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Resource and Trajectory Optimization in UAV-powered Wireless Communication System

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Abstract Unmanned aerial vehicle (UAV) is a promising enabler of Internet of Things (IoT) due to its highly flexible features. Combined with wireless power transfer (WPT) technique, UAV can provide energy for IoT nodes, which can extend the lifetime of energy constrained communication system. This paper studies resource and trajectory optimization in UAV-powered wireless communication system, which consists of two UAVs and two ground nodes (GNs). The system works in a way that the two UAVs alternately charge the two GNs through wireless power transfer and two GNs also alternately send their information to the corresponding UAV with the harvested energy, which can effectively reduce the interference while receiving the information of GNs. Aiming to maximize the minimum throughput of two GNs, wireless resource and UAVs' trajectories are jointly optimized with the constraints of UAV collision avoidance, flying speed, and transmit power. Successive convex programming (SCP) and block coordinate descent (BCD) are utilized to solve the optimization problem. Simulation results show that the proposed scheme achieves larger minimum throughput than the benchmark scheme.

Keywords UAV, wireless power transfer, trajectory optimization, resource allocation

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1 Introduction

With the advent of 5G where massive connectivity is a major design objective, Internet of Things (IoT) has been rapidly integrated into our lives. IoT consists of a massive number of devices whose lifetimes are limited by battery capacity [1–3]. On the other hand, recently, radio frequency (RF) energy transfer system has been demonstrated by Farinholt in laboratory, and has been deployed in field experiments on the Alamosa Canyon Bridge in New Mexico [4]. Wireless power transfer (WPT) technology makes it possible to charge the batteries from RF signals for the IoT nodes, which can effectively extend the lifetime of the energy-constrained wireless systems [5–7]. Information transmission power optimization and time allocation in wireless systems powered by WPT have been studied in [8, 9].

Unmanned aerial vehicle (UAV) has been applied in various scenarios due to its highly flexible features. Due to the short-distance line-of-sight energy transmission links, UAV communication can improve the energy harvesting efficiency [10–12]. Motivated by various applications of UAV in IoT, e.g., information collecting from IoT nodes [13, 14], relay forwarding for the IoT network [15] and IoT value-added services

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providing [16], the combination of WPT technology and UAV has attracted significant research interest from academia and industry. A new UAV enabled WPT framework was proposed in [17], in which UAV acts as energy transmitter (ET) to charge for numerical energy receivers (ERs) by flying over a large area. In [18], through optimizing the trajectory of UAV, minimum harvested energy at ERs is maximized with the constraint of UAV's maximum speed. In [19], the performance of UAV enabled WPT system is maximized by optimizing antenna angle, in which UAV carries directional antenna to transmit energy for ground nodes (GNs).

In UAV-powered wireless communication system, the trajectory of UAV and resource allocation are two main factors which will significantly affect the system throughput. In [20], energy transfer efficiency is maximized by optimizing UAV trajectory through enhanced learning. The energy consumption of rotary-wing UAV is minimized with joint communication time allocation and UAV trajectory optimization while satisfying the throughput requirements of GNs, in which UAVs communicate with multiple GNs [21]. In [22], resource allocation and UAV trajectory are jointly optimized to maximize the minimum throughput with time and energy constraints. In [23], UAV trajectory is optimized in multi-user single-UAV network to maximize the throughput in wireless powered network. [11] and [24] studied two-UAVs and two-GNs wireless powered network to maximize the minimum throughput of GNs with the flight speed and users energy constraints. In [25], a multi-UAV and multi-ground-nodes IoT wireless powered network is studied, in which UAVs serve GNs through time division multiple address.

However, in existing UAV-powered wireless communication systems, multiple GNs simultaneously transmit their information to UAVs, causing interferences when receiving the information of GNs at UAVs, which would degrade the system throughput. To reduce the interference, in this paper, we propose a resource and trajectory optimization scheme in a two-UAVs and two-GNs UAV-powered wireless communication system. Specifically, two UAVs alternately charge two GNs through WPT and two GNs also alternately send their information to the corresponding UAV with the harvested energy. The main contributions of this paper are summarized as follows:

- To effectively reduce the interference received at UAVs, we propose a resource and trajectory optimization scheme in a two-UAVs and two-GNs UAV-powered wireless communication system. In the proposed scheme, through alternately power charging and information receiving, the interference can be reduced while receiving information at UAVs.
- We formulate a joint optimization problem to maximize the minimum throughput of two GNs, through optimizing the wireless resource and UAVs' trajectories with the constraints of UAV collision avoidance, flying speed and transmit power. SCP and BCD are utilized to solve the optimization problem.
- We carry out simulations to evaluate and illustrate the performance of the proposed scheme.

The rest of this paper is organized as follows. The two-UAVs and two-GNs system model and optimization problem is described in Section 2. In Section 3, the original optimization problem is approximated to a convex optimization problem and solved by CVX. In Section 4, the simulation results are presented. Section 5 concludes this paper.

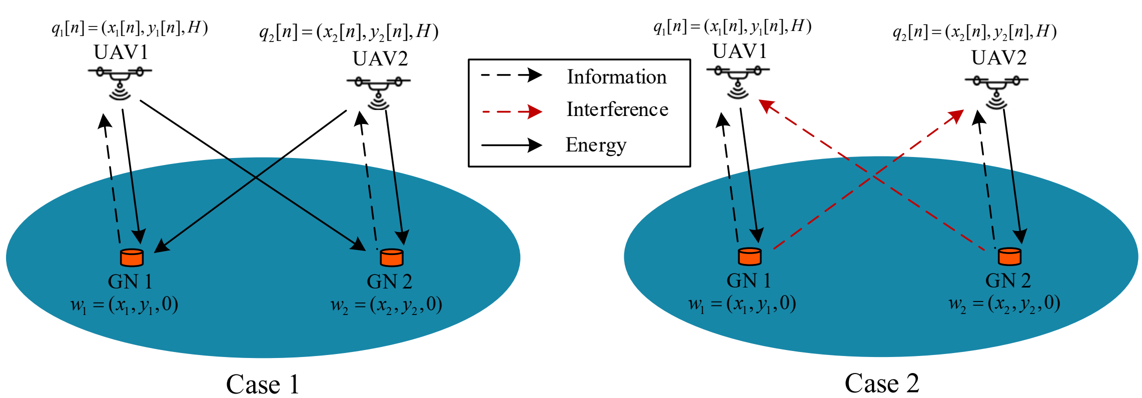

Figure 1 System model

2 System model and problem formulation

2.1 System model

We consider an UAV-powered wireless communication system, which consists of two UAVs and two GNs. We assume two UAVs have sufficient energy. They charge two GNs nodes through WPT by transmitting some special energy signals in the downlink. Two GNs transmit their information to UAVs by utilizing the harvested energy in the uplink. UAVs are assumed to fly from the given start point to the end point at an fixed altitude H within a limited flight time T. We consider the energy neutrality constraint at each GN, such that the energy used for information transmitting in the uplink does not exceed the energy harvested from the downlink. The flight time T is equally divided into N time slots, i.e., $\delta = T/N$. In each time slot, UAV j is assumed to be hovered at a fixed location $q_j[n] = (x_j[n], y_j[n]), j \in \{1,2\}, n \in \mathcal{N} = \{0,1,2,...,N\}$. The start and end point of UAV j is denoted as $q_j[0]$ and $q_j[N]$, respectively. The UAVs are supposed to know the location of each GN, which is fixed at $w_i = (x_i, y_i, 0), i \in \{1,2\}$.

