Jointly Optimal Fair Data Collection and Trajectory Design Algorithms in UAV-Aided Cellular Networks

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***Abstract*—Due to the flexible deployment and low cost of unmanned aerial vehicle (UAV), the integration of UAV and wireless cellular networks is widely regarded as a promising technology to enhance the performance of wireless cellular communications. This paper considers a UAV-aided wireless cellular communication system with multiple adjacent ground users (GUs), where the primary mission of UAV is to collect data from all of the GUs. We take the GUs as the topological nodes and combine their communication ranges to construct a ground topology structure (GTS), with the purpose of designing a reasonable trajectory for the UAV to execute the data collection tasks, while ensuring the fairness of transmission among all of GUs. In order to solve these problems, we utilize parallel projection algorithm onto homogeneous and heterogeneous GTS respectively to obtain a group of waypoints which construct the UAV trajectory, we formulate the fairness of data collection as a min-max problem. Finally, simulation experiments show the trajectory design results of the homogeneous and heterogeneous GTS respectively. Numerical results further vaildate the effectiveness of our proposed algorithms.**

***Index Terms*—Unmanned aerial vehicle (UAV), wireless cellular networks, trajectory design, projection algorithms.**

I. Introduction

Unmanned aerial vehicle (UAV) has been continuously developed and put into applications of various fields over the past years, such as cargo delivery, video streaming, surveillance and monitoring, search and rescue, etc. Since it can be equipped with communication modules and advanced batteries, UAV is gaining increasing popularity in wireless cellular networks to satisfy quality-of-service (QoS) requirements for on-demand deployment [1]. Based on these advantages, the UAV can act as a data collector flying over the scattered ground users (GUs), which provides short-distance line-of-sight (LoS) communication links and ensures the completion of assigned data collection tasks. However, as a result of the constraints of communication links including distance and the signal-to-noise ratio (SNR) of the minimum requirements, each GU has a limited effective communication range, and UAV can only collect data from the GU within its communication range [2]. Therefore, how to effectively accomplish data collection tasks in the limited communication domain through UAV trajectory optimization has attracted the attention of many researchers.

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For UAV trajectory optimization in wireless cellular networks, a large number of scholars have contributed their research achievements. In [1], a segment-based trajectory optimization algorithm (STOA) was proposed to avoid repeated visits of GUs in order to shorten trajectory length, and a group-based trajectory optimization algorithm (GTOA) was proposed to decrease the computation complexity for the GUs which have large-scale and high-density deployment. In [2], the authors used graph theory and convex optimization to optimize the trajectory of UAV so as to minimize the mission completion time, subject to a minimum received SNR constraint of the UAV-cellular communication links. Looking-before-crossing algorithm was proposed in [3] to solve the flight speed scheduling of the UAV's data collection tasks from GUs moving along a straight line. The authors of [4] solved the UAV trajectory optimization problem by relative algorithms of traveling salesman problem (TSP) and convex optimization techniques. Most of these works used sorting algorithm to GUs, such as the TSP algorithm, and lead the UAV to communicate with GUs according to the order, but without considering multiple GUs simultaneous communication links. In [1], for example, the UAV simply passed through communication fields of a set of GUs with a straight trajectory to ensure the shortest task execution time, without considering the data transmission process between GUs and UAV.

In this paper, we consider the case where GUs are densely located on the ground with their communication ranges intersecting with one another, as shown in Fig. 1, and UAV is dispatched to carry out the missions of data collection from these GUs. It is well known that UAV frequently turns direction during flight thus generating more energy consumption than moving in a straight-line flying. In the scenario considered in this paper, the UAV only needs to pass through the middle area of the ground topology structure (GTS) (i.e., the public communication area of some GUs) and simultaneously communicate with GUs to complete the tasks of data collection, rather than flying sequentially over the airspace of each GU and communicating with it. Therefore, we adopt OFDMA (orthogonal frequency division multiple access) technology to divide the total bandwidth into several orthogonal non-overlapping subcarriers, and allocate different subcarriers to different GUs to realize multiple access. Because different GUs occupy non-overlapping subcarriers, in the ideal synchronization case of communications, the system has no interference between multiple GUs, i.e., no multiple access interference (MAI). Also, subject to UAV with throughput constraints, we propose a real-time adjustable trajectory design algorithm combined with the process of data collection tasks.

