UAV-Assisted SWIPT in Jamming Environment: Joint Power and Trajectory Optimization

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ABSTRACT

Simultaneous wireless information and power transfer (SWIPT) can provide power and information synchronously, which assists to solve the problem of the limited battery capacity and inconvenient charging of Internet of Things (IoT) devices. In this paper, we investigate a SWIPT system assisted by UAV in jamming environment, where the UAV can transfer power to nodes and nodes can collect energy from the UAV. In order to maximize the minimum throughput among all IoTDs, we jointly optimize the transmit power of IoTDs and the trajectory of UAV during a fix period, while ensuring the lowest energy requirement of each node and avoiding jamming. However, the problem we proposed is NP-hard and difficult to be settled efficiently by existing methods. To address the intractable problem, we develop an iterative algorithm based on the successive convex approximation (SCA) approach. Simulation results indicate that our joint optimization can improve the minimum throughput greatly.

CCS CONCEPTS

• **Networks** → *Mobile networks.*

KEYWORDS

UAV communications, SWIPT, anti-jamming, SCA, joint optimization

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1 INTRODUCTION

With the rapid growth in the demands of the collection and exchange of information between individuals and things, the research on Internet of Things (IoT) has attracted significant attention [1]. However, most of the devices in IoT network are powered by batteries, which needs to be replaced frequently to extend the life of the whole network [2]. Especially in some scenarios, it is inconvenient or expensive to replace batteries. In addition, the devices need to receive instructions from the control center. Hence, a technology called simultaneous wireless information and power transfer (SWIPT) was proposed to solve this intractable problem. In [3–5], UAV-assisted SWIPT is used to transfer energy and data to IoTDs simultaneously, due to the high maneuverability of UAV. In [6], the authors study the problem of transferring energy and information, where they optimize the UAV trajectory and time resource allocations jointly to maximize average throughput of devices. In [7], the minimum received energy was maximized by trajectory design and energy optimization with considering speed constraints in SWIPT.

However, the openness of wireless channel makes UAV-enabled communication easy to be interfered or eavesdropped [8–10]. To enhance the minimum throughput of devices, [11] optimizes the UAV trajectory to fly far away from the jammer . The authors in [12] investigate a resource allocation problem based on enhancing the secrecy rate by optimizing the UAV trajectory transmit and power, where there are multiple eavesdroppers beside the receivers. To keep the savety of SWIPT system,the authors maximize data rate considering SINR by changing UAV power and trajectory [13]. Authors maximize the secrecy throughput by optimizing PS ratio to enhance the security in SWIPT system [14]. In [15], the authors enhance the average secrecy rate of OFDMA systems by optimizing the trajectory of jamming UAV and the power of base station. Using reinforcement learning method, authors reduce energy consumption and enhance communication quality by optimizing transmit power of relay UAV in [16].

In this paper, we investigate an optimization problem for UAV-assisted SWIPT in jamming environment. Our goal is to maximize the minimum throughput among the all of IoTDs during a fix period, subject to a minimum energy requirement constraint. Different from the work in [11], we optimize the node transmitting power and UAV flight trajectory jointly, in order to avoid the impact of jamming on throughput effectively. To solve this non-convex problem, we develop an iterative algorithm called Joint Power and Trajectory

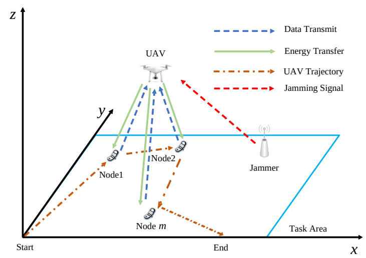


Figure 1: System model.

Optimization for Anti-jamming by the successive convex approximation (SCA) approach. Simulation results prove that in different scenes, our algorithm can improve the throughput of nodes when the power of the jammer changes.