The distance between GN i and UAV j in time slot n is given by

$$d_{w_i,q_j}[n] = \sqrt{||q_j[n] - w_i||^2 + H^2}, i,j \in \{1,2\} \tag{1}$$

The channel power gain between GN i and UAV j in time slot n is given by [26]- [27]

$$h_{w_i,q_j}[n] = \beta d_{w_i,q_j}^{-2}[n] = \frac{\beta}{||q_j[n] - w_i||^2 + H^2}, i,j \in \{1,2\} \tag{2}$$

where β denotes the channel power gain at distance $d_0 = 1m$.

Each time slot δ is further divided into two phases, $\delta_E[n]$ and $\delta_I[n]$, where $\delta_E[n] + \delta_I[n] \leqslant \delta$. In phase $\delta_E[n]$, UAV j transmits independent energy signals to charge the GNs. In phase $\delta_I[n]$, GN i transmits information to its corresponding UAV i.

To reduce the interference, UAVs alternately charge GNs in phase $\delta_E[n]$, and GNs alternately transmit information to UAVs in phase $\delta_I[n]$. Based on the values relationship between $\delta_E[n]$ and $\delta_I[n]$, the time allocation of $\delta_E[n]$ and $\delta_I[n]$ will have two different cases as shown in Fig. 2.

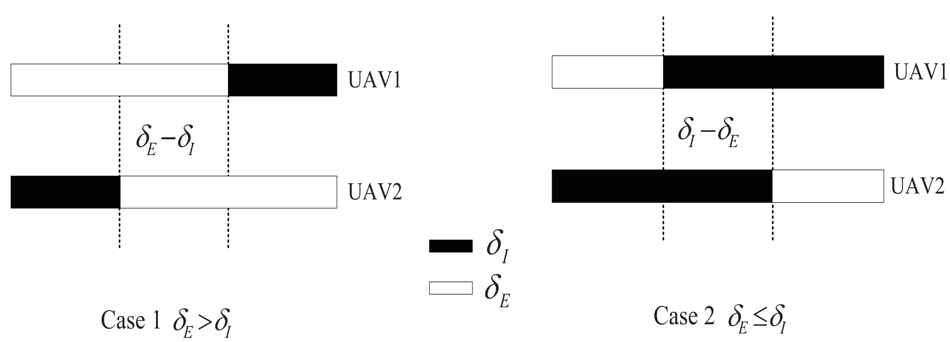

Figure 2 Time allocation two cases

2.1.1 *Case 1*

In Case 1, the phase time of $\delta_E[n]$ is larger than the phase time of $\delta_I[n]$, i.e., $\delta_E[n] > \delta_I[n]$. In Fig. 2, we can find that GN 1 and GN 2 alternately transmit their information to UAV 1 and UAV 2, respectively, at different time. Thus, interference can be fully avoided at both UAVs 1). Then, SINR received at UAV i is given by

$$\gamma_i[n] = \frac{Q_i[n] h_{w_i,q_i}[n]}{\sigma^2} \tag{3}$$

1) The energy signals transmitted by UAVs used to charge GNs may be consisted of several continuous 1 or 0 [28]- [29]. Known interference cancellation (KIC) based method can be used to cancel the interference. Thus, the transmission of energy signals of UAVs will not cause interference to the information receiving of GNs.

where $Q_i[n]$ denotes the information transmission power of GN i in time slot n, σ^2 denotes the received noise power at UAV.

Achievable average information rate from GN i to UAV i in time slot n is given by

$$r_i[n] = \frac{\delta_I[n]}{\delta} \log_2 \left(1 + \frac{Q_i[n]h_{w_i,q_i}[n]}{\sigma^2}\right) \tag{4}$$

In Fig. 2, we can find that there is an overlap time of energy signals transmission, i.e., $\delta_E[n] - \delta_I[n]$. Thus, each GN can harvest energy from two UAVs in this overlap time. Then, the energy harvested at GN i from UAV i and UAV j can be given by

$$E_{w_i,q_i}[n] = \delta_E[n]\eta P h_{w_i,q_i}[n] \tag{5}$$

$$E_{w_i,q_j}[n] = (\delta_E[n] - \delta_I[n])\eta P h_{w_i,q_j}[n] \tag{6}$$

where η denotes the energy conversion efficiency at GN, P denotes the energy transfer power at UAVs.

2.1.2 *Case 2*

In Case 2, the phase time of $\delta_E[n]$ is smaller than the phase time of $\delta_I[n]$, i.e., $\delta_E[n] \leqslant \delta_I[n]$. In Fig.2, we can find that it exists an overlap time of information transmission, i.e., $\delta_I[n] - \delta_E[n]$, which means that GN 1 and GN 2 simultaneously transmit their information during this overlap time. Thus, interference will be caused at UAVs in this time.

Achievable average information rate from GN i to UAV i in time slot n is given by

$$r_i[n] = \frac{\delta_E[n]}{\delta} \log_2 \left(1 + \frac{Q_i[n]h_{w_i,q_i}[n]}{\sigma^2}\right) + \frac{\delta_I[n] - \delta_E[n]}{\delta} \log_2 \left(1 + \frac{Q_i[n]h_{w_i,q_i}[n]}{Q_j[n]h_{w_j,q_i}[n] + \sigma^2}\right) \tag{7}$$

The energy harvested at GN i from UAV i and UAV j can be given by

$$E_{w_i,q_i}[n] = \delta_E[n]\eta P h_{w_i,q_i}[n] \tag{8}$$

$$E_{w_i,q_j}[n] = 0 \tag{9}$$

2.2 Problem formulation

The average information rate throughput from GN i to UAV i in the whole flight time T is given by

$$R_i = \frac{1}{N} \sum_{n=1}^{N} r_i[n] \tag{10}$$

The energy received at GN i in time slot n is given by

$$E_{w_i}[n] = E_{w_i,q_i}[n] + E_{w_i,q_j}[n] \tag{11}$$

The total energy received at GN i in the whole flight time T is given by

$$E^i_{total} = \sum_{n=1}^{N} E_{w_i}[n] \tag{12}$$

The total energy cost of GN i is given by

$$Q^i_{total} = \sum_{\mathrm{n}=1}^{N} Q_i[n]\delta_I[n] \tag{13}$$

With the objective to maximize the minimum throughput of two GNs R_i, by joint optimizing of UAVs' trajectories $\mathcal{A} = \{q_i[n]\}$, time allocation $\mathcal{B} = \{\delta_I[n], \delta_E[n]\}$, and GNs' transmit power $\mathcal{C} = \{Q_i[n]\}$, with the time, power, UAVs' collision avoidance and maximum speed constraints, the optimization problem is formulated as

$$\text{(P1)}: \max_{\{\mathcal{A},\mathcal{B},\mathcal{C}\}} \min_{i\in\{1,2\}} R_i \tag{14}$$

subject to

$$\begin{aligned}
C1:&\quad Q^i_{total} \leqslant E^i_{total}, \forall i \in \{1,2\}\\
C2:&\quad \delta_E[n] + \delta_I[n] \leqslant \delta, \forall n \in N\\
C3:&\quad 0 \leqslant \delta_I[n] \leqslant \delta, 0 \leqslant \delta_E[n] \leqslant \delta, \forall n \in N\\
C4:&\quad ||q_j[n] - q_j[n-1]||^2 \leqslant S^2_{\max}, \forall n \in N, j \in \{1,2\}\\
C5:&\quad ||q_1[n] - q_2[n]||^2 \geqslant d^2_{\min}, \forall n \in N
\end{aligned}$$

where $C1$ denotes that the transmit power of GN i should not exceed the energy harvested from UAVs, $C2$ and $C3$ denote that time allocated for information transmitting, energy harvesting and their summation should be smaller than one time slot, $C4$ denotes that UAVs' speed in each time slot should not exceed the maximum flying speed, $C5$ denotes that distance between two UAVs should be larger than the minimum inter-UAV distance.