The main contributions of this paper are summarized as follows:

- We construct the data transmission rate model between UAV and GUs based on GTS.
- We adjust parallel projection method to calculate the waypoints which consist the UAV trajectory.
- We analyze both homogeneous and heterogeneous GTS respectively and propose the corresponding algorithms to design the UAV trajectory based on the modified parallel projection method.

The rest of the paper is organized as follows. In section II, we introduce the GTS and the data transmission model of UAV. Parallel projection method is adjusted in section III-A to find the waypoints. Section III-B propose the trajectory design algorithms of homogeneous and heterogeneous GTS respectively based on the modified parallel projection method. Section IV shows the experimental results to validate effectiveness of the proposed algorithms. Finally, we conclude our work in section V.

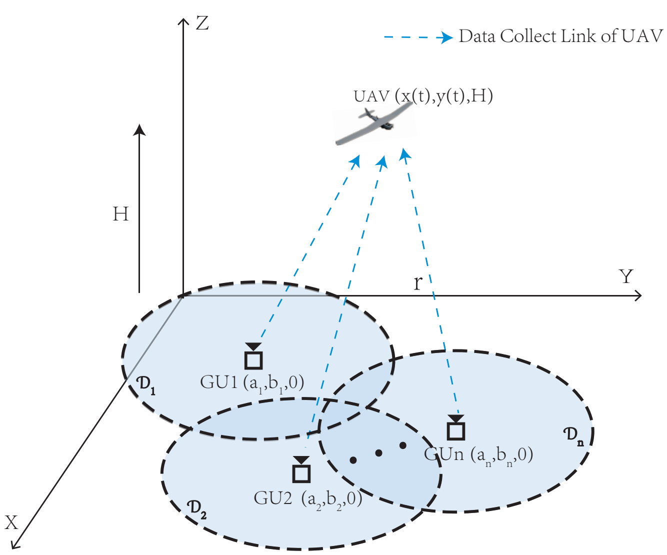


Fig. 1. The illustration of the wireless cellular communication links between UAV and GUs.

II. System Model

Considering a UAV-aided wireless cellular communication system where a UAV is employed as a mobile data collector to gather data from N ground users (GUs), denoted by the set $\mathcal{N} = \{1, \ldots, N\}$. Assume that each GU has a known threshold of horizontal communication distance with UAV which is denoted as r_n, then the nth GU's communication range can be denoted as a disk $\mathcal{D}_n$ of radius r_n (as shown in Fig. 1), and the UAV starts its data collection task with nth GU only if it enters the inner part of $\mathcal{D}_n$, $n \in \mathcal{N}$. Obviously, the N GUs and all of the communication circles $\mathcal{D}_n$, $n \in \mathcal{N}$ construct the GTS.

Without loss of generality, we construct a 3-D Cartesian coordinate system where the UAV's pre-determined initial location is located at the origin $(0, 0, 0)$, and the UAV is assumed to fly from the initial location to a pre-determined final location (x_F, y_F, H) at a constant speed V and altitude H above the ground. We denote $(x(t), y(t), H)$ as the time-varying coordinate of the UAV during the total tasks execution time T, where $0 \leq t \leq T$. Besides, the coordinate of nth GU is denoted as $(a_n, b_n, 0)$, $n \in \mathcal{N}$, and all GUs' locations and communication radius are assumed to be pre-determined, and we assume the final location and the whole GTS are both in the first quadrant.

For simplicity, we define $\boldsymbol{g}_n = [a_n, b_n]^T, \boldsymbol{u}_0 = [x_0, y_0]^T, \boldsymbol{u}_F = [x_F, y_F]^T$ and $\boldsymbol{u}(t) = [x(t), y(t)]^T$ to represent the above locations projected on the horizontal ground plane, respectively, where $\boldsymbol{u}(0) = \boldsymbol{u}_0$, $\boldsymbol{u}(T) = \boldsymbol{u}_F$. Thus the time-varying distance from nth GU to the UAV is:

$$d_n(t) = \sqrt{H^2 + \|\boldsymbol{u}(t) - \boldsymbol{g}_n\|^2}, \ 0 \leq t \leq T. \tag{1}$$

