Energy-efficient Trajectory Planning and Speed Scheduling for UAV-assisted Data Collection

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***Abstract*—Unmanned aerial vehicle (UAV) assisted data collection is a promising technology, where a base station (BS) is mounted on a UAV to collect data from ground sensors (GSs). However, it is very challenging to save the energy of UAV while completing the tasks of data collection. In this work, a novel energy consumption model of UAV is adopted, where the UAV flies at a proper speed is the most energy efficient, *i.e.,* the UAV will cost more energy when it flies faster or slower. According to this model, we investigate the Energy-efficient Trajectory Planning and Speed Scheduling (*ETPSS*) problem, aiming at minimizing the total energy consumption of UAV by determining flight trajectory and speed of UAV while completing the task of data collection for each GS. To solve this problem, we decompose it into two sub-problems, i.e., trajectory design and speed scheduling, and propose a three-step scheme named Energy-efficient Trajectory and Speed Optimization (*ETSO*). Moreover, the second step of *ETSO* optimally solves the speed scheduling sub-problem. Finally, we conduct simulation experiments, and the results demonstrate that the *ETSO* performs well on energy efficiency.**

***Index Terms*—UAV, Data Collection, Energy Saving, Trajectory Planning, Speed Scheduling**

I. INTRODUCTION

With the popularity of Internet of Thing (IoT), billions of ground sensors (GSs) in IoT are deployed widely to apply in scenarios such as smart city and smart transportation. These GSs aim to collect data and periodically uploads the data to nearby base stations (BSs) for further analysis. However, most GSs are limited by its maximum battery storage, and are sometimes deployed in area far from the BS. Directly uploading data to the remote BS is quite energy consuming, for long-distance transmission will cost much energy. Therefore, it is critical to reduce energy consumption of GSs by cutting down the transmission distance between the BS and GSs.

UAV-assisted data collection is a promising technology and has attached much attention [1]. By deploying a small BS on UAV, the UAV collects data from GSs when it flies close to them. In such way, energy consumption of GSs is reduced, for transmission distances between the UAV and GSs are shortened. Compared to method utilizing ground base station, UAV-assisted data collection is more flexible due to its high mobility [2][3], and has been widely applied for military and civil use. A scenario of the UAV-assisted data collection is illustrated in Fig. 1. In this figure, a UAV-mounted BS is utilized to collect data from a group of GSs when flying close to them.

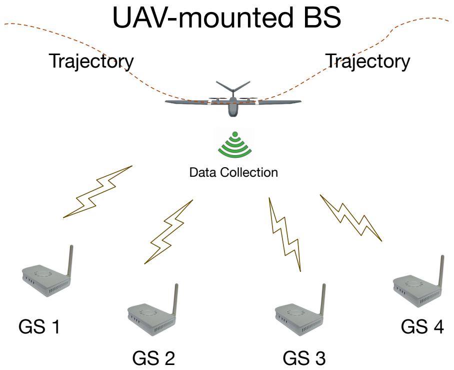

Fig. 1: An illustration of UAV-assisted data collection scenario, where a small BS is mounted on UAV to collect data from GSs when flying close to them.

Currently, many research works have been conducted to study the UAV-assisted wireless communication [3, 4, 5, 6, 7, 8, 9, 10, 11, 12], mainly focusing on trajectory planning and data transmission. Among all of these works, energy is important for UAV, for on-board energy fundamentally limits its working time. However, when taking energy consumption into consideration, existing literatures either ignore influence of propulsion energy [11, 12] or utilize a simple energy consumption model for the UAV [4, 6, 7, 11, 12]. According to works [1, 5], propulsion energy occupies nearly 95% of UAV's total energy. These research works also reveal that propulsion energy is affected by the flight speed of UAV largely . Thus, allocating the proper flight speed to the UAV is feasible to reduce its energy consumption. However, in related works, they only consider coarse-grained energy consumption model. For instance, some of them [4, 8, 9] assume that propulsion energy is a linear function to flight speed. Other works [6, 7] assume proportion energy is proportion to square of flight speed. Thus, a sophisticated propulsion energy consumption model for UAV is adopted in this work, where UAV flies at a proper speed consumes the minimum energy, *i.e.,* it will cost more energy when flying faster or slower.

This paper aims to minimize UAV's energy consumption by finding out the proper flight speed and trajectory while completing tasks of data collection.

The main challenges are summarized as follows:

- Trajectory and flight speed are two factors considered to reduce energy consumption of UAV. For example, the UAV that flies along the longer trajectory may sometimes save energy, and the UAV that flies at lower speed might consume more energy. Therefore, it is essential to find a method that considers the trajectory planning and speed scheduling of UAV together to minimize its energy consumption.
- In reality, there exists a flight speed v^* that the UAV costs the least energy, *i.e.,* it will cost more energy when flying faster or slower. However, task from each GS has its own data amount, and the UAV sometimes does not have enough time to collect all the data with flight speed v^*. Therefore, finding out a feasible speed of UAV to minimize its energy consumption while completing the task of data collection in time is also important.