3 Problem solution

In this section, we maximize the minimum throughput of two GNs through joint optimization of UAVs' trajectories, time allocation and GNs' transmit power.

In Section 2, we find that the average information rate throughput and the total energy received for GNs have different values in Case 1 and Case 2. Thus, the problem solution needs to be obtained according to the above two different cases.

3.1 Solution of Case 1

Substituting (4)-(6) into (10) (12) and (13), the optimization problem (P1) is written as

$$\text{(P2)}: \max_{\{\mathcal{A},\mathcal{B},\mathcal{C}\}} \min_{i\in\{1,2\}} \frac{1}{N}\sum_{n=1}^{N} \frac{\delta_I[n]}{\delta} \log_2\left(1 + \frac{\beta Q_i[n]}{(||q_i[n] - w_i||^2 + H^2)\sigma^2}\right) \tag{15}$$

subject to

$$\begin{aligned}
&C6: \sum_{\text{n}=1}^{N} Q_i[n]\delta_I[n] \leqslant \sum_{n=1}^{N}\left(\frac{\delta_E[n]\eta\beta P}{||q_i[n] - w_i||^2 + H^2} + \frac{(\delta_E[n] - \delta_I[n])\,\eta\beta P}{||q_j[n] - w_i||^2 + H^2}\right), \forall i \in \{1,2\}\\
&C2 - C5
\end{aligned}$$

It is easy to find that the constraints of $C6$, $C4$ and $C5$ are non-convex. Thus, the optimization problem (P2) is non-convex [30], which is hard to obtain the optimal solution.

By introducing an auxiliary variable R, the optimization problem (P2) can be equivalently reformulated as

$$\text{(P2.1)}: \max_{\{\mathcal{A},\mathcal{B},\mathcal{C}\},R} R \tag{16}$$

subject to

$$\begin{aligned}
&C7: \frac{1}{N}\sum_{n=1}^{N} \frac{\delta_I[n]}{\delta} \log_2\left(1 + \frac{\beta Q_i[n]}{(||q_i[n] - w_i||^2 + H^2)\sigma^2}\right) \geqslant R\\
&C2 - C6
\end{aligned}$$

Although the optimization problem (P2.1) is still non-convex, we can obtain the solution through SCP and BCD techniques [23, 24]. In the following, time allocation $\mathcal{B} = \{\delta_I[n], \delta_E[n]\}$, GNs' transmit power $\mathcal{C} = \{Q_i[n]\}$ and UAVs' trajectories $\mathcal{A} = \{q_i[n]\}$ can be obtained by considering the others as given in an alternating manner.

3.1.1 *Time Allocation*

With given GNs' transmit power $\mathcal{C}$ and UAVs' trajectories $\mathcal{A}$, the time allocation optimization problem is formulated as

$$(P2.2): \max_{\{\mathcal{B}\},R} R \tag{17}$$

subject to

$$\begin{aligned}
C8: &\quad \frac{1}{N}\sum_{n=1}^{N}\frac{\delta_I[n]}{\delta}\log_2\left(1+\frac{\beta Q_i[n]}{(||q_i[n]-w_i||^2+H^2)\sigma^2}\right) \geqslant R, \forall i \in \{1,2\}\\
C9: &\quad \sum_{\mathrm{n=1}}^{N} Q_i[n]\delta_I[n] \leqslant \sum_{n=1}^{N}\left(\frac{\delta_E[n]\eta\beta P}{||q_i[n]-w_i||^2+H^2}+\frac{\left(\delta_E[n]-\delta_I[n]\right)\eta\beta P}{||q_j[n]-w_i||^2+H^2}\right), \forall i \in \{1,2\}\\
C10: &\quad \delta_E[n]+\delta_I[n] \leqslant \delta, \forall n \in N\\
C11: &\quad 0 \leqslant \delta_I[n] \leqslant \delta, 0 \leqslant \delta_E[n] \leqslant \delta, \forall n \in N
\end{aligned}$$

Problem (P2.2) can be solved by standard optimization techniques [31], such as CVX, as it is a linear program.

3.1.2 *Trajectory Optimization*

With given time allocation $\mathcal{B}$ and GNs' transmit power $\mathcal{C}$, the trajectory optimization problem is formulated as

$$(P2.3): \max_{\{\mathcal{A}\},R} R \tag{18}$$

subject to

$$\begin{aligned}
C12: &\quad \frac{1}{N}\sum_{n=1}^{N}\frac{\delta_I[n]}{\delta}\log_2\left(1+\frac{\beta Q_i[n]}{(||q_i[n]-w_i||^2+H^2)\sigma^2}\right) \geqslant R, \forall i \in \{1,2\}\\
C13: &\quad \sum_{\mathrm{n=1}}^{N} Q_i[n]\delta_I[n] \leqslant \sum_{n=1}^{N}\left(\frac{\delta_E[n]\eta\beta P}{||q_i[n]-w_i||^2+H^2}+\frac{\left(\delta_E[n]-\delta_I[n]\right)\eta\beta P}{||q_j[n]-w_i||^2+H^2}\right), \forall i \in \{1,2\}\\
C14: &\quad ||q_j[n]-q_j[n-1]||^2 \leqslant S_{\mathrm{max}}^2, \forall n \in N, j \in \{1,2\}\\
C15: &\quad ||q_1[n]-q_2[n]||^2 \geqslant d_{\mathrm{min}}^2, \forall n \in N
\end{aligned}$$

Since the constraints of $C12$, $C13$ and $C15$ are non-convex, the optimization problem (P2.3) is a non-convex problem, in which the optimal solution is difficult to obtain. SCP technique can be utilized in solving optimization problem (P2.3), in which the trajectory optimization problem is approximated to a convex problem in each iteration. Then, UAV trajectory can be obtained by updating it in an iterative manner.

Assuming the initial trajectory of UAV i is denoted as $q_i^{(0)}[n]=\left(x_i^{(0)}[n], y_i^{(0)}[n]\right)$, and the trajectory of UAV i after k-th iteration is denoted as $q_i^{(k)}[n]=\left(x_i^{(k)}[n], y_i^{(k)}[n]\right)$. Any convex function can be globally lower bounded with its first-order Taylor expansion. Thus, with any given UAVs' trajectories $\{q_i^{(k)}[n]\}$, we can obtain

$$\begin{aligned}
r_i[n] &= \frac{\delta_I[n]}{\delta}\log_2\left(1+\frac{\beta Q_i[n]}{(||q_i[n]-w_i||^2+H^2)\sigma^2}\right)\\
&\geqslant \frac{\delta_I[n]}{\delta}\left(\log_2\left((||q_i[n]-w_i||^2+H^2)\sigma^2+\beta Q_i[n]\right)-\hat{r}_{i,1}[n]\right)
\end{aligned} \tag{19}$$

where

$$\hat{r}_{i,1}[n] \triangleq \log_2\left((||q_i^k[n]-w_i||^2+H^2)\sigma^2\right)+\frac{\log_2(e)(||q_i[n]-w_i||^2-||q_i^k[n]-w_i||^2)}{(||q_i^k[n]-w_i||^2+H^2)} \tag{20}$$