The data transmission channels between the UAV and GUs are assumed to be LoS channels. The Doppler effect is assumed to be perfectly compensated due to the UAV's mobility. In our model, we consider that the UAV can communicate with multiple GUs simultaneously by employing OFDMA, i.e., assigning each GU a fraction of total bandwidth/transmit power [5]. As such, it can be assumed that each GU suffers no interference from the other GUs. Therefore, the instantaneous channel power gain from the nth GU to the UAV can be expressed as:

$$h_n(t) = \beta_0 d_n^{-2}(t) = \frac{\beta_0}{H^2 + \|\boldsymbol{u}(t) - \boldsymbol{g}_n\|^2}, \ 0 \leq t \leq T, \tag{2}$$

where β_0 denotes the channel power gain at the reference distance $d_0 = 1m$. Denote the total available channel bandwidth by B in Hertz (Hz), which is equally divided into K subcarriers. Thus, the instantaneously channel capacity from the UAV to the nth GU in bits/second can be expressed as:

$$\begin{aligned} R_n(t) &= \frac{B}{K} log_2\left(1 + \frac{P h_n(t)}{\sigma^2}\right) \\ &= \frac{B}{K} log_2\left(1 + \frac{\gamma_0}{H^2 + \|\boldsymbol{u}(t) - \boldsymbol{g}_n\|^2}\right), \end{aligned} \tag{3}$$

where P is the transmit power from the GUs to the UAV which is assumed constant during the missions complement period, and σ^2 is the additive white Gaussian noise (AWGN) at the uplink from nth GU, $\gamma_0 = \beta_0 P / \sigma^2$ is the reference received SNR at $d_0 = 1m$. Since the UAV can only transmit data from the nth GU when it enters the communication range $\mathcal{D}_n$, we need to introduce an auxiliary variable to represent the UAV's communication status with each GU during the mission execution period. So we define the binary variable $\xi_n(t)$, which equals to 1 if UAV is flying above the inner area of range $\mathcal{D}_n$, and 0 otherwise. Thus, we have the following constraints:

$$\sum_{n=1}^{N} \xi_n(t) \le N, \ \forall t \in [0,T], \quad \xi_n(t) \in \{0,1\}, \ \forall t \in [0,T], n \in \mathcal{N}. \tag{4}$$

Then the total amount of data that can be transmitted from the nth GU to the UAV over the duration T can be expressed as:

$$\bar{R}_n = \int_0^T \xi_n(t) \frac{B}{K} log_2 \left(1 + \frac{\gamma_0}{H^2 + \|\boldsymbol{u}(t) - \boldsymbol{g}_n\|^2}\right) dt. \tag{5}$$

III. Trajectory Design

A. Parallel Projection Method for Waypoints Locating

We transform the trajectory design problem into the locating problem of a set of waypoints, which are connected with the straight line according the order to form the trajectory of the UAV. In this part, we adjust the Parallel Projection Method (PPM) based on GTS to calculate the location of the waypoints by reformulating some rules of PPM.

Methods such as projection onto convex sets (POCS) have been used for sensor nodes localization in wireless networks [6], which sequentially projects an initial point onto each communication disk (convex set) until convergence to a common boundary point or area (see [7] for details). The unique orthogonal projection of start point $\boldsymbol{x}$ onto convex set $\mathcal{D}_n$ is denoted as [8]:

$$\mathcal{P}_{\mathcal{D}_n}(\boldsymbol{x}) = \boldsymbol{g}_n + r_n \frac{\boldsymbol{x} - \boldsymbol{g}_n}{\|\boldsymbol{x} - \boldsymbol{g}_n\|}. \tag{6}$$

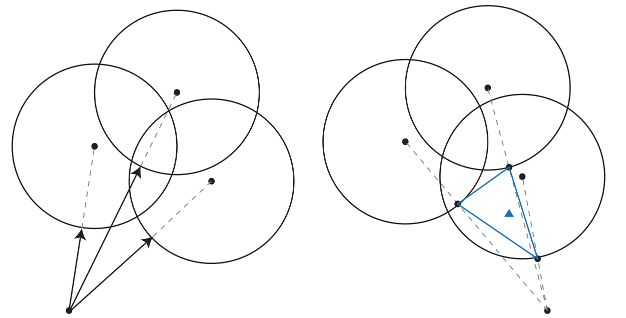
As shown in Fig. 2, the PPM is an improvement for the projection method in (6), and it projects on all disks $\mathcal{D}_n$ at each iteration and takes the centroid of the polygon formed by these N projection points as the next iteration point [9]. Thus, the single-step parallel projection function can be denoted as:

$$\boldsymbol{\beta}^{l+1} = \boldsymbol{\beta}^l + \lambda^l \left(\frac{1}{N}\sum_{n=1}^{N} \mathcal{P}_{\mathcal{D}_n}(\boldsymbol{\beta}^l) - \boldsymbol{\beta}^l\right), \quad n \in \mathcal{N}, \tag{7}$$

where $\boldsymbol{\beta}^l$ is the iteration point of PPM, $\lambda^l \in [\epsilon, 2-\epsilon]$ for $0 < \epsilon < 1$ is called the relaxation parameter, and geometrically, it represents the step size as the $\boldsymbol{\beta}^l$ moves to $\boldsymbol{\beta}^{l+1}$.