The main contributions of this paper are listed as follows:

- We propose a UAV-assisted data collection scenario and adopt a novel flight energy consumption model [1] in this work, where the UAV has a proper speed that consumes the least energy, *i.e.,* the UAV will cost more energy when flying faster or slower.
- The Energy-efficient Trajectory Planning and Speed Scheduling (*ETPSS*) problem is formulated, which aims at minimizing UAV's energy by allocating proper trajectory and flight speed to it while completing the tasks of data collection. We then decompose the *ETPSS* problem into two sub-problems and present a three-step scheme named Energy-efficient Trajectory and Speed Optimization (*ETSO*).
- We present the Optimal Speed Scheduling Algorithm (*OSSA*), which is the second step of *ETSO*, to optimally solve the speed scheduling sub-problem in *ETPSS* by determining UAV's proper flight speed.
- We conduct several experiments to show the performance of *ETSO*. The simulation results reveal that the *ETSO* scheme performs well on energy efficiency.

The following paper is organized as follows. In section II, network model and energy consumption model are introduced and the *ETPSS* problem is formulated based on these models. In section III, we propose a three-step *ETSO* scheme to solve the *ETPSS* problem. Finally, the experiment results are provided in section IV, and the paper is concluded in section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. Network model

There are m GSs deployed in an open area, named as $M = \{SN_1, SN_2, ..., SN_m\}$. Each GS is located in (x_i, y_i) and has a communication range of Cr_i with c_i data to be uploaded, where $i = \{1, 2, ..., m\}$. A small BS is mounted on UAV, and the UAV takes off from airport located at point u, i.e., location (u_a, u_b). The altitude of UAV is H, and the it flies around to collect data from m GSs. The UAV is only allowed to collects data from GS when flying close to them, and it is capable of receiving data from at most a one GS each time.

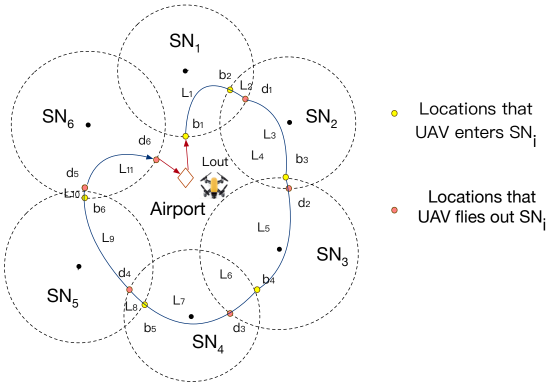

Fig. 2: An illustration of network model. The UAV-mounted BS flies along a trajectory $L = \{L_1, L_2, ...\}$ to collect data from m GSs. Trajectory L intersects the range circle of SN_i at b_i and d_i, and the UAV is only allowed to serve SN_i between b_i and d_i.

We define R as transmission rate between the UAV and a GS, which is a fixed value known in advance. Therefore, the service time for GS i is $t_i = \frac{c_i}{R}$. We assume the communication range of each GS overlaps with at most one of its neighboring GSs, for GSs are not intensively deployed in our scenario, which is shown in Fig. 2.

Assuming the UAV flies along trajectory L and collects data from SN_1 to SN_m. We define set D as 'key points' illustrating intersecting points between trajectory L and range circles of each GS. Specifically, point $b_i \in D$ and $d_i \in D$ are denoted as 'entering key point' and 'departing key point', representing points that the UAV enters or departs from communication range of SN_i. Since we assume each GS is overlapped with at most one of its neighboring sensors, the set of D can be illustrated as $D = \{D_1 = b_1, D_2 = b_2, D_3 = d_1, D_4 = b_3, ..., D_{2m} = d_m\}$. The airport and $2m$ key points divide trajectory L into $2m+1$ parts, denoted as $L = \{L_1, L_2, ...L_{2m+1}\}$ and length of curve L_i is defined as:

$$l_i = \int_{L_i} \mathrm{d}l \tag{1}$$

B. Energy consumption model

Communication energy and propulsion energy are two parts that should be considered in energy consumption model. However, in reality, the propulsion energy of UAV is much larger than its communication energy. Thus, we only take propulsion energy of UAV into consideration. We adopt the propulsion energy model from [1],

$$p = c_1 \cdot v^3 + \frac{c_2}{v}, \tag{2}$$

where p denotes the UAV's propulsion power, and two parameters c_1, c_2 are affected by UAV's weight and length of wings. It is obvious that power p is related to UAV's flight speed, and there exists an optimal flight speed v^* that the UAV will cost more energy when it flies faster or slower.

Then, the minimum energy-consumption flight speed v^* can be worked out. The derivation of Eq. (2) is:

$$p'(v) = (3c_1 \cdot v^2 - \frac{c_2}{v^2})$$

We then work out speed v^* as:

$$v^* = \sqrt[4]{\frac{c_2}{3c_1}} \tag{3}$$

C. Problem formulation

A graph model $G = (D \cup \{u\}, L)$ is utilized to formulate the problem, where D is the set of key points, u is the point of airport, and L is the trajectory of UAV. We first introduce constraints and formulate the *ETPSS* problem.

We define the straight distance between two points a and b as $dis(a, b)$. For each two neighboring key points D_i and D_{i+1}, trajectory L must obey the *shortest trajectory constraints*, i.e., length of trajectory between D_i and D_{i+1} must be larger than straight distance between them.

$$\int_{L(D_i,D_{i+1})} \mathrm{d}l \geq dis(D_i, D_{i+1}). \tag{C1}$$

where $L_{(D_i,D_{i+1})} \in L$ represents trajectory path between point b_i and d_i in L.