$$
\begin{aligned}
\mathrm{E}_{total}^{i}[n] &= \frac{\delta_E[n]\eta\beta P}{\left\|q_i[n]-w_i\right\|^2+H^2}+\frac{\left(\delta_E[n]-\delta_I[n]\right)\eta P\beta}{\left\|q_j[n]-w_i\right\|^2+H^2}\\
&\geqslant \frac{2\delta_E[n]\eta\beta P}{\left\|q_i^k[n]-w_i\right\|^2+H^2}-\frac{\delta_E[n]\eta P\beta\left(H^2+\left\|q_i[n]-w_i\right\|^2\right)}{\left(\left\|q_i^k[n]-w_i\right\|^2+H^2\right)^2}\\
&+\left(\delta_E[n]-\delta_I[n]\right)\left(\frac{2\eta P\beta}{\left\|q_j^k[n]-w_i\right\|^2+H^2}-\frac{\eta P\beta(H^2+\left\|q_j[n]-w_i\right\|^2)}{\left(\left\|q_j^k[n]-w_i\right\|^2+H^2\right)^2}\right)\\
&\triangleq \mathrm{E}_{total}^{lb}[n]
\end{aligned}
\tag{21}
$$

$$
||q_1[n]-q_2[n]||^2 \geqslant -||q_1^k[n]-q_2^k[n]||^2+2(q_1^k[n]-q_2^k[n])^T(q_1[n]-q_2[n]) \tag{22}
$$

Denote $z=||q_i[n]-w_i||^2$ and $z_0=||q_i^k[n]-w_i||^2$, (20) can be written as

$$
\hat{r}_{i,1}[n] \triangleq \log_2\left((z_0+H^2)\sigma^2\right)+\frac{\log_2(e)(z-z_0)}{z_0+H^2} \tag{23}
$$

The equality holds for (19) when $z=z_0$. Thus, inequality (19) is tight for $q_i[n]=q_i^{(k)}[n]$ [23]. Denote $z'=||q_j[n]-w_i||^2$ and $z'_0=||q_j^k[n]-w_i||^2$, (21) can be written as

$$
\begin{aligned}
\mathrm{E}_{total}^{i}[n] &\geqslant \frac{2\delta_E[n]\eta\beta P}{z_0+H^2}-\frac{\delta_E[n]\eta P\beta\left(z+H^2\right)}{\left(z_0+H^2\right)^2}\\
&+\left(\delta_E[n]-\delta_I[n]\right)\left(\frac{2\eta P\beta}{z'_0+H^2}-\frac{\eta P\beta(z'+H^2)}{\left(z'_0+H^2\right)^2}\right)\\
&\triangleq \mathrm{E}_{total}^{lb}[n]
\end{aligned}
\tag{24}
$$

where the equality holds for (24) when $z=z_0$ and $z'=z'_0$. Thus, the inequality in (21) is tight for $q_i[n]=q_i^{(k)}[n]$ and $q_j[n]=q_j^{(k)}[n]$. Similarly, equality holds for (22) when $q_1[n]=q_1^{(k)}[n]$ and $q_2[n]=q_2^{(k)}[n]$. Thus, (22) is tight for $q_1[n]=q_1^{(k)}[n]$

Based on the above tight inequalities, the non-convex items in constraints can be replaced with their respect lower bounds in (19), (21), (22) at each iteration $k+1$, with the trajectory obtained at the previous iteration k. Specifically, UAV trajectory $\{q_i^{(k+1)}\}$ is updated as

$$
q_i^{(k+1)}[n]=arg\max_{\{\mathcal{A}\},R} R, \forall i\in\{1,2\} \tag{25}
$$

subject to

$$
\begin{aligned}
&C16: \ \frac{1}{N}\sum_{n=1}^{N}\frac{\delta_I[n]}{\delta}\left(\log_2\left((||q_i[n]-w_i||^2+H^2)\sigma^2+\beta Q_i[n]\right)-\hat{r}_{i,1}^{(k)}[n]\right)\geqslant R, \forall i\in\{1,2\}\\
&C17: \ \sum_{\mathrm{n}=1}^{N}Q_i[n]\delta_I[n]\leqslant\sum_{\mathrm{n}=1}^{N}\mathrm{E}_{total}^{lb,(k)}[n]\\
&C18: \ ||q_j^{(k)}[n]-q_j^{(k)}[n-1]||^2\leqslant S_{\max}^2, \forall n\in N, j\in\{1,2\}\\
&C19: \ -||q_1^{(k)}[n]-q_2^{(k)}[n]||^2+2(q_1^{(k)}[n]-q_2^{(k)}[n])^T(q_1[n]-q_2[n])\geqslant d_{\min}^2, \forall n\in N
\end{aligned}
$$

It is easy to find that the constraints of (C17) and (C19) are linear while (C16) is convex. Thus, in the k-th iteration optimization problem (25) is convex, which can be solved by standard optimization techniques.

The objective function in problem (25) is a lower bound for that in problem (P2.3). At each iteration k, the objective value of problem (P2.3) obtained by $q_i^{(k)}[n]$ is no smaller than that obtained by $q_i^{(k-1)}[n]$ in the previous iteration $(k-1)$. As the optimal value of problem (P2.3) is bounded above, the UAV trajectory will be converged through SCP and BCD with given time allocation $\{\delta_I[n], \delta_E[n]\}$ and power allocation $Q_i[n]$.

3.1.3 *Transmit Power Allocation*

With given time allocation $\mathcal{A}$ and UAVs' trajectories $\mathcal{B}$, the transmit power allocation optimization problem is formulated as

$$(P2.4): \max_{\{\mathcal{C}\},R} R \tag{26}$$

subject to

$$C20: \ \frac{1}{N}\sum_{n=1}^{N}\frac{\delta_I[n]}{\delta}\log_2\left(1+\frac{\beta Q_i[n]}{(||q_i[n]-w_i||^2+H^2)\sigma^2}\right) \geqslant R, \forall i\in\{1,2\}$$

$$C21: \ \sum_{n=1}^{N}Q_i[n]\delta_I[n] \leqslant \sum_{n=1}^{N}\left(\frac{\delta_E[n]\eta\beta P}{||q_i[n]-w_i||^2+H^2}+\frac{(\delta_E[n]-\delta_I[n])\,\eta\beta P}{||q_j[n]-w_i||^2+H^2}\right), \forall i\in\{1,2\}$$

Problem (P2.4) is a typical convex problem, which can be solved by standard optimization techniques.

In summary, subproblems (P2.2), (P2.3) and (P2.4) are solved in a alternating manner which ensures the objective function of problem (P2.1) to be monotonically nondecreasing after each iteration with all variables updated. Finally, the solution to (P2.1) will be converged through the proposed algorithm.

3.2 Solution of Case 2

Substituting (7-9) into (10), (12), (13), the optimization problem (P3) is written as

$$\begin{aligned}\text{(P3)}: \max_{\{\mathcal{A},\mathcal{B},\mathcal{C}\}} \min_{i\in\{1,2\}} \ & \frac{1}{N}\sum_{n=1}^{N}\frac{\delta_E[n]}{\delta}\log_2\left(1+\frac{Q_i[n]\beta}{(||q_i[n]-w_i||^2+H^2)\sigma^2}\right)\\ &+\frac{1}{N}\sum_{n=1}^{N}\frac{\delta_I[n]-\delta_E[n]}{\delta}\log_2\left(1+\frac{\frac{Q_i[n]\beta}{||q_i[n]-w_i||^2+H^2}}{\frac{Q_j[n]\beta}{||q_i[n]-w_j||^2+H^2}+\sigma^2}\right)\end{aligned} \tag{27}$$

subject to

$$C22: \sum_{n=1}^{N}Q_i[n]\delta_I[n] \leqslant \sum_{n=1}^{N}\frac{\delta_E[n]\eta\beta P}{||q_i[n]-w_i||^2+H^2}, \forall i\in\{1,2\}$$
$$C2-C5$$

It is easy to find that constraint (C22), (C4), (C5) are non-convex. Thus, optimization problem (P3) is non-convex, which is hard to solve.