For the trajectory design problem in this paper, PPM is used to push the initial point $\boldsymbol{u}_0$ of the UAV to $\boldsymbol{u}_F$ after a finite number of iterations (the iteration point is the waypoint mentioned in the previous paper), rather than converging to a point within GTS. Therefore, we need to make some modifications to the traditional PPM to make it suitable for our trajectory design problem. Next we use the mathematical model to describe the modified parallel projection method (MPPM) for waypoints locating.

We assume $\mathcal{L} = \{1, 2, \dots, L\}$ as the set of waypoints $\boldsymbol{\beta}^l$ on the trajectory of UAV, and $\boldsymbol{\beta}^1 = \boldsymbol{u}_0$, $\boldsymbol{\beta}^L = \boldsymbol{u}_F$, $\boldsymbol{\beta}^l = [x^l, y^l]^T, \forall l \in \mathcal{L}$. In order to make the waypoints go forward



(a) PPM. (b) Waypoint.

Fig. 2. Illustrations of the parallel projection algorithm, where the Fig. (a) show the projection process from one start point to all disks, and the blue triangle in Fig. (b) is the result point of single parallel projection.

continuously from the $\boldsymbol{u}_0$ to $\boldsymbol{u}_F$ at the iterations, we make the following modification for (6), and we need to introduce another auxiliary variable δ_n to represent the UAV which had passed by some $\mathcal{D}_n$ during the mission execution period if it equals to 1, and 0 otherwise. Since our waypoints is constantly moving toward the final location, once the UAV flies out of some $\mathcal{D}_n$, it will not enter this inner area again. Therefore, we can combine the variable δ_n to represent the unique projection of $\boldsymbol{\beta}^l$ as follows:

$$\mathcal{P}_{\mathcal{D}_n}(\boldsymbol{\beta}^l) = \begin{cases} \boldsymbol{g}_n, & \xi_n = 1 \wedge y^l \le b_n, \\ \boldsymbol{\beta}^l + r_n \frac{\boldsymbol{u}_F - \boldsymbol{\beta}^l}{\|\boldsymbol{u}_F - \boldsymbol{\beta}^l\|}, & \xi_n = 0 \wedge \delta_n = 1, \\ \boldsymbol{g}_n + r_n \frac{\boldsymbol{\beta}^l - \boldsymbol{g}_n}{\|\boldsymbol{\beta}^l - \boldsymbol{g}_n\|}, & otherwise. \end{cases} \tag{8}$$

It makes the waypoint at each MPPM iteration, for each $\mathcal{D}_n$, and projects toward the location $\boldsymbol{g}_n$ when it has entered $\mathcal{D}_n$ but not beyond $\boldsymbol{g}_n$. After leaving $\mathcal{D}_n$, it just needs to project on the final location $\boldsymbol{u}_F$. In other cases, the current waypoint $\boldsymbol{\beta}^l$ is projected on the boundary point on $\mathcal{D}_n$ closest to it in the traditional projection method. In this way, we obtained N different projection points at one iteration, which is denoted as $\mathcal{P}_{\mathcal{D}_n}(\boldsymbol{\beta}^l) = [x_n^l, y_n^l], \forall n \in \mathcal{N}, l \in \mathcal{L}$.