Besides, the UAV has to spend at least t_i time collecting data from each GS SN_i within its communication range (b_i, d_i), which is:

$$\int_{L(b_i,d_i)} \frac{\mathrm{d}l}{v(l)} \geq t_i, i \in \{1, 2, ..., m\} \tag{C2}$$

where $v(l)$ denotes the flight speed of UAV in curve $l \in L$.

However, since two neighboring GSs' communication ranges are overlapped, the UAV might collect data from SN_{i-1} or SN_{i+1} while flying within communication range of SN_i. The following constraint is proposed to let the UAV collects data from the first i sensors within accumulative deadline $\sum_i^m t_i$:

$$\int_{L(b_1,d_i)} \frac{dl}{v(l)} \geq \sum_i^m t_i, i \in \{1, 2, ..., m\} \tag{C3}$$

Constraints (C2) and (C3) describe the *service time constraints* of this problem. However, if the UAV flies slower, more time will be spent to finish trajectory L, which also consumes more energy. Thus, we define a deadline T for all sensors, where $T = \sum_{i=1}^m t_i$. The *deadline constraint* is written as:

$$\int_{L(b_1,d_m)} \frac{dl}{v(l)} \leq T. \tag{C4}$$

Finally, all key points $b_i, d_i \in D$ must be located on the range circle of each sensor, denoted as:

$$dis(b_i, SN_i) = dis(d_i, SN_i) = Cr_i, i \in \{1, 2, ..., m\} \tag{C5}$$

According to the propulsion energy consumption model in Eq. (2), we have the propulsion power $p(l)$ as $p(l) = c_1 \cdot v(l)^3 + \frac{c_2}{v(l)}, \forall l \in L$. Therefore, the total energy consumption of the UAV is:

$$E = \int_L p(l) \frac{\mathrm{d}l}{v(l)} \tag{4}$$

We now define the $ETPSS$ problem as follows:

Definition 1 (ETPSS problem): A UAV-mounted BS is dispatched to collect data from m GSs. Each GS has an individual data transmission task c_i with its own service time t_i. How to optimize the flight trajectory and speed and minimize UAV's energy while satisfying the constraints expressed above?

We formulate the *ETPSS* problem in (P1).

$$(P1) : \min_{v(l),L} \quad \int_L p(l) \frac{\mathrm{d}l}{v(l)} \tag{5}$$

$$\text{s.t.} \quad (C1), (C2), (C3), (C4), (C5) \tag{6}$$

III. PROBLEM DECOMPOSITION AND ALGORITHM DESIGN

It is hard to solve the *ETPSS* problem by using mathematical tools, e.g., variable L is corresponding to another variable $v(l)$. We then decompose the *ETPSS* problem into two subproblems, i.e., Shortest Trajectory Design (*STD*) and Flight Speed Scheduling (*FSS*)

Definition 2 (STD problem): A UAV-mounted BS is dispatched to collect data from m GSs. How to find a shortest trajectory for UAV while flying through the locations of all GSs?

We express the mathematical model of *STD* problem in (P2),

$$(P2) : \min_{L} \quad \int_L \mathrm{d}l \tag{7}$$

$$\text{s.t.} \quad (x_i, y_i) \in L, \forall i \in M \tag{8}$$

where Eq. (9) illustrates that location of all GSs must be included in trajectory L.

Since trajectory L_{out} (seen as red lines in Fig. 2) outside the communication ranges of all GSs does not have the *service time constraints*, the flight speed for trajectory L_{out} can be worked out in advance. We only consider speed scheduling problem along trajectory $L(D_1, D_{2m})$.

Definition 3 (FSS problem): A UAV-mounted BS is dispatched to collect data from m GSs in a certain trajectory $L(D_1, D_{2m})$. Each GS has an individual data transmission task c_i with its own service time t_i. How to minimize UAV's energy consumption by determining its flight speed while satisfying the *service time constraints* Eq. (C2) and Eq. (C3), and *deadline constraints* Eq. (C4)?

$$(P3) : \min_{v(l)} \quad \int_{L(D_1,D_{2m})} p(l) \frac{\mathrm{d}l}{v(l)} \tag{9}$$

$$\text{s.t.} \quad (C2), (C3), (C4) \tag{10}$$

According to problem decomposition presented above, we propose a three-step scheme named *ETSO* that includes three algorithms, i.e., Initial Trajectory Algorithm (*ITA*), Optimal Speed Scheduling Algorithm (*OSSA*), and Trajectory Adjustment Algorithm (*TAA*). Detailed steps for *ETSO* are shown in Fig. 3. Specifically, Algorithm *ITA* first achieves an initial