Similar to the solution of Case 1, we introduce an auxiliary variable R, the optimization problem (P3) is equivalently reformulated as

$$\text{(P3.1)}: \max_{\{\mathcal{A},\mathcal{B},\mathcal{C}\},R} R \tag{28}$$

subject to

$$C23: \ \frac{1}{N}\sum_{n=1}^{N}\frac{\delta_E[n]}{\delta}\log_2\left(1+\frac{Q_i[n]\beta}{(||q_i[n]-w_i||^2+H^2)\sigma^2}\right)$$

$$+\frac{1}{N}\sum_{n=1}^{N}\frac{\delta_I[n]-\delta_E[n]}{\delta}\log_2\left(1+\frac{\frac{Q_i[n]\beta}{||q_i[n]-w_i||^2+H^2}}{\frac{Q_j[n]\beta}{||q_i[n]-w_j||^2+H^2}+\sigma^2}\right)\geqslant R,\forall i\in\{1,2\}$$

$$C2-C5,C22$$

Similar to the solution of Case 1, optimization problem (P3.1) can be solved iteratively by applying SCP and BCD techniques.

3.2.1 *Time Allocation*

With given GNs' transmit power $\mathcal{C}$ and UAVs' trajectories $\mathcal{A}$, the time allocation optimization problem is formulated as

$$(P3.2):\max_{\{\mathcal{B}\},R} R \tag{29}$$

subject to

$$\begin{aligned}
C24:\ & \frac{1}{N}\sum_{n=1}^{N}\frac{\delta_E[n]}{\delta}\log_2\left(1+\frac{Q_i[n]\beta}{(||q_i[n]-w_i||^2+H^2)\sigma^2}\right)\\
&+\frac{1}{N}\sum_{n=1}^{N}\frac{\delta_I[n]-\delta_E[n]}{\delta}\log_2\left(1+\frac{\frac{Q_i[n]\beta}{||q_i[n]-w_i||^2+H^2}}{\frac{Q_j[n]\beta}{||q_i[n]-w_j||^2+H^2}+\sigma^2}\right)\geqslant R,\forall i\in\{1,2\}\\
C25:\ & \sum_{n=1}^{N}Q_i[n]\delta_I[n]\leqslant\sum_{n=1}^{N}\frac{\delta_E[n]\eta\beta P}{||q_i[n]-w_i||^2+H^2},\forall i\in\{1,2\}\\
C26:\ & \delta_E[n]+\delta_I[n]\leqslant\delta,\forall n\in N\\
C27:\ & 0\leqslant\delta_I[n]\leqslant\delta[n],0\leqslant\delta_E[n]\leqslant\delta,\forall n\in N
\end{aligned}$$

Problem (P3.2) can be solved by stand optimization techniques because it is a linear program.

3.2.2 *Trajectory Optimization*

With given GNs' transmit power $\mathcal{C}$ and time allocation $\mathcal{B}$, the trajectory optimization problem is formulated as

$$(P3.3):\max_{\{\mathcal{A}\},R} R \tag{30}$$

subject to

$$\begin{aligned}
C28:\ & \frac{1}{N}\sum_{n=1}^{N}\frac{\delta_E[n]}{\delta}\log_2\left(1+\frac{Q_i[n]\beta}{(||q_i[n]-w_i||^2+H^2)\sigma^2}\right)\\
&+\frac{1}{N}\sum_{n=1}^{N}\frac{\delta_I[n]-\delta_E[n]}{\delta}\log_2\left(1+\frac{\frac{Q_i[n]\beta}{||q_i[n]-w_i||^2+H^2}}{\frac{Q_j[n]\beta}{||q_i[n]-w_j||^2+H^2}+\sigma^2}\right)\geqslant R,\forall i\in\{1,2\}\\
C29:\ & \sum_{n=1}^{N}Q_i[n]\delta_I[n]\leqslant\sum_{n=1}^{N}\frac{\delta_E[n]\eta\beta P}{||q_i[n]-w_i||^2+H^2},\forall i\in\{1,2\}\\
C30:\ & ||q_j[n]-q_j[n-1]||^2\leqslant S_{\max}^2,\forall j\in\{1,2\},\forall n\in N\\
C31:\ & ||q_1[n]-q_2[n]||^2\geqslant d_{\min}^2,\forall n\in N
\end{aligned}$$

It is easy to find that constraint (C28), (C29) and (C31) are non-convex. Thus, (P3.3) is non-convex, whose optimal solution is difficult to be obtained. Similar as in (3.1.2), we obtain the solution through first-order Taylor expansion.

$$\begin{aligned} r_{i,1}[n] &= \frac{\delta_E[n]}{\delta}\log_2\left(1+\frac{Q_i[n]\beta}{(||q_i[n]-w_i||^2+H^2)\sigma^2}\right) \\ &\geqslant \frac{\delta_E[n]}{\delta}\log_2\left((||q_i[n]-w_i||^2+H^2)\sigma^2+Q_i[n]\beta\right)-\frac{\delta_E[n]}{\delta}\hat{r}_{i,1}[n] \end{aligned} \tag{31}$$

$$\begin{aligned} r_{i,2}[n] &= \frac{\delta_I[n]-\delta_E[n]}{\delta}\log_2\left(1+\frac{\frac{Q_i[n]\beta}{||q_i[n]-w_i||^2+H^2}}{\frac{Q_j[n]\beta}{||q_i[n]-w_j||^2+H^2}+\sigma^2}\right) \\ &\geqslant \frac{\delta_I[n]-\delta_E[n]}{\delta}\hat{r}_{i,2}[n]-\frac{\delta_I[n]-\delta_E[n]}{\delta}\log_2\left(\frac{Q_j[n]\beta}{||q_i[n]-w_j||^2+H^2}+\sigma^2\right) \end{aligned} \tag{32}$$

where

$$\hat{r}_{i,1}[n] \triangleq \log_2\left((||q_i^k[n]-w_i||^2+H^2)\sigma^2\right)+\frac{\log_2(e)(||q_i[n]-w_i||^2-||q_i^k[n]-w_i||^2)}{||q_i^k[n]-w_i||^2+H^2} \tag{33}$$

$$\hat{r}_{i,2}[n] \triangleq A_i^k[n]-\sum_{l=1}^{2}B_i^k[n](||q_i[n]||-w_l|^2-||q_i^k[n]-w_l||^2) \tag{34}$$

where

$$A_i^k[n] = \log_2\left(\sum_{l=1}^{2}\frac{Q_l[n]\beta}{||q_i^k-w_l||^2+H^2}+\sigma^2\right) \tag{35}$$

$$B_i^k[n] = \frac{\log_2(e)\frac{Q_l[n]\beta}{(||q_i^k[n]-w_l||^2+H^2)^2}}{\sum\limits_{l=1}^{2}\frac{Q_l[n]\beta}{||q_i^k[n]-w_l||^2+H^2}+\sigma^2} \tag{36}$$

$$\begin{aligned} \mathrm{E}_{total}^{i}[n] &= \frac{\eta\beta P\delta_E[n]}{||q_i[n]-w_i||^2+H^2} \\ &\geqslant \frac{2\eta P\beta\delta_E[n]}{||q_i^k[n]-w_i||^2+H^2}-\frac{\eta P\beta\delta_E[n](||q_i[n]-w_i||^2+H^2)}{(||q_i^k[n]-w_i||^2+H^2)^2} \\ &\triangleq \hat{E}_{total}^{lb}[n] \end{aligned} \tag{37}$$

$$||q_1[n]-q_2[n]||^2 \geqslant -||q_1^k[n]-q_2^k[n]||^2+2(q_1^k[n]-q_2^k[n])^T(q_1[n]-q_2[n]) \tag{38}$$