In order to maintain a relative fairness in the communication between UAV and N GUs, each waypoint should be adjusted accordingly. However, the traditional PPM algorithm does not always meet our requirements by calculating the average coordinate value (i.e., centroid [11]) of N projection points, such as when the location of a few projection points deviate too much, the location of the next waypoint can be unbalanced. In order to avoid this situation, we reformulate the relationship between N projection points and waypoint $\boldsymbol{\beta}^{l+1}$ as a min-max problem, so as to make the N distances between $\boldsymbol{\beta}^{l+1}$ and N projection points in the lth iteration as balanced as possible. So we make the following modification for (7):

$$\min_{\boldsymbol{\beta}} \max_{n \in \mathcal{N}} \quad \|\boldsymbol{\beta} - \mathcal{P}_{\mathcal{D}_n}(\boldsymbol{\beta}^l)\|^2 \tag{9}$$

$$\text{s.t.} \quad \min_{n \in \mathcal{N}} x_n^l \le x \le \max_{n \in \mathcal{N}} x_n^l, \tag{9a}$$

$$\min_{n \in \mathcal{N}} y_n^l \le y \le \max_{n \in \mathcal{N}} y_n^l, \tag{9b}$$

where $\boldsymbol{\beta} = [x, y]^T$ is the optimization variable, and constraints (9a) and (9b) limit the range of $\boldsymbol{\beta}$ to the scope of N projection points. After getting the optimal solution $\boldsymbol{\beta}^*$ from (9), we use λ^l to control the step size of $\boldsymbol{\beta}^l$ go forward to $\boldsymbol{\beta}^*$, so that the iterative equation of $\boldsymbol{\beta}^l$ is expressed as:

$$\boldsymbol{\beta}^{l+1} = \boldsymbol{\beta}^l + \lambda^l(\boldsymbol{\beta}^* - \boldsymbol{\beta}^l),\ n \in \mathcal{N}. \tag{10}$$

If $\lambda^l = 1$, then $\boldsymbol{\beta}^{l+1} = \boldsymbol{\beta}^*$.

B. Trajectory Design Algorithm for GTS

Let us propose two trajectory design algorithms for homogeneous and heterogeneous GTS respectively.

For homogeneous GTS, each GU has the same communication radius $r_n = r, \forall n \in \mathcal{N}$ and unknown data collection volume $\mathcal{R}_n$, while assume $\mathcal{R}_n = +\infty, \forall n \in \mathcal{N}$. In order to satisfy the fairness of UAV when collecting data from N GUs, we only need to directly use the MPPM mentioned in the previous part to calculate the waypoints of the trajectory in this situation. The trajectory design algorithm for homogeneous GTS is given by Algorithm 1.

Algorithm 1 MPPM for Homogeneous GTS

Input:

Each GU's location $\boldsymbol{g}_n$, communication radius r_n and data volume $\mathcal{R}_n$, $\forall n \in \mathcal{N}$;
The initial location $\boldsymbol{u}_0$ and final location $\boldsymbol{u}_F$ of UAV;
Maximum number of iterations for MPPM I, step size λ, algorithm accuracy ε.

Output:

Waypoints set $\mathcal{L}$;

1: $\boldsymbol{\beta}^1 = \boldsymbol{u}_0$;
2: **for** $l = 2; l < I; l++$ **do**
3:   **for** $n = 1; n < N; n++$ **do**
4:     Obtain ith projection point $\mathcal{P}_{\mathcal{D}_n}(\boldsymbol{\beta}^l)$ on $\mathcal{D}_n$ by equation (8);
5:     **if** $\|\boldsymbol{\beta}^l - \boldsymbol{g}_n\| > r_n$ and $b_n - r_n < y_n^l < b_n$ **then**
6:       $\mathcal{P}_{\mathcal{D}_n}(\boldsymbol{\beta}^l) = \boldsymbol{g}_n$;
7:     **end if**
8:   **end for**
9:   Obtain $l+1$th optimal solution $\boldsymbol{\beta}^*$ by solving the min-max problem in (9);
10:   $\boldsymbol{\beta}^{l+1} = \boldsymbol{\beta}^l + \lambda^l(\boldsymbol{\beta}^* - \boldsymbol{\beta}^l)$;
11:   **if** $\|\boldsymbol{\beta}^{l+1} - \boldsymbol{u}_F\| \le \varepsilon$ **then**
12:     break;
13:   **end if**
14: **end for**
15: **return** waypoints set $\mathcal{L}$.

In the above pseudo codes 5-7 of Algorithm 1, we handle the exception when the UAV has not entered the inner region of $\mathcal{D}_n$, the current waypoint will project to its boundary, but the waypoint continuously pushes forward and passes the $\mathcal{D}_n$ on the outside and cannot enter its inner region all the time. Once that happens, we project the current waypoint directly on the $\boldsymbol{g}_n$ to avoid missing the opportunity of data transmission between UAV and the nth GU.