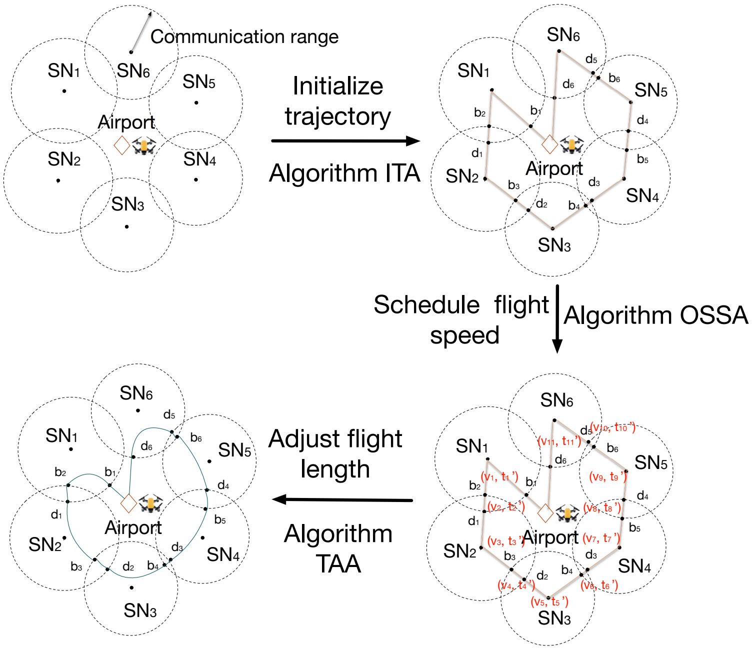

Fig. 3: Steps for the $ETSO$ scheme. First, the initial trajectory is designed through locations of each GS by Algorithm *ITA*. Then, flight speed v_i and time t_i' are scheduled for the UAV on each trajectory $L_i \in L$ using Algorithm *OSSA*. Finally, Algorithm TAA minimizes UAV's energy consumption by adjusting trajectory length of each trajectory $L_i \in L$.

trajectory for *STD* problem. Then, an optimal speed scheduling Algorithm *OSSA* is proposed to get the optimal flight speed for *FSS* problem. Finally, an adjustive Algorithm *TAA* is presented to cut down the UAV's energy consumption by reducing or incrasing the trajectory length.

A. Initial Trajectory Algorithm (ITA)

We first present an algorithm named *ITA* to solve the *STD* problem, which initializes the UAV's flight trajectory.

Algorithm 1 ITA

```
Input:  GSs' location: $[x_i, y_i]$
        GSs' number: $m$
        Initial location of UAV: $[u_a, u_b]$
        Communication range of GS: $Cr_i$
Output: Initial UAV's Trajectory $L$
1: Construct the graph $G = (V, E)$, $V = M \cup \{u\}$, $E = \{e_{ij} | dis(SN_i, SN_j) \leq Cr_i + Cr_j\} \cup \{e_{ui}, \forall i\}$
2: Use Simulated Annealing (SA) algorithm to find the shortest trajectory $L$ in graph $G = (V, E)$
3: Return the initial trajectory $L$
```

In Algorithm 1, the initial graph $G = (V, E)$ is first constructed, in which V is set of vertexes including all GSs and the airport, denoted as $V = M \cup \{u\}$, and E is the set of edges that contains edges e_{ui} through the airport u and edge $e_{ij} \in E$, $\{i, j\} \in M$ among all GSs. Communication ranges of SN_i and SN_j in e_{ij} must be overlapped, as shown in Eq.(11):

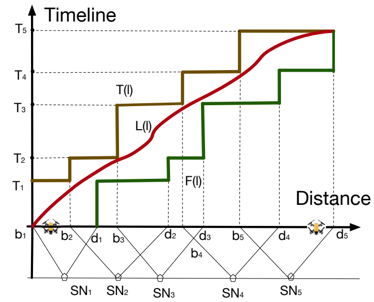

Fig. 4: The graphical visualization of the *FSS* problem. In this diagram, UAV reaches position l in time t, and the slope of $L(l)$ equals to $\frac{1}{v(l)}$. We set a lower bound $F(l)$ and an upper bound $T(l)$ to restrict the flight speed of UAV according to constraints (C2), (C3) and (C4). We aim to find the optimal curve $L(l)$ in this diagram.

$$dis(SN_i, SN_j) \leq Cr_i + Cr_j \tag{11}$$

The problem is then transferred as the Traveling Salesman Problem (TSP), where vertex $v \in V$ represents city and edges $e_{ij} \in E$ are the distances between these cities in TSP. We utilize Simulated Annealing (SA) algorithm [13] in *ITA* to solve the TSP and find the shortest trajectory L (line 2), where L is the initial trajectory worked out by Algorithm *ITA*.

Time complexity of *ITA* mainly focuses on solving the TSP. Since we utilize Simulated Annealing (*SA*) algorithm to solve the TSP, the computation complexity of *ITA* is $O(m^2 * 2^m)$.

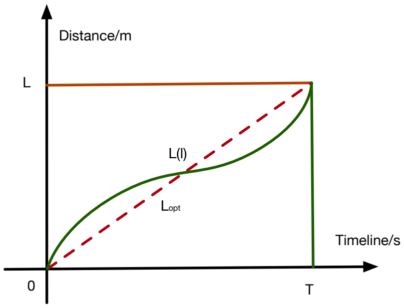

Fig. 5: The UAV that flies at a constant speed costs less energy consumption than that in a varying speed.

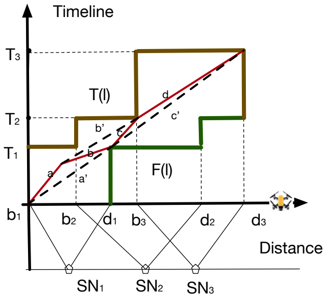

Fig. 6: Curves that disobey Lemma 2 will cost more energy.

B. Optimal Speed Scheduling Algorithm (OSSA)

Based on Algorithm ITA, we achieve an initial trajectory L. The *ETPSS* problem is transferred as a speed scheduling problem with a fixed trajectory length, which matches the *FSS* problem. We then propose an Optimal Speed Scheduling Algorithm (*OSSA*) to solve the *FSS* problem by determining the proper flight speed for UAV along trajectory L.