Similar to problem (P2.1), the non-convex items in constraints can be replaced with their respect lower bounds at each iteration $k+1$, with the trajectory obtained at the previous iteration k. Specifically, $\{q_i^{(k+1)}[n]\}$ is updated as

$$q_i^{(k+1)}[n] = \max_{\{\mathcal{A}\},R} R, \forall i\in\{1,2\} \tag{39}$$

subject to

$$\begin{aligned} C32:\ & \frac{1}{N}\sum_{n=1}^{N}\left(\frac{\delta_E[n]}{\delta}\log_2\left((||q_i[n]-w_i||^2+H^2)\sigma^2+\beta Q_i[n]\right)-\frac{\delta_E[n]\hat{r}_{i,1}[n]}{\delta}\right) \\ & +\frac{1}{N}\sum_{n=1}^{N}\left(\frac{(\delta_I[n]-\delta_E[n])\hat{r}_{i,2}[n]}{\delta}-\frac{\delta_I[n]-\delta_E[n]}{\delta}\log_2\left(\frac{Q_j[n]\beta}{||q_i[n]-w_j||^2+H^2}+\sigma^2\right)\right)\geqslant R, \forall i\in\{1,2\} \end{aligned}$$

$$C33: \sum_{n=1}^{N} Q_i[n]\delta_I[n] \leqslant \sum_{n=1}^{N} \hat{E}_{total}^{lb}[n], \forall i \in \{1,2\}$$
$$C34: ||q_j[n]-q_j[n-1]||^2 \leqslant S_{max}^2, \forall j \in \{1,2\}, \forall n \in N$$
$$C35: -||q_1^k[n]-q_2^k[n]||^2 + 2(q_1^k[n]-q_2^k[n])^T(q_1[n]-q_2[n]) \geqslant d_{\min}^2, \forall n \in N$$

Constraint (C32), (C33), (C34) are convex while constraint (C35) is linear. Thus, the problem (39) is a convex optimization problem at the k-th iteration, whose solution can be converged through standard optimization technique under given time allocation $\{\delta_I[n], \delta_E[n]\}$ and power allocation $Q_i[n]$.

3.2.3 *Transmit Power Allocation*

With given time allocation $\mathcal{B}$ and UAVs' trajectories $\mathcal{A}$, the transmit power allocation optimization problem is formulated as

$$(P3.4): \max_{\{\mathcal{C}\},R} R \tag{40}$$

subject to

$$C36: \frac{1}{N}\sum_{n=1}^{N} \frac{\delta_E[n]}{\delta} \log_2\left(1+\frac{Q_i[n]\beta}{(||q_i[n]-w_i||^2+H^2)\sigma^2}\right) + \frac{1}{N}\sum_{n=1}^{N} \frac{\delta_I[n]-\delta_E[n]}{\delta} \log_2\left(1+\frac{\frac{Q_i[n]\beta}{||q_i[n]-w_i||^2+H^2}}{\frac{Q_j[n]\beta}{||q_i[n]-w_j||^2+H^2}+\sigma^2}\right) \geqslant R, \forall i \in \{1,2\}$$
$$C37: \sum_{n=1}^{N} Q_i[n]\delta_I[n] \leqslant \sum_{n=1}^{N} \frac{\delta_E[n]\eta\beta P}{||q_i[n]-w_i||^2+H^2}, \forall i \in \{1,2\}$$

Constraint (C37) is linear while constraint (C36) is non-convex. Through first-order Taylor expansion, we can obtain

$$\begin{aligned} r_{i,2}[n] &= \frac{\delta_I[n]-\delta_E[n]}{\delta} \log_2\left(1+\frac{\frac{Q_i[n]\beta}{||q_i[n]-w_i||^2+H^2}}{\frac{Q_j[n]\beta}{||q_i[n]-w_j||^2+H^2}+\sigma^2}\right) \\ &\geqslant \frac{\delta_I[n]-\delta_E[n]}{\delta}\left(\log_2\left(\frac{Q_i[n]\beta}{||q_i[n]-w_i||^2+H^2}+\frac{Q_j[n]\beta}{||q_i[n]-w_j||^2+H^2}+\sigma^2\right)-\hat{r}_{i,2}[n]\right) \end{aligned} \tag{41}$$

where

$$\hat{r}_{i,2}[n] \triangleq \log_2\left(\frac{Q_j^k[n]\beta}{||q_i[n]-w_j||^2+H^2}+\sigma^2\right) + \frac{\log_2(e)\beta}{(||q_i[n]-w_j||^2+H^2)\sigma^2+Q_j^k[n]\beta}(Q_j[n]-Q_j^k[n]) \tag{42}$$

With the lower bound in (42), $Q_j^{(k+1)}[n]$ is updated as

$$Q_j^{(k+1)} = \max_{\{\mathcal{C}\},R} R, \forall j \in \{1,2\} \tag{43}$$

subject to

$$C38: \frac{1}{N}\sum_{n=1}^{N} \frac{\delta_E[n]}{\delta} \log_2\left(1+\frac{Q_i[n]\beta}{(||q_i[n]-w_i||^2+H^2)\sigma^2}\right) + \frac{1}{N}\sum_{n=1}^{N} \frac{\delta_I[n]-\delta_E[n]}{\delta}\left(\log_2\left(\frac{Q_i[n]\beta}{||q_i[n]-w_i||^2+H^2}+\frac{Q_j[n]\beta}{||q_i[n]-w_j||^2+H^2}+\sigma^2\right)-\hat{r}_{i,2}[n]\right)$$

$$\geqslant R, \forall i \in \{1,2\}$$

$$C39: \sum_{n=1}^{N} Q_i[n]\delta_I[n] \leqslant \sum_{n=1}^{N} \frac{\delta_E[n]\eta\beta P}{||q_i[n]-w_i||^2+H^2}, \forall i \in \{1,2\}$$

Constraint (C38) is convex while constraint (C39) is linear. Thus, optimization problem (43) at k-th iteration is a convex optimization problem whose solution can be obtained through standard optimization techniques. Similar to case1, subproblems (P3.2), (P3.3) and (P3.4) are solved in an alternating manner.

The overall algorithm including Case 1 and Case 2 is shown in Algorithm 1.