For heterogeneous GTS, each GU may have different communication radius r_n and presupposed data collection volume. Therefore, new communication constraints may be added to the UAV during its flight, that is, the UAV needs to complete quantitative data collection tasks, i.e., the throughput constraints are:

$$\bar{R}_n \ge \mathcal{R}_n,\ n \in \mathcal{N}, \tag{11}$$

where $\mathcal{R}_n$ denotes the data volume of nth GU. Besides, the auxiliary variable ξ_n expressed in (4) can also be redefined to determine whether the UAV is transmitting data from the nth GU.

We need to adjust the calculation of each $\boldsymbol{\beta}^l$ to ensure the fairness of communication under the constrained-throughput, so that the waypoints obtained by solving the min-max problem in (9) is closer to the GU with smaller communication radius r_n or larger volume of data transmission. So we reformulate the problem (9) into the following form:

$$\min_{\boldsymbol{\beta}} \max_{n \in \mathcal{N}} \quad \omega_n \|\boldsymbol{\beta} - \mathcal{P}_{\mathcal{D}_n}(\boldsymbol{\beta}^l)\|^2 \tag{12}$$

$$\text{s.t.} \qquad (9\text{a}), (9\text{b}), \tag{12a}$$

where ω_n is the weight when the communication radius r_n and data volume $\mathcal{R}_n, \forall n \in \mathcal{N}$ are given, which makes the waypoints closer to the GUs with larger data volume $\mathcal{R}_n$ and smaller communication radius r_n. Therefore, the weight ω_n can be given as:

$$\omega_n = \frac{\mathcal{R}_n / r_n}{\sum_{i=1}^{N} \mathcal{R}_n / r_n}, \quad n \in \mathcal{N}. \tag{13}$$

Therefore, we can find a set of fair waypoints in the heterogeneous GTS by solving the weighted min-max problem (12) at every iteration. Meanwhile, because we already know the volume of data that UAV needs to collect from each GU, and we can calculate the volume of data that have been transmitted between UAV and each GU by the data transmission model (5) with the given speed V of UAV. Then we can derive whether the UAV has completed each GU's transmission tasks before the current waypoint. For the GU whose data transmission has been completed, it can be removed from the set $\mathcal{N}$, and the new set $\mathcal{N}$ and GTS can be used to calculate the next waypoint. In this way, we can greatly enhance the efficiency of our algorithm to design a more reasonable trajectory of UAV. Based on Algorithm 1, the trajectory design algorithm for heterogeneous GTS is given by Algorithm 2.

As the heterogeneous GTS becomes a dynamic topology construction, for the last GU which still has unfinished missions, the waypoint can only be projected onto the boundary of the $\mathcal{D}_n$ constantly. The pseudo codes 6-8 of Algorithm 2 is used to deal with such exceptional case, i.e., when the distance between two waypoints is less than a certain precision, we make the current waypoint advance to the final location with a proper distance, so that the trajectory can jump out of the limit range. In fact, this only happens when the last GU never completes the data transmission task. In addition, once all of the data collection tasks are completed, the UAV flies to the final location directly as expressed in Algorithm 2 (16-19).

Algorithm 2 MPPM for heterogeneous GTS

Input:

Input of Algorithm 1.

Output:

Output of Algorithm 1;

$\boldsymbol{\beta}^1 = \boldsymbol{u}_0$;
for $l = 2; l < I; l++$ **do**
  Pseudo codes 3-8 of Algorithm 1;
  Obtain $l+1$th waypoint $\boldsymbol{\beta}^*$ by solving the weighted min-max problem in (12);
  $\boldsymbol{\beta}^{l+1} = \boldsymbol{\beta}^l + \lambda^l(\boldsymbol{\beta}^* - \boldsymbol{\beta}^l)$;
  if $\|\boldsymbol{\beta}^l - \boldsymbol{\beta}^{l-1}\| \leq \epsilon$ **then**
    $\boldsymbol{\beta} = \boldsymbol{\beta} + \lambda^l r_n \frac{\boldsymbol{u}_F - \boldsymbol{\beta}^l}{\|\boldsymbol{u}_F - \boldsymbol{\beta}^l\|}$;
  end if
  for $n = 1; n < N; n++$ **do**
    Obtain the data volume $\bar{R}_l$ by (5) during the flight of the UAV from waypoint $\boldsymbol{\beta}^l$ to $\boldsymbol{\beta}^{l+1}$ in $\mathcal{D}_n$;
    $\mathcal{R}_n = \mathcal{R}_n - \bar{R}_l$;
    if $\mathcal{R}_n \leq 0$ **then**
      Remove $\boldsymbol{g}_n$ from the GU set $\mathcal{N}$;
    end if
  end for
  if $\mathcal{R}_n \leq 0, \forall n \in \mathcal{N}$ **then**
    $\boldsymbol{\beta}^{l+1} = \boldsymbol{u}_F$;
    break;
  end if
end for
Pseudo codes 11-15 of Algorithm 1.