To better illustrate the *FSS* problem, we first introduce the graphical visualization of *FSS* [14]. As shown in Fig. 4, the X-axis represents the length of trajectory, and the accumulative flight time is expressed in Y-axis, where $T_i = \sum_1^i t_i$. Curve $L(l)$ in Fig. 4 represents the accumulation flight-speed curve for UAV, where the slope of $L(l)$ is equals to $\frac{1}{v(l)}$. Hence, how to find the optimal flight speed $v_{opt}(l)$ is transferred as finding the optimal accumulation curve $L_{opt}(l)$.

An optimal flight speed for UAV with minimum propulsion power must satisfy the *constant speed property*.

Lemma 1 (Constant speed property): UAV flying in a constant speed consumes less energy than flying in a changing speed.

Proof 1: Seen in Fig. 5, we utilize a distance-time diagram to illustrate problem in a more clearly way.

If speed of UAV changes, its energy consumption can be worked out as:

$$E_{L(l)} = \int_0^L p(v(l))\frac{\mathrm{d}l}{v(l)} = \int_0^L \frac{p(v(l))}{v(l)}\,\mathrm{d}l \tag{12}$$

UAV's energy consumption in constant-speed sceanrio is expressed as:

$$E_{opt}^L = p(\tfrac{L}{T}) \cdot T = p(\frac{\int_0^L \mathrm{d}l}{\int_0^L \frac{\mathrm{d}l}{v(l)}}) \cdot \int_0^L \frac{\mathrm{d}l}{v(l)} \tag{13}$$

Based on Jensen's inequation in [15], we get

$$p(\frac{\int_0^L v(l)\cdot\frac{\mathrm{d}l}{v(l)}}{\int_0^L \frac{\mathrm{d}l}{v(l)}}) \leq \frac{\int_0^L p(v(l))\cdot\frac{\mathrm{d}l}{v(L)}}{\int_0^L \frac{\mathrm{d}l}{v(l)}} \tag{14}$$

Multiplying T ($\int_0^L \frac{\mathrm{d}l}{v(l)}$) in Eq. (14), which is:

$$p(\frac{\int_0^L v(l)\cdot\frac{\mathrm{d}l}{v(l)}}{\int_0^L \frac{\mathrm{d}l}{v(L)}}) \cdot \int_0^L \frac{\mathrm{d}l}{v(l)} \leq \int_0^L p(v(l)) \cdot \frac{\mathrm{d}l}{v(l)} \tag{15}$$

$$p(\tfrac{L}{T}) \cdot T \leq \int_0^L p(v(l)) \cdot \frac{\mathrm{d}l}{v(l)} \tag{16}$$

$$E_{opt}^L \leq E_{L(l)} \tag{17}$$

■

Based on Lemma 1, we propose the *optimal curve property* that an optimal curve $L(l)$ must obey.

Lemma 2 (Optimal curve property):

- *Lemma 2.1*: $L(l)$ must intersect with corner of upper bound $T(l)$ or lower bound $F(l)$.
- *Lemma 2.2*: Assume in point d_i, we have $L(d_i) = F(d_i)$, the slope change must be negative.
- *Lemma 2.3*: Assume in point b_i, we have $L(b_i) = T(b_i)$, the slope change must be positive.

Proof 2: We prove Lemma 2 by contradiction, seen in Fig. 6. Line a and b disobey the Lemma 2.1, there exists a straight line a' with lower energy consumption. Line b and c, line c and d also disobey Lemma 2.2 and Lemma 2.3, and there exists straight line b' and c' with lower energy consumption. Overall, solution obeys Lemma 2 should be the optimal solution.

■

Lemma 3 (Uniqueness): If an accumulative curve $L(l)$ satisfies Lemma 2, curve $L(l)$ must be unique.

Proof 3: Assuming there are two solutions that satisfies optimal curve property, e.g., curve L_1 and L_2. We suppose curves l_1 and l_2 satisfy Eq. (18):

$$\begin{cases} l_1(l) = l_2(l) & 0 \leq l \leq \alpha, \beta \leq l \leq L \\ l_1(l) \neq l_2(l) & \alpha < l < \beta \end{cases} \tag{18}$$

We assume $l_1(i) \leq l_2(i), \quad i \in (\alpha, \beta)$, which is:

$$F(i) \leq l_1(i) < l_2(i) \leq T(i), \quad i \in (\alpha, \beta) \tag{19}$$

Based on Lemma 2.1 and Eq. (19), $l_1(i)$ must intersect at one corner of $F(i)$ $(i < \beta)$, for Eq. (19). $l_2(i)$, similar to $l_1(i)$, should intersect at $T(i)$ $(i \in (\alpha, \beta))$. To let $l_1(\beta) = l_2(\beta)$, l_1 should be a convex curve and l_2 should be a concave curve, which separately violate Lemma 2.2 and Lemma 2.3. Therefore, l_1 and l_2 cannot satisfy the Lemma 2 at the same time, and thus curve satisfies Lemma 2 must be unique.

■

According to Lemma 1∼3, we propose our offline algorithm *OSSA* in Algorithm 2.

