves GUs with low preference factors whenever possible, to reduce back-and-forth flights between GUs. Hence, Proposed Scheme 1 can flexibly balance between flight distances and the preference factors of the GUs, for which it achieves the lowest sum CoDD despite the fact that it has a longer trajectory than the one obtained with Baseline Scheme 1.

Fig. 3 evaluates the sum CoDD of the considered schemes versus the radius of service disk, D, for certain (i.e., d=0 m) and uncertain (d=30 m) GU locations, which are shown in solid and dashed lines, respectively. Here, approach proposed in Section IV-D, referred to as Proposed Scheme 2 is included for computational convenience. Provided results are simulated with K=12 GUs and each point is averaged over a number of independent realizations for given parameter settings. From Fig. 3 we observe that, when the GUs' locations are perfectly known, the sum CoDD of all considered schemes decreases and increases with D in the small and large regimes, respectively. This is because, for small Ds (e.g., when $D < H$), the UAV-to-GU communication experiences a high likelihood of LoS propagation, whereby relatively high data rates can be achieved according to (7); in this case, increasing D rarely affects the communication time but can significantly reduce the flight time, as the UAV can initiate communication to the GUs within a larger disk and reduce the flight distance. On the contrary, for large Ds (e.g., when $D > H$), the likelihood of LoS propagation reduces significantly, as D increases; hence, according to (7), the data rate for fixed-rate transmission significantly reduces, which penalizes the communication time. Therefore, there exists an optimal radius of the service disk that strikes the best trade-off between flight time and communication time.

Fig. 3 also shows that, when the GUs' locations are uncertain, the same trade-offs can also be observed for the Baseline Scheme 1 and the Proposed Scheme 2, except that they suffer from non-negligible performance losses. To mitigate potential communication outages caused by uncertain GU locations, the UAV-to-GU communication has to lower its data rate and hence requires a longer time for communication. However, for the Baseline Scheme 1, the increase of communication time even exceeds the decrease of flight time, such that its sum CoDD always increases with D for the considered settings of uncertain GU locations. Nevertheless, compared with the Baseline schemes, the Proposed Scheme 2 always achieve the best performance for both certain and uncertain GU locations. For example, when D=40 m and d=30 m, the sum CoDD of the Proposed Scheme 2 is 60% (18%) lower than that of Baseline Scheme 2 (Baseline Scheme 1), by exploiting knowledge of flight distances and the tolerance factors for trajectory planning.

Finally, Fig. 4 evaluates the CoDD performance of the considered schemes for different number K of GUs. Provided

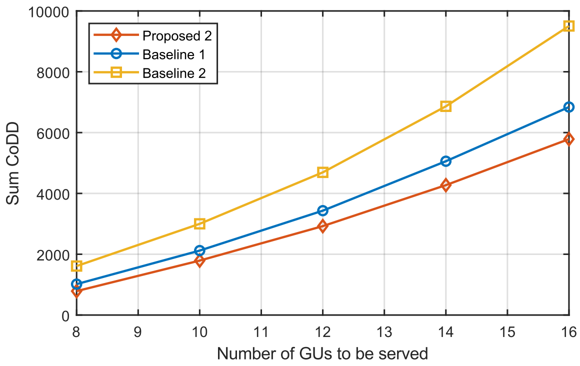


Fig. 4. Sum CoDD of the considered schemes versus number of GUs, K.

results are simulated with $d = 30$m and $D = 40$m and each point is averaged over a number of independent realizations for given parameter settings. From Fig. 4 we observe that the performance gap between the Proposed Scheme 2 and the considered Baseline schemes increases as the number of GUs grows. This is because, with a large number of GUs, the Proposed Scheme 2 has more degrees of freedom (e.g. more GUs may be tolerant to stale information and the UAV is now allowed to transmit in a larger area) in optimizing the GU scheduling and the UAV trajectory; therefore, the proposed scheme can achieve large performance gains over the baseline schemes. For example, for $K = 16$, the sum CoDD of the Proposed Scheme 2 is 66% (20%) lower than that of Baseline Scheme 2 (Baseline Scheme 1).

VI. Conclusion

In this paper, we proposed a generic framework for joint optimization of the scheduling of GUs and the UAV's trajectory so as to minimize the sum CoDD in UAV-assisted delay-sensitive communications. Thereby, a disk-based fixed-rate transmission was investigated for facilitating timely communications despite uncertain user locations. Moreover, the individual GUs' costs caused by message delivery delays were modeled using a class of delay-aware cost functions. Exploiting the underlying structure, we proposed two approaches to solve the formulated optimization problem, which determine the order of serving the GUs via approximate DP followed by further fine-tuning the exact link scheduling and UAV trajectory via convex optimization. Simulation results showed that the proposed schemes can achieve significantly lower sum CoDD than several baseline schemes, as the former can flexibly balance between the traveled distances and the GU's tolerances of delivery delays in optimizing the GUs' serving order.

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