IV. Simulation and Numerical Analysis

In this section, we provide numerical results to show the performance of our proposed trajectory design algorithms. The simulation parameters and values are summarized in Table I.

TABLE I
SIMULATION PARAMETERS AND VALUES

Parameter	Value
Altitude of UAV H	$100m$
Transmission power P	$30dBm$
Velocity of UAV V	$8m/s$
Noise power σ^2	$-110dBm$
Reference channel power β_0	$-20dB$
Communication bandwidth B	$10MHz$
Number of subcarriers K	10
Experimental ground range	$1500m \times 1500m$
Initial location $\boldsymbol{u}_0$	$(0, 0, 100)$
Final location $\boldsymbol{u}_F$	$(1200, 1500, 100)$
Number of GUs N	6

We choose six points as the location of GUs that have a relatively ideal intersection of communication range under the constraints of spatial distribution. Then, the proposed MPPM algorithm for homogeneous and heterogeneous GTS is respectively used to obtain a group of waypoints on the UAV trajectory. Next, we will show the experimental process and results of MPPM algorithms in detail under these two situations.

TABLE II
SIMULATION PARAMETERS AND VALUES

GUn	$\boldsymbol{g}_n/m$	r_n/m	$\mathcal{R}_n/bit$
GU_1	$[503.6, 604.8]^T$	360	2.2×10^9
GU_2	$[519.2, 873.2]^T$	350	2.0×10^9
GU_3	$[959.2, 692.4]^T$	400	1.2×10^9
GU_4	$[853.6, 540.4]^T$	360	1.5×10^9
GU_5	$[654.0, 445.0]^T$	380	1.6×10^9
GU_6	$[867.0, 867.0]^T$	350	1.8×10^9

We first consider the situation of homogeneous GTS, i.e., the six GUs have same communication radius and data volume. So we set that all of the radius $r_n = 400m$, the coordinates of each GU are shown in Table II, and the step size parameter $\lambda^1 = 1, \lambda^l = 0.5$ where $l > 1$. Then the UAV trajectory designed by the MPPM algorithm of homogeneous GTS is shown in Fig. 3, where the trajectory connected by the waypoints goes through the middle area of the GTS and maintains a fair distance from all GUs as far as possible. Although the trajectory is connected by a number of straight lines, it is generally in a smooth state.

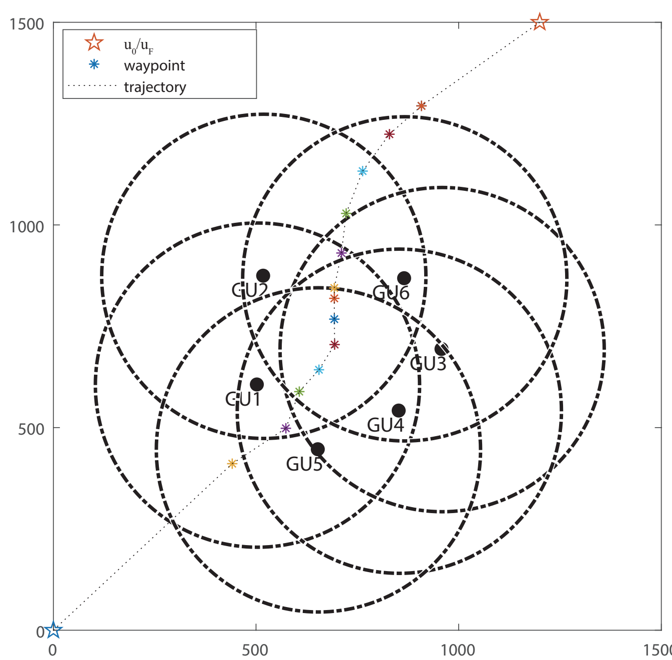


Fig. 3. Illustration of the UAV trajectory designed by the MPPM algorithm of homogeneous GTS.