The basic idea of Algorithm *OSSA* is illustrated as follows: we attempt to connect all corners of $T(l)$ and $F(l)$, and check

Algorithm 2 OSSA

```
Input:  Number of GS $m$
        Location that UAV enters $SN_i$: $b_i$
        Location that UAV flies out $SN_i$: $d_i$
        Service time for $SN_i$: $t_i$
Output: Flight speed $v_j$
        Propulsion energy $E_{fly}$
 1: $i = 1$, $j = 1$, $v = \emptyset$, $E_{fly} = 0$, $q_1 = (0, 0)$
 2: while $i <= m$ do
 3:     $l_j$ is the line from $q_i$ to $(d_i, F(d_i))$
 4:     $l'_j$ is the line from $q_i$ to $(b_i, T(b_i))$
 5:     $s_j$ is slope of $l_j$
 6:     $s'_j$ is slope of $l'_j$
 7:     if Extension line of $l_j$ intersects $T(l)$ then
 8:         $v_j = \frac{1}{s_j}$
 9:         $v = v \cup \{v_j\}$
10:         $j = j + 1$, $q_j = (d_i, F(d_i))$
11:     end if
12:     if Extension line of $l'_j$ intersects $F(l)$ then
13:         $v_j = \frac{1}{s'_j}$
14:         $v = v \cup \{v_j\}$
15:         $j = j + 1$, $q_j = (b_i, T(b_i))$
16:     end if
17:     $i = i + 1$
18: end while
19: Calculate $E_{fly}$ based on $v$ and $q$
20: Return $v$, $E_{fly}$
```

whether the connected line is feasible. This step continues until the result line is infeasible and the last feasible solution is the output result.

Specifically, two set F_t and F_f are defined as sub-lines that intersect with upper bound $T(l)$ or lower bound $F(l)$. When the algorithm starts, the boundary sub-line between F_t and F_f is found during each iteration. E.g., if a line $l_j \in F_f$ whose extension line connects with $T(l)$ (line 7) or a line $l_j \in F_t$ whose extension line intersects with $F(l)$ (line 12), we select this line as the boundary line of current iteration. The above steps repeat until all m GSs are served by the UAV.

Theorem 1: Algorithm *OSSA* optimally solves the *OTS* problem with computation complexity of $O(n^2)$.

Proof: Lemma 2 and Lemma 3 prove that if an algorithm whose result satisfies Lemma 2, it should be the unique optimal algorithm.

For Lemma 2.1, Algorithm $OSSA$ will intersect with $F(l)$ or $T(l)$, indicating Algorithm $OSSA$ satisfies Lemma 2.1.

For Lemma 2.2, we assume that solution of $OSSA$ intersects $F(l)$ in iteration j, and in next step the slope satisfies $s_{j+1} > s_j$. To this end, L_{j+1} is included in the set $F_{tj} \in F_t$. Thus, the hypothesis is incorrect.

For Lemma 2.3, we assume that solution of $OSSA$ intersects $T(t)$ in iteration j, and in next step the slope satisfies $s_{j+1} < s_j$. To this end, L_{j+1} is included in the set $F_{fj} \in F_f$. Thus, the hypothesis is incorrect. Overall, $OSSA$ is the optimal algorithm for the *FSS* problem.

In each iteration, we test each corner of $F(l)$ and $T(l)$ to find the feasible line. When it comes to the worst case, the UAV will check all points to find the feasible line. Under this circumstance, the sum of step is $2m^2 - 2m$, and thus time complexity of $OSSA$ is $O(m^2)$.

■

C. Trajectory Adjust Algorithm (TAA)

Based on Algorithm *ITA* and Algorithm *OSSA*, an initial trajectory L though all GSs with the optimal flight speed and flight time t' is achieved. Algorithm *TAA* is proposed to cut down UAV's energy consumption by adjusting the length of each trajectory $L_i \in L$.

Algorithm 3 TAA

```
Input:  Flight speed for each trajectory $l_i$: $v_i$
        Flight time for each trajectory $l_i$: $t'_i$
        Location of key points: $b_i$, $d_i$
Output: UAV's flight speed for each trajectory $l_i$: $v_i$
        Total propulsion energy $E_{fly}$
 1: Calculate the minimum-power flight speed $v^*$ according
    to Eq. (3)
 2: Calculate the energy consumption $E_{out}$ for path $L_{out}$
 3: while $i <= 2m - 1$ do
 4:     Calculate the flight distance by $l^*_i = v^* \cdot t'_i$
 5:     if $l^*_i$ satisfies constraints (C1) then
 6:         $l_i = l^*_i$
 7:         Update $E_{fly}$ with speed $v^*$ and time $t'_i$
 8:     else
 9:         $l_i = dis(D_i, D_{i+1})$
10:         Update $E_{fly}$ with speed $\frac{dis(D_i, D_{i+1})}{t'_i}$ and time $t'_i$
11:     end if
12:     $i = i + 1$
13: end while
14: $E_{fly} = E_{fly} + E_{out}$
15: return $v_i$, $E_{fly}$
```

Since UAV's optimal speed with the least energy consumption v^* is worked out by Eq. (3), and $v^* = \sqrt[4]{\frac{c_2}{3c_1}}$ does not correspond to distance l_i. The basic idea for Algorithm *TAA* is to try our best to adjust UAV's flight speed close to v^*. Since flight time $t'_i \in t'$ in each trajectory L_i has been allocated in Algorithm *OSSA*, we could obtain the proper trajectory length l^*_i by multiplying speed v^* with time t'_i.