Algorithm 1

Input: $w_k, q_i[0], q_i[N], T, P, V_{max}, d_{min}$
Initialize: $q_i[n], Q_i[n]$
Set $\delta_E[n] \geqslant \delta_I[n]$.
Let $\hat{\delta}_E^1[n] = \delta_E[n], \hat{\delta}_I^1[n] = \delta_I[n], \hat{q}_i^1[n] = q_i[n], \hat{Q}_i^1[n] = Q_i[n]$
Repeat
  Solve problem P(2.2) by using CVX for given $\{\hat{q}_i^1[n], \hat{Q}_i^1[n]\}$, and denote the obtained time allocation as $\{\delta_E^1[n], \delta_I^1[n]\}$.
  Solve problem P(2.3) by using CVX for given $\{\delta_E^1[n], \delta_I^1[n], \hat{Q}_i^1[n]\}$, and denote the obtained UAV trajectory as $q_i^1[n]$.
  Solve problem P(2.5) by using CVX for given $\{\delta_E^1[n], \delta_I^1[n], q_i^1[n]\}$, and denote the obtained power allocation as $Q_i^1[n]$.
  Calculate minimum uplink throughput R^1 according to $\{\delta_E^1[n], \delta_I^1[n], q_i^1[n], Q_i^1[n]\}$.
  Update $\hat{\delta}_E^1[n] = \delta_E^1[n], \hat{\delta}_I^1[n] = \delta_I^1[n], \hat{q}_i^1[n] = q_i^1[n], \hat{Q}_i^1[n] = Q_i^1[n]$
Until the fractional increase of the objective value is below a threshold ϵ>0.
Set $\delta_E[n]<\delta_I[n]$
Let $\hat{\delta}_E^2[n] = \delta_E[n], \hat{\delta}_I^2[n] = \delta_I[n], \hat{q}_i^2[n] = q_i[n], \hat{Q}_i^2[n] = Q_i[n]$
Repeat
  Solve problem P(3.2) by using CVX for given $\{\hat{q}_i^2[n], \hat{Q}_i^2[n]\}$, and denote the obtained time allocation as $\{\delta_E^2[n], \delta_I^2[n]\}$.
  Solve problem P(3.3) by using CVX for given $\{\delta_E^2[n], \delta_I^2[n], \hat{Q}_i^2[n]\}$, and denote the obtained UAV trajectory as $q_i^2[n]$.
  Solve problem P(3.5) by using CVX for given $\{\delta_E^2[n], \delta_I^2[n], q_i^2[n]\}$, and denote the obtained power allocation as $Q_i^2[n]$.
  Calculate minimum uplink throughput R^2 according to $\{\delta_E^2[n], \delta_I^2[n], q_i^2[n], Q_i^2[n]\}$.
  Update $\hat{\delta}_E^2[n] = \delta_E^2[n], \hat{\delta}_I^2[n] = \delta_I^2[n], \hat{q}_i^2[n] = q_i^2[n], \hat{Q}_i^2[n] = Q_i^2[n]$
Until the fractional increase of the objective value is below a threshold ϵ>0.
If $R^1 \geqslant R^2$
  $R = R^1, \delta_E[n] = \hat{\delta}_E^1[n], \delta_I[n] = \hat{\delta}_I^1[n], q_i[n] = \hat{q}_i^1[n], Q_i[n] = \hat{Q}_i^1[n]$
Else
  $R = R^2, \delta_E[n] = \hat{\delta}_E^2[n], \delta_I[n] = \hat{\delta}_I^2[n], q_i[n] = \hat{q}_i^2[n], Q_i[n] = \hat{Q}_i^2[n]$
Output $R, \delta_E[n], \delta_I[n], q_i[n], Q_i[n]$

4 Simulation Results

In this section, simulation results are presented to valid the performance of our proposed scheme. The performance comparison between our proposed scheme and the scheme proposed in [24]. In the scheme proposed in [24], two UAVs simultaneously transmit energy and receive information, which caused serious interference to each other during the information receiving. We assume that the flying altitude of UAVs is $H = 5m$. The minimum safety distance between two UAVs $d_{\min}$ is set to be 1m. Energy conversion efficiency $\eta = 0.6$.

Fig. 3 shows the UAVs trajectory of our proposed scheme and the scheme proposed in [24], in which UAV 1 flies from $(-2,-2)$ to $(-2,2)$ while UAV 2 flies from $(2,-2)$ to $(2,2)$ in limited time T. GN 1 locates at $(-5,0)$ while GN 2 locates at (5,0). The maximum flying time of UAV is set to be $T = 30s$, the energy transfer power P equals to 10W. As UAV 1 and UAV 2 serves for GN 1 and GN 2, respectively, we define GN 1 and GN 2 as corresponding node of UAV 1 and UAV 2, respectively.

In Fig. 3, we find that UAV tends to stay far away from the non-corresponding node in order to reduce interference in the scheme proposed in [24]. In the scheme proposed in this paper, UAV flies directly to its corresponding node because interference from non-corresponding node can be effectively reduced. In Fig. 4, the location of GN 2 is changed into $(5,-1)$. We can find the UAVs trajectory of our proposed scheme and scheme proposed in [24] are similar as shown in Fig. 3.

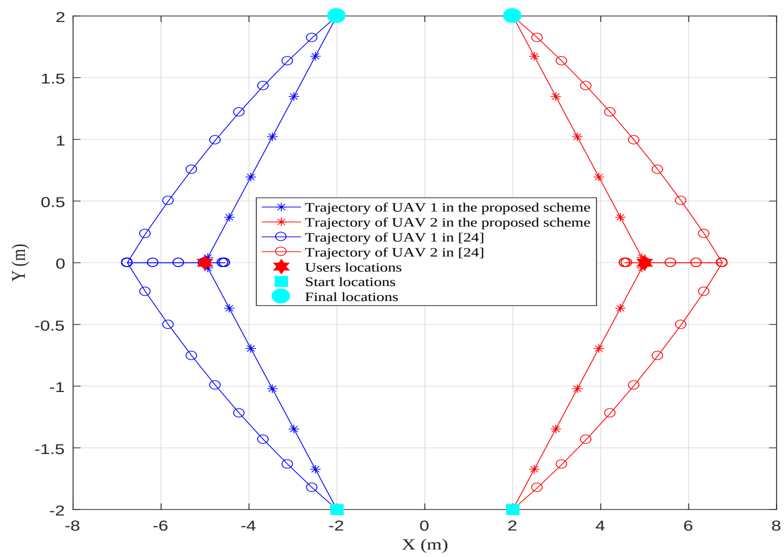

Figure 3 Trajectory of UAV with symmetric user location

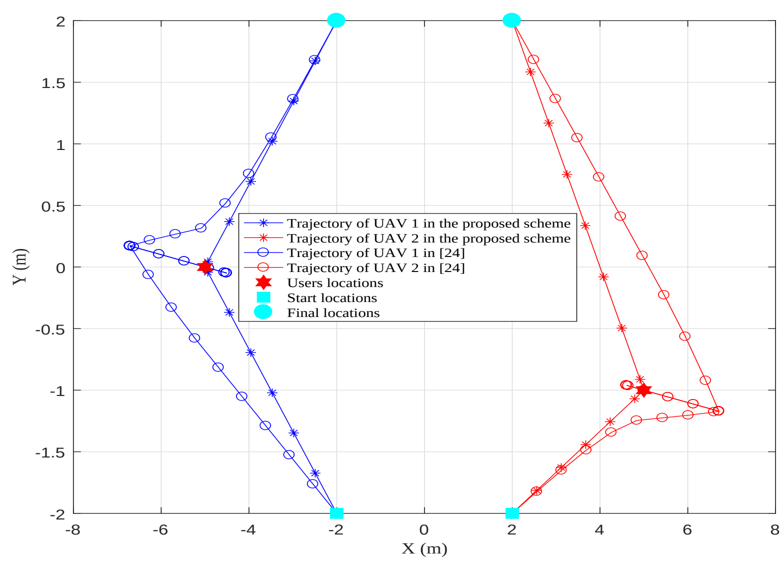

Figure 4 Trajectory of UAV with asymmetric GN location

Fig. 5 shows the minimum uplink throughput versus the distance between two GNs with different energy transfer power. In Fig. 5, we can find that our proposed scheme always outperforms the scheme proposed in [24], which is because that the interference can be effectively reduced in our proposed scheme. We can also observe from Fig. 5 that the minimum uplink throughput of our proposed scheme decreases with the increase of the distance, while the minimum uplink throughput of scheme proposed in [24] increases first then decreases. It is because that the interference in our proposed scheme can be reduced, however, the received energy at GNs becomes smaller when the distance between two GNs, which can be illustrated from Fig. 6. In contrast, in the scheme proposed in [24], the interference will be decreased when the distance between two GNs increases, which results in the increase of the minimum uplink throughput. However, with the distance further increases, the channel between the GNs and UAVs becomes worse, which results the decreasing of the minimum uplink throughput.