Next, we consider the situation of heterogeneous GTS, i.e., the N GUs have different communication radius and presupposed data transmission volume. The specific parameters and values of each GU are shown in Table II, and the step size parameter $\lambda^l = 0.4, \forall l \in \mathcal{L}$. Then the UAV trajectory designed by the MPPM algorithm of heterogeneous GTS is shown in Fig. 4, where the blue dotted lines with the arrow and the words "GU_n" marked with blue font point to different waypoints. These represent that the UAV had completed its data collection tasks with the GU_n before flying to the pointed waypoints. As can be seen from Fig. 4, since GU_1 and GU_2 need to transmit the largest amount of data, the first half of the trajectory is integrally biased to the left of GTS. In addition, after all the data is transmitted, the UAV flies directly to the final location $\boldsymbol{u}_F$. Although the trajectory in the dynamic GTS also traverses the intermediate region and completes all tasks in the form of synchronous transmission, it is obvious that the trajectory in Fig. 4 is less smooth than that in Fig. 3. This is because the change of GTS causes the waypoints to deviate from the original direction, and how to smooth the trajectory obtained by the MPPM algorithm is left for future work.

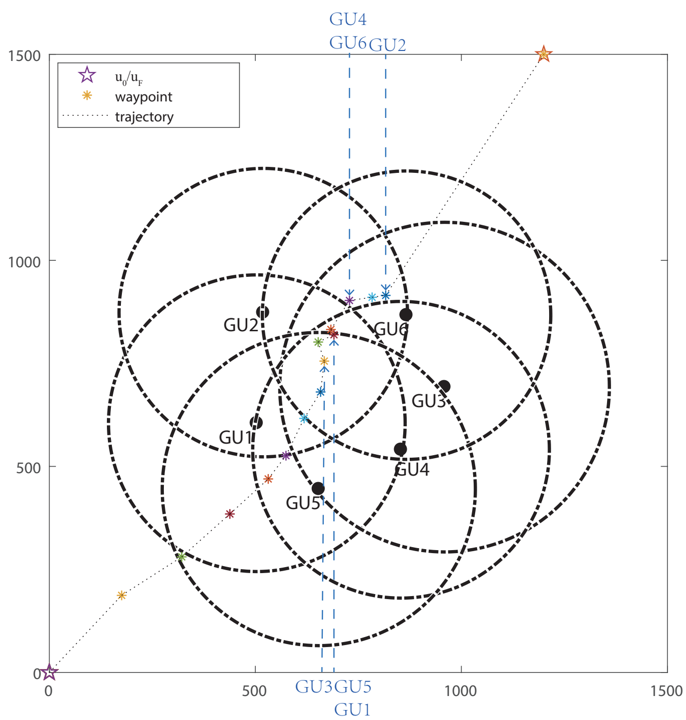


Fig. 4. Illustration of the UAV trajectory designed by the MPPM algorithm of heterogeneous GTS. The blue dotted lines with the arrow and the words "GU_n" marked with blue font point to different waypoints. These represent that the UAV had completed its data collection tasks with the GU_n before flying to the pointed waypoints.

As can be seen from the above experimental results, when the UAV needs to perform data collection tasks with mutiple GUs at the same time, the proposed algorithms have a relatively ideal performance in the corresponding GTS. The trajectory designed by the algorithms not only saves the flight distance and energy consumption of the UAV, but also takes the communication fairness and throughput constraints into consideration, thus improving the working efficiency of the UAV in wireless cellular networks.

V. Conclusion

In this paper, we studied a jointly optimal fair data collection and trajectory design problem of UAV in the wireless cellular networks. We considered the case where GUs are densely distributed on the ground, and adjusted the parallel projection algorithm for homogeneous and heterogeneous GUs' topology structure. The algorithms were mainly used to find the waypoints that constitute the UAV trajectory, and these waypoints guarantee the fairness of data collection by solving the (weighted) min-max problem. We also considered calculating the current data collection volume of the UAV while planning the next waypoint to determine whether the mission is completed or not, and dynamically changing the structure of GTS by deleting the GU that has been completed in data transmission task, so as to avoid unnecessary calculation amount. Such a trajectory of the UAV not only avoids detour, but also adjusts the distance with all GUs to ensure the fairness of data collection. Simulation results showed that the proposed algorithms based on MPPM are effective and efficient for trajectory design of UAV.

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