Specifically, Algorithm *TAA* first calculates the propulsion energy E_{out} of UAV for trajectory L_{out} outside the communication ranges of all GSs (red lines in Fig. 2). Then we check each trajectory $L_i \in L$ to find whether it is feasible to adjust the flight speed of UAV to v^* under the constraints of (C1) in trajectory L_i(line 5). If the length $l^*_i = v^* \cdot t'_i$ satisfies constraint (C1), we use length l^*_i (line 5∼7). If not, the UAV flies along the straight trajectory directly (line 8∼10). The above steps repeat until the UAV finishes trajectory L.

Table 1: Simulation Parameters

Parameters	Values	Meaning
t_i	$[0.5, 2]$s	Service time for SN_i
m	[10,1000]	Number of GSs
v	[5,100]	Flight speed of UAV
H	100m	Flight altitude of UAV
c_1	$9.26 * 10^{-4}$	Parameter of energy model
c_2	2250	Parameter of energy model
Cr	[30,50]m	Communication range for GSs

Time complexity of Algorithm *TAA* is $O(m)$, for *TAA* checks each trajectory $L_i \in L$ and adjust the trajectory to reduce energy consumption of network.

IV. EXPERIMENT

In our experiments, GSs are randomly generated in area of $2km \times 2km$ with communication range Cr varies from $30m$ to $50m$. The UAV takes off from airport and flies at altitude $H = 100m$ with speed ranging from $5m/s$ to $100m/s$. A small base station (BS) is mounted on UAV to receive the data transmission from GSs whose number m varies from 10 to 1000. Symbol c_1 and c_2 are parameters of propulsion energy in Eq. 2, where $c_1 = 9.26 \times 10^{-4}$ and $c_2 = 2250$. We define the service time for GS SN_i as t_i, whose value ranges from $0.5s$ to $2s$. Table 1 shows the parameters used in experiment part.

The *ETSO* scheme is compared with algorithms listed as follows:

- *Task Completion Speed (TCS)*: UAV reaches departing key point d_i at time $t = \sum_{j=1}^{i} t_j$ for each GS $SN_i \in M$, in order to complete its data transmission task.
- *NoTAA*: The *ETSO* scheme without Algorithm *TAA*.
- *TAA-ALG*: The UAV flies along the trajectory worked out by *TAA* and speed scheduling algorithm using online Algorithm *ALG* proposed in [16].

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Fig. 7 shows the energy consumption of different speed scheduling Algorithm *TCS*, *TAA-ALG* and *ETSO* under the same trajectory calculated by Algorithm TAA when number of GSs is varying from 50 to 1000. It is seen that the *ETSO* scheme achieves the best among the three algorithms, because it optimizes both trajectory length and flight speed, and results in the least energy consumption. Besides, energy consumption of Algorithm *TCS* costs more than that of Algorithm *TAA-ALG*, for *TAA-ALG* aims to minimize UAV's energy consumption with all GSs known by it, while Algorithm TCS only considers the deadline of each task. Moreover, with the increasing number of GSs, all energy consumption of all three algorithms will cost more.

Fig. 8 shows the UAV's energy consumption of different trajectory design Algorithm *NoTAA* and Algorithm *ETSO* when number of GSs varies from 50 to 1000. Results demonstrate that the *ETSO* scheme cost less energy than that of *NoTAA*, because the UAV in Algorithm *NoTAA* has to fly through locations of each GS, whose trajectory length is longer than that of *ETSO*. In addition, when number of GSs increases, the gap between two algorithms is also increasing.

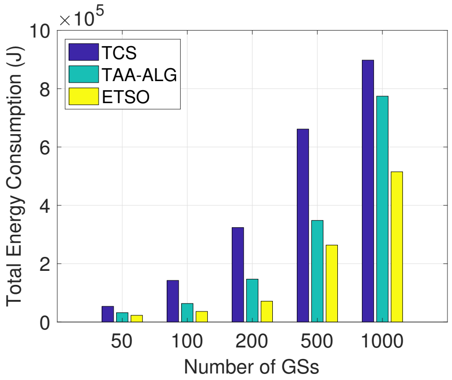

Fig. 7: The impact of GS number on energy consumption with different speed scheduling algorithms

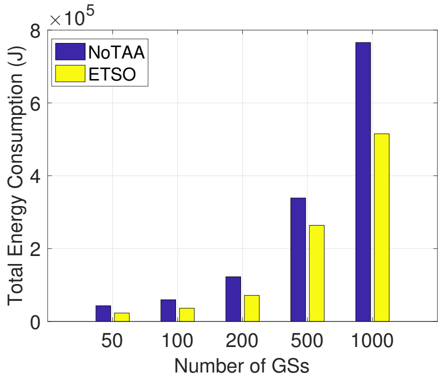

Fig. 8: The impact of GS number on energy consumption with different trajectory design algorithms

Fig. 9 illustrates the average flight speed of the UAV in the *ETSO* scheme, Algorithm *NoTAA*, *TCS*, and Algorithm *TAA-ALG* when number of GSs changes from 50 to 1000. It is seen that flight speed in Algorithm *ETSO* is almost stable, and near the minimum-power speed v^* ($v^* = 29.97m/s$ in this scenario, seen as baseline in Fig. 9), for Algorithm *TAA* attempts to shorten the trajectory by constructing a new trajectory with speed v^*. Speed of Algorithm *TCS* changes a lot through 50 to 1000 nodes, for Algorithm *TCS* does not take energy consumption of UAV into consideration. Therefore, Algorithm *TCS* costs the most energy consumption among the three algorithms.