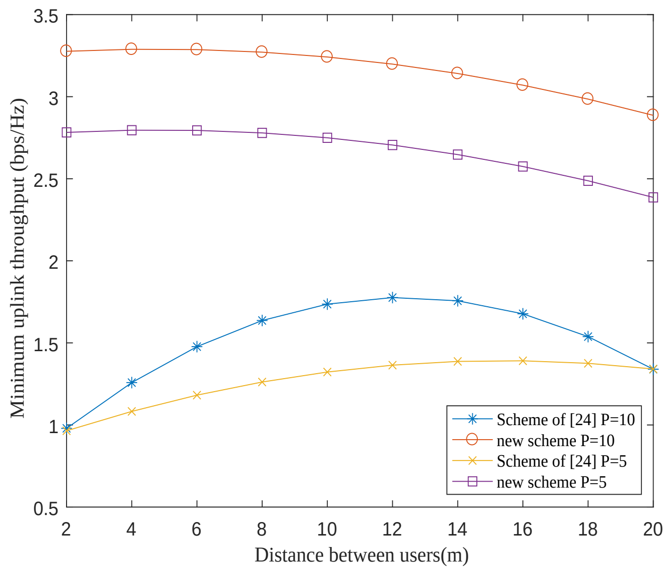

Figure 5 Minimum uplink throughput versus the distance between two GNs

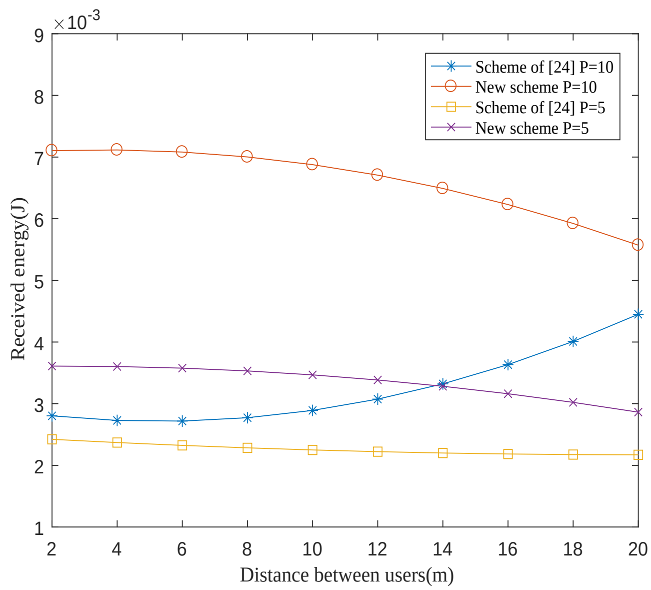

Figure 6 Received energy of GNs

Fig. 6 shows the received energy of GNs versus the distance between two GNs with different energy transfer power. From Fig. 6, we can observe that our proposed scheme can receive larger energy compared to the scheme proposed in [24]. This is because that in our proposed scheme, UAVs fly closer to its corresponding node during the whole flight time as shown in Fig. 3. We can also find from Fig. 6 that the received energy of our proposed scheme decreases with the distance due to the worse channel between GNs and UAVs.

Fig.7 shows the minimum uplink throughput versus the UAVs flight time T with different energy transfer power. In Fig. 7, we can find that our proposed scheme achieves much larger throughput than the scheme proposed in [24]. We can also observe that the minimum uplink throughput increases with the UAVs flight time, which is because that more time can be utilized to transmit signal and power with larger flight time. However, the minimum uplink throughput achieves the upper bound by the solution

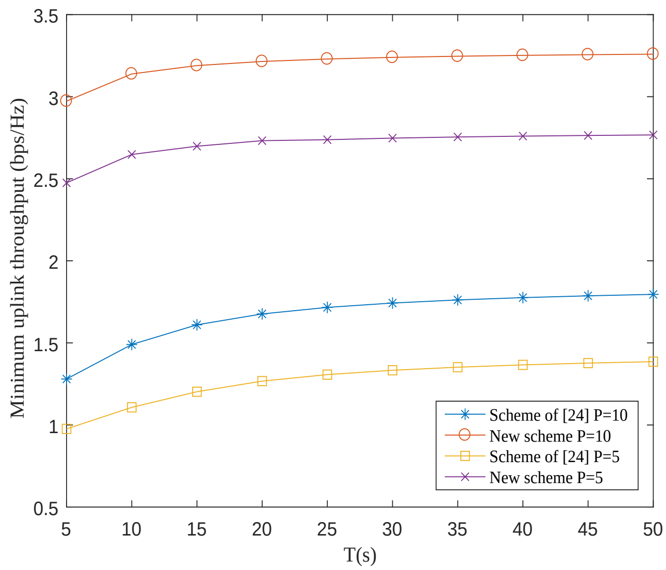

Figure 7 Minimum uplink throughput versus time of flight T

to P2 or P3 when T is sufficiently large.

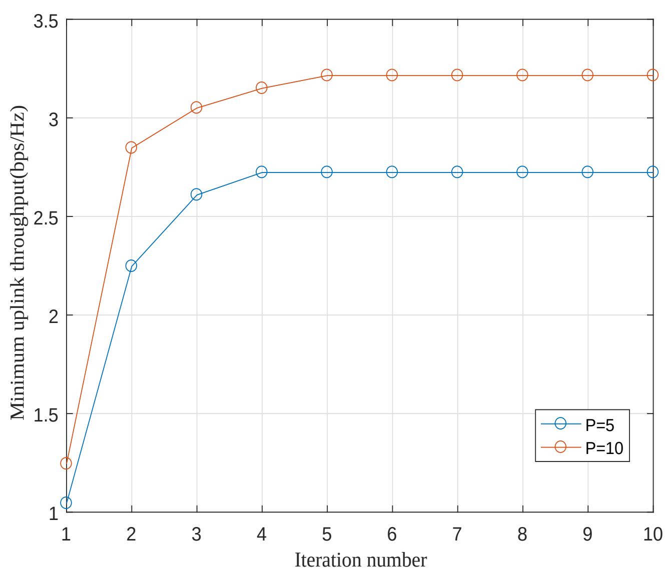

Figure 8 Convergence process of the proposed algorithm

Fig.8 shows the convergence process of the proposed algorithm, in which $T = 20s$. GN 1 and GN 2 locate at (-5,0) and (5,0), respectively. It is easy to find that the minimum uplink throughput increases monotonically, which verifies the convergence of the proposed alternative optimizing algorithm.

5 Conclusion

In this paper, we have proposed a resource and trajectory optimization scheme in UAV-powered wireless communication system which can effectively reduce the interference caused by the GNs' transmission. In the proposed scheme, the two UAVs alternately charge two GNs through wireless power transfer and two

GNs also alternately send information to their respective UAV with the harvested energy. To maximize the minimum throughput of two GNs, we have studied joint optimization of UAVs' trajectories, time allocation and GNs' transmit power with the time, power, UAVs' collision avoidance and maximum speed constraints. Simulation results show that our proposed scheme can achieve larger minimum uplink throughput than the benchmark scheme.

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