2 SYSTEM MODEL AND PROBLEM FORMULATION

2.1 System Model

It can be seen from Fig. 1, multiple IoT devices and an interference source are randomly distributed within a certain range of mission area. The UAV starts from the starting point and returns to the end point after completing the mission which includes collecting data from and transferring energy to these nodes. Denote $\mathcal{M} = \{1, 2, \ldots m, \ldots M\}$ as IoT Devices. The coordinate of each device is $w_m = (x_m, y_m, 0)$. In the mission area, there is a jammer, whose coordinate is $w_s = (x_s, y_s, 0)$. In our considered model, the coordinates of all nodes and jammer are fixed.

To harvest enough energy and transmit data, a finite operating duration T is guaranteed. The time period T is split into N slots equally, and the length of each time slot is denoted as δ, i.e., $\frac{T}{N}$. The three-dimensional coordinate of the UAV in the n-th time slot is denoted as $L[n] = (x[n], y[n], z[n])$, $n = 1, 2, ..., N$, and the flight trajectory of the UAV is the set of all slot positions. In addition, the coordinate of the start point is $L^{Initial} = (x^{Initial}, y^{Initial}, z^{Initial})$, and the coordinate of the end point is $L^{Final} = (x^{Final}, y^{Final}, z^{Final})$. Due to the hardware limitation of UAV, the maximum flight speed is $V_{\max}$. To save energy, there is a minimum height and a maximum height limitation for UAV during the whole flight time. To sum up, the flight trajectory $L[n]$ of UAV have the following limitations

$$L[0] = L^{Initial}, L[N] = L^{Final} \tag{1}$$

$$\|L[n] - L[n-1]\| \le V_{\max}\delta, \forall n \in \mathcal{N} \tag{2}$$

$$H_{\min} \le z[n] \le H_{\max} \tag{3}$$

In open areas, there is no obstacle between UAV and ground nodes, and thus, we adopt line-of-sight link model in this paper [17]. Assuming that the upstream and downstream links are the same, the total channel gain between UAV and each node is given by

$$g_{u,m} = \beta_0 d_{u,m}^{-2}[n], \forall n \in \mathcal{N}, \forall m \in \mathcal{M} \tag{4}$$

where β_0 is the channel gain at per unit distance, and the distance between UAV and m-th node is donated by $d_{u,m}[n]$. Thus, the total

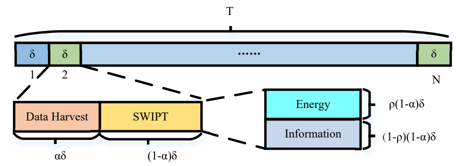


Figure 2: Time and power split model.

channel gain between the jammer and the UAV can be written as

$$g_{s,u} = \beta_0 d_{s,u}^{-2}[n], \forall n \in \mathcal{N} \tag{5}$$

where $d_{s,u}[n]$ is the distance between the jammer and the UAV.

As shown in Fig. 2, each time slot is divided into two portions, and the split ratio is α. In the first portion, the UAV collects data that stored locally in the nodes. In the second portion, the nodes harvest power from the mission UAV. Each node is equipped with an energy distributor with a split ratio ρ, which split the received RF signal into two portions. Specifically, in proportion one, the UAV transfer energy to the nodes, and in proportion two, the UAV transmit information to the nodes.

According to the Shannon theory, during the task time T, the data rate of the m-th node to the UAV at the n-th time slot can be given as

$$r_m[n] = B\log_2\left(1 + \frac{p_m[n]g_{u,m}[n]}{p_s g_{s,u}[n] + B\sigma^2}\right), \forall n \in \mathcal{N}, \forall m \in \mathcal{M} \tag{6}$$

where $p_m[n]$ is transmit power of the m-th node at the n-th slot, p_s is the power of the jammer, B means the bandwidth of each node for communication, and σ^2 is the power spectrum density of Gaussian white noise.

The total throughput of the m-th node that transmits to UAV within the whole task time T can be expressed as

$$\begin{aligned} R_m &= \alpha\delta \sum_{n=1}^{N} r_m[n] \\ &= \alpha\delta B \sum_{n=1}^{N} \log_2\left(1 + \frac{p_m[n]g_{u,m}[n]}{p_s g_{s,u}[n] + B\sigma^2}\right), \forall m \in \mathcal{M} \end{aligned} \tag{7}$$

The instantaneous energy received by m-th node at n-th time slot is written as

$$E_m[n] = \eta\rho p_{u,m}[n]g_{u,m}[n], \forall n \in \mathcal{N}, \forall m \in \mathcal{M} \tag{8}$$

where $\eta \in [0, 1]$ is the conversion efficiency of energy, $p_{u,m}[n]$ is the power of the UAV that distributed to m-th node at n-th slot. Note that, we mainly focus on the energy harvested in our considered model, and hence, we make $\rho = 1$. Then, the total energy collected by m-th node whthin the task period T can be expressed as

$$\begin{aligned} E_m &= (1-\alpha)\delta \sum_{n=1}^{N} E_m[n] \\ &= (1-\alpha)\delta \sum_{n=1}^{N} \frac{\eta\beta_0 p_{u,m}[n]}{\|L[n] - w_m\|^2}, \forall m \in \mathcal{M} \end{aligned} \tag{9}$$

2.2 Problem Formulation

Considering the fairness of nodes in the system, we study the problem of maximizing the minimum throughput among all nodes by optimizing the transmit power of nodes and the trajectory of UAV, while satisfying the energy demand of each node. Thus, the problem we need to solve can be described as

$$\begin{aligned}
\text{(P1)} \quad & \max_{p_m[n], L[n]} \quad \min_{m} \ R_m \\
s.t. \quad & C1 : E_m \geq E^{req}, \forall m \in \mathcal{M} \\
& C2 : 0 \leq p_m[n] \leq p_m^{\max}, \forall n \in \mathcal{N}, \forall m \in \mathcal{M} \\
& C3 : \delta \sum_{n=1}^{N} p_m[n] \leq E_{com}, \forall m \in \mathcal{M} \\
& C4 : L[0] = L^{Initial}, L[N] = L^{Final} \\
& C5 : \|L[n] - L[n-1]\| \leq V_{\max}\delta, \forall n \in \mathcal{N} \\
& C6 : H_{\min} \leq z[n] \leq H_{\max}, \forall n \in \mathcal{N}
\end{aligned} \tag{10}$$

where E^{req} denotes the lowest energy requirement of each node. Constraint $C1$ satisfies the minimum energy demand for each node. Constraint $C2$ ensures that the transmitting power of m-th node is less than its maximum $p_m^{\max}$ at any time. Constraint $C3$ means that there is an upper limit E_{com} for the energy that m-th node can use to transfer data, where $E_{com} = p_0 T$ and p_0 is the average transmitting power of each node.

Note that, the objective function in (10) is non-convex about the variables $p_m[n]$ and $L[n]$. Moreover, the constraint $C1$ is also non-convex. Therefore, the problem P1 is a non-convex one involving multiple variables. It is NP-hard and difficult to be solved directly by existing methods.

3 JOINT TRANSMIT POWER AND TRAJECTORY OPTIMIZATION

To solve problem P1, an auxiliary variable R is introduced. Thus, without losing optimality, the problem P1 can be equivalently transformed to P2 as follows.

$$\begin{aligned}
\text{(P2)} \quad & \max_{p_m[n], L[n], R} \ R \\
s.t. \quad & C1 - C6 \\
& C7 : R_m \geq R, \forall m \in \mathcal{M}
\end{aligned} \tag{11}$$

These constraints above contain several non-convex variables, so the problem P2 is still a non-convex one. Fortunately, it can be approximated to a convex problem by several iterations, known as the successive convex approximation (SCA). Based on this technology, we can approximately transform a non-convex problem to a convex problem. Meanwhile, to deal with the two variables of transmit power and UAV trajectory, we decompose the problem into two sub-problems: transmit power optimization with given trajectory and trajectory optimization with given transmit power in the next two sections. Finally, a joint optimization algorithm called Joint Power and Trajectory Optimization for Anti-jamming is proposed to solve the two sub-problems alternatively.

3.1 Transmit Power Optimization with Given Trajectory

In some specific scenes, the flight trajectory of UAV is fixed. Given the trajectory of UAV, we optimize the transmit power of nodes, and the problem P2 can be transformed to

$$\begin{aligned}
\text{(P3)} \quad & \max_{p_m[n], R} \ R \\
s.t. \quad & C2, C3 \\
& C8 : \alpha\delta \sum_{n=1}^{N} B\log_2\left(1 + \frac{p_m[n] g_{u,m}[n]}{p_s g_{s,u}[n] + B\sigma^2}\right) \geq R, \forall m \in \mathcal{M}
\end{aligned} \tag{12}$$

Since $\log_2(1+x)$ is concave, C8 is a convex set of with respect to $p_m[n]$. Then, we can prove the problem P3 is a standard convex problem. Thus P3 can be solved easily by preexisting convex optimization techniques.

3.2 Trajectory Optimization with Given Transmit Power

Firstly, the auxiliary variables $G_{u,m}[n]$ and $I_{s,u}[n]$ are introduced, with the following constraints

$$\begin{aligned}
& p_m[n] g_{u,m}[n] \geq \frac{1}{G_{u,m}[n]}, \ \forall n \in \mathcal{N}, \forall m \in \mathcal{M} \\
& p_s g_{s,u}[n] + B\sigma^2 \leq I_{s,u}[n], \ \forall n \in \mathcal{N}
\end{aligned} \tag{13}$$

Accordingly, the problem P2 can be converted to

$$\begin{aligned}
\text{(P4)} \quad & \max_{L[n], G_{u,m}[n], I_{s,u}[n], R} \ R \\
s.t. \quad & C4 - C6 \\
& C9 : \alpha\delta \sum_{n=1}^{N} B\log_2\left(1 + \frac{1}{G_{u,m}[n] I_{s,u}[n]}\right) \geq R, \forall m \in \mathcal{M} \\
& C10 : (1-\alpha)\delta \sum_{n=1}^{N} \frac{\eta p_{u,m}[n] \beta_0}{\|L[n] - w_m\|^2} \geq E^{req}, \forall m \in \mathcal{M} \\
& C11 : p_m[n] g_{u,m}[n] \geq \frac{1}{G_{u,m}[n]}, \ \forall n \in \mathcal{N}, \forall m \in \mathcal{M} \\
& C12 : p_s g_{s,u}[n] + B\sigma^2 \leq I_{s,u}[n], \ \forall n \in \mathcal{N}
\end{aligned} \tag{14}$$

Note that, since $f(x,y) = \log_2(1 + 1/xy)$ is convex with respect to x and y, constraint C9 is non-convex. Thus, we apply the first-order Taylor expansion transform it into a convex constraint. Specifically, for any given slack point (x_0, y_0), the lower bound of $f(x,y)$ is given by

$$\log_2\left(1 + \frac{1}{xy}\right) \geq \log_2\left(1 + \frac{1}{x_0 y_0}\right) - \frac{(x - x_0)}{\ln 2\left(x_0 + x_0^2 y_0\right)} - \frac{(y - y_0)}{\ln 2\left(y_0 + y_0^2 x_0\right)} \tag{15}$$

Based on (15), given $G^i_{u,m}[n]$ and $I^i_{s,u}[n]$ at the i-th iteration, we can get the lower bound $R^{i+1}_{m,lb}[n]$ of $R^{i+1}_m[n]$, which is given by

$$\begin{aligned} R^{i+1}_m[n] &\geq R^{i+1}_{m,lb}[n] \\ &= \alpha\delta B \sum_{n=1}^{N} \left(\begin{array}{l} A^i\left(G^{i+1}_{u,m}[n]-G^i_{u,m}[n]\right)+B^i\left(I^{i+1}_{s,u}[n]-I^i_{s,u}[n]\right) \\ +\log_2\left(1+\dfrac{1}{G^i_{u,m}[n]I^i_{s,u}[n]}\right) \end{array} \right) \end{aligned} \tag{16}$$

where

$$\begin{aligned} A^i &= -\frac{1}{\ln 2\left(G^i_{u,m}[n]+\left(G^i_{u,m}[n]\right)^2 I^i_{s,u}[n]\right)}, \\ B^i &= -\frac{1}{\ln 2\left(I^i_{s,u}[n]+\left(I^i_{s,u}[n]\right)^2 G^i_{u,m}[n]\right)}. \end{aligned} \tag{17}$$

Moreover, according to (9), E_m is a non-convex function with respect to $L[n]$, and thus, constraint $C10$ is non-convex. Similarly, we can transform this constraint into a convex one by using the first-order Taylor expansion. Specifically, given $L^i[n]$ at the i-th iteration, we can obtain the lower bound $E^{i+1}_{m,lb}[n]$ of $E^{i+1}_m[n]$, i.e.,

$$\begin{aligned} & E^{i+1}_m[n] \geq E^{i+1}_{m,lb}[n] \\ &= \frac{\eta\beta_0 p_{u,m}[n]}{\left\|L^i[n]-w_m\right\|^2} - \frac{\eta\beta_0 p_{u,m}[n]\left(\left\|L^{i+1}[n]-w_m\right\|^2-\left\|L^i[n]-w_m\right\|^2\right)}{\left(\left\|L^i[n]-w_m\right\|^2\right)^2} \end{aligned} \tag{18}$$

Then, constraint $C11$ can be transformed as

$$\frac{\|L[n]-w_m\|^2}{\beta_0 p_m[n]} \leq G_{u,m}[n] \tag{19}$$

Obviously, we can see that (19) is a convex constraint.

Similarly, constraint $C12$ can be transformed as

$$p_s \frac{\beta_0}{\|L[n]-w_s\|^2} + B\sigma^2 \leq I_{s,u}[n] \tag{20}$$

However, constraint $C12$ is non-convex with respect to $L[n]$. In this case, we introduce a slack variable $d_s[n]$ to translate this constraint equivalently, which is given by

$$\|L[n]-w_s\|^2 \geq d_s[n], \quad \forall n \in \mathcal{N} \tag{21}$$

$$p_s\beta_0 d_s^{-1}[n] + B\sigma^2 \leq I_{s,u}[n], \quad \forall n \in \mathcal{N} \tag{22}$$

Since the function $\|L[n]-w_s\|^2$ is convex at $L[n]$, the inequation (21) is non-convex. It can be transformed to (23) , by using the first-order Taylor expansion.

$$\begin{aligned} \|L[n]-w_s\|^2 &\geq \|L_0[n]-w_s\|^2 + 2\left(L[n]-L_0[n]\right)\left(L_0[n]-w_s\right)^T \\ &\geq d_s[n], \forall n \in \mathcal{N} \end{aligned} \tag{23}$$

To this end, the problem P4 can be transformed as

$$\begin{aligned} \text{(P5)} \quad & \max_{L[n], G_{u,m}[n], I_{s,u}[n], d_s[n], R} R \\ s.t. \quad & C1-C6 \\ & C13: \delta\sum_{n=1}^{N} R^{i+1}_{m,lb}[n] \geq R, \forall m \in \mathcal{M} \\ & C14: \delta\sum_{n=1}^{N} E^{i+1}_{m,lb}[n] \geq E^{req}, \forall m \in \mathcal{M} \\ & C15: \frac{\left\|L^i[n]-w_m\right\|^2}{\beta_0 p_m[n]} \leq G^i{}_{u,m}[n], \forall n \in \mathcal{N}, \forall m \in \mathcal{M} \\ & C16: p_s\beta_0\frac{1}{d^i_s[n]} + B\sigma^2 \leq I^i{}_{s,u}[n] \forall n \in \mathcal{N} \\ & C17: d_s{}^i[n] \leq \|L_0[n]-w_s\|^2 \\ & \qquad + 2\left(L^i[n]-L_0[n]\right)\left(L_0[n]-w_s\right)^T, \forall n \in \mathcal{N} \\ & C18: d_s[n] \geq 0, \forall n \in \mathcal{N} \end{aligned} \tag{24}$$

The problem P5 is a standard convex problem that can be solved using preexisting convex optimization methods, for instance, we can use CVX toolbox or inner-point technology.

3.3 Overall Algorithm

The table below gives the whole process of our Joint Power and Trajectory Optimization for Anti-jamming algorithm.

Algorithm 1 Joint Optimization Algorithm for P5

1: Initialize: i=0, the transmit power of each node $p^0_m[n]$ and the trajectory of UAV $L^0[n]$.
2: **While**
3: With the given trajectory of UAV $L^i[n]$ and solve the problem P3, then obtain the optimal solution $P^{i+1}_m[n]$.
4: Fix the transmit power of each node $P^{i+1}_m[n]$ and solve the problem P4, then obtain the optimal solution $L^{i+1}[n]$.
5: $i = i + 1$.
6: **Until** $\frac{R^{i+1}-R^i}{R^i} \leq \varepsilon$ or the algorithm reaches the maximum number of iterations.
7: Return the optimal result of maximum throughput R, transmit power of the nodes $p^*_m[n]$ and trajectory of UAV $L^*[n]$.

3.4 Analysis of Proposed Algorithm

3.4.1 Convergence Analysis. Base on a series of transformations above, the original problem is approximated to a convex one by SCA. Although the total throughput R is increasing during each iteration, there is an upper bound for the power of both nodes and UAV, and thus, the throughput will not increase indefinitely. As a result, our joint optimization algorithm is convergent.

3.4.2 Complexity Analysis. In this paper, we use the interior point method to solve convex problems. The algorithm complexity of interior point method is $O(x^{3.5})\log(1/\varepsilon)$, and x is the number of variables [18]. The variable in the first subproblem is $p_m[n]$, whose number is MN. The variables in the second subproblem are

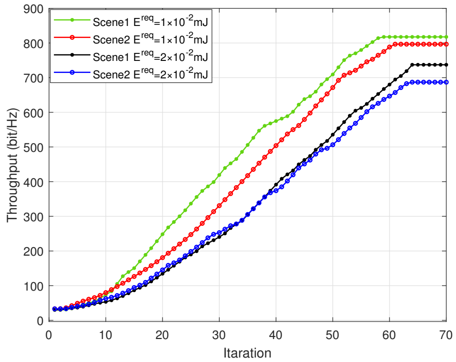


Figure 3: Convergence behavior in two scenes.

$L[n] = (x[n], y[n], z[n])$, $G_{u,m}[n]$, $I_{s,u}[n]$, $d_s[n]$, and the total number is $(5 + M)\,N$. Therefore, the complexity of the joint optimization algorithm is $O(I((5 + 2M)N)^{3.5}) \log(1/\varepsilon)$, where M donates the number of nodes, N donates the number of time slots, and I is the number of iterations when the throughput converges, and ε is the solution accuracy.

4 NUMERICAL RESULTS AND DISCUSSION

To prove the effectiveness of the joint optimization algorithm of nodes' transmit power and UAV's trajectory, several experiments were performed on the Matlab platform, using function of "fmincon".

4.1 Basic Setup

We consider a $100m \times 100m \times 40m$ area, containing three nodes and a jammer. The starting point and end point of UAV is (0,0,10) and (100,100,10), respectively. The initial trajectory is a straight trajectory at the altitude h =10 m, from the starting point to the end point. Nodes' communication bandwidth B =1MHz, noise power spectral density is σ^2 =-169dBm/Hz and unit channel gain $\beta_0 = 10^{-3}$. Node energy acquisition efficiency $\eta = 0.5$, time slot length δ =0.5s and time splitting ratio $\alpha = 0.5$. UAV's transmit power $p_{u,m}$ =1000mW and nodes' maximum transmit power $p_m^{\max}$ =300mW. UAV's minimum altitude $H_{\min}$ =5m, maximum altitude $H_{\max}$ =20m and maximum speed $V_{\max}$ = 20m/s due to the hardware limit of UAV. Accuracy tolerance for throughput $\varepsilon = 10^{-4}$. Nodes' coordinates are (40,10,0), (40,80,0) and (90,80,0), respectively.