V. CONCLUSION

The energy-efficient trajectory planning and speed scheduling problem for UAV-assisted data collection system is studied in this paper. Different from other works, we utilized a practical energy model, and focused on finding the proper trajectory and UAV's speed to minimize UAV's energy consumption. To be more specific, the *ETPSS* problem is first formulated for UAV-assisted data collection system and is decomposed it into two sub-problems *STD* and *FSS*. Then, a three-step *ETSO* scheme was proposed to solve the *ETPSS* problem. First, Algorithm ITA was designed to find an initial

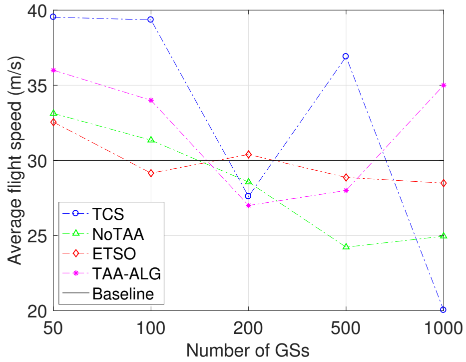

Fig. 9: The impact of GS number on average flight speed

trajectory. Then, Algorithm *OSSA* was presented for optimal speed scheduling. Finally, Algorithm *TAA* reduced the energy consumption of UAV by adjusting its trajectory length. We proved Algorithm *OSSA* to be the optimal algorithm for the *FSS* problem, and simulation results demonstrated that *ETSO* performs well on energy efficiency.

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REFERENCES

[1] Y. Zeng, Q. Wu, and R. Zhang, "Accessing from the sky: A tutorial on UAV communications for 5G and beyond," *Proceedings of the IEEE*, vol. 107, no. 12, pp. 2327–2375, 2019.

[2] P. Yang, X. Cao, C. Yin, Z. Xiao, X. Xi, and D. Wu, "Proactive drone-cell deployment: Overload relief for a cellular network under flash crowd traffic," *IEEE Transactions on Intelligent Transportation Systems*, vol. PP, no. 99, pp. 1–16, 2017.

[3] Y. Zeng, J. Xu, and R. Zhang, "Energy minimization for wireless communication with rotary-wing UAV," *IEEE Transactions on Wireless Communications*, vol. 18, no. 4, pp. 2329–2345, 2019.

[4] Y. Wang, Z. Hu, X. Wen, Z. Lu, and J. Miao, "Minimizing data collection time with collaborative UAVs in wireless sensor networks," *IEEE Access*, vol. 8, pp. 98 659–98 669, 2020.

[5] Z. Yong and Z. Rui, "Energy-efficient UAV communication with trajectory optimization," *IEEE Transactions on*

[6] S. Eom, H. Lee, J. Park, and I. Lee, "UAV-aided wireless communication design with propulsion energy con-

Wireless Communications, vol. 16, no. 6, pp. 3747–3760, 2017.

straint," *2018 IEEE International Conference on Communications (ICC)*, pp. 1–6, 2018.

[7] C. Zhan and Y. Zeng, "Aerial-Ground cost tradeoff for multi-UAV-enabled data collection in wireless sensor networks," *IEEE Transactions on Communications*, vol. 68, no. 3, pp. 1937–1950, 2020.

[8] J. Gong, T. Chang, C. Shen, and X. Chen, "Flight time minimization of UAV for data collection over wireless sensor networks," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 9, pp. 1942–1954, 2018.

[9] Z. Yu, Y. Gong, S. Gong, and Y. Guo, "Joint task offloading and resource allocation in UAV-enabled mobile edge computing," *IEEE Internet of Things Journal*, vol. 7, no. 4, pp. 3147–3159, 2020.

[10] Y. Liang, W. Xu, W. Liang, J. Peng, X. Jia, Y. Zhou, and L. Duan, "Nonredundant information collection in rescue applications via an energy-constrained UAV," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 2945–2958, 2019.

[11] H. Guo and J. Liu, "UAV-enhanced intelligent offloading for internet of things at the edge," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 4, pp. 2737–2746, 2020.

[12] J. Zhang, L. Zhou, Q. Tang, E. C. . Ngai, X. Hu, H. Zhao, and J. Wei, "Stochastic computation offloading and trajectory scheduling for UAV-assisted mobile edge computing," *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 3688–3699, 2019.

[13] P. Shi and S. Jia, "A hybrid artificial bee colony algorithm combined with simulated annealing algorithm for traveling salesman problem," in *2013 International Conference on Information Science and Cloud Computing Companion*, 2013, pp. 740–744.

[14] W. Ye, J. Luo, F. Shan, W. Wu, and M. Yang, "Offspeeding: Optimal energy-efficient flight speed scheduling for uav-assisted edge computing," *Computer Networks*, vol. 183, p. 107577, 2020. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1389128620312196

[15] M. A. Zafer and E. Modiano, "A calculus approach to energy-efficient data transmission with quality-of-service constraints," *IEEE/ACM Transactions on Networking*, vol. 17, no. 3, pp. 898–911, 2009.

[16] W. Wu, J. Wang, M. Li, K. Liu, F. Shan, and J. Luo, "Energy-efficient transmission with data sharing in participatory sensing systems," *IEEE Journal of Selected Area Communications*, vol. 34, no. 12, pp. 4048–4062, 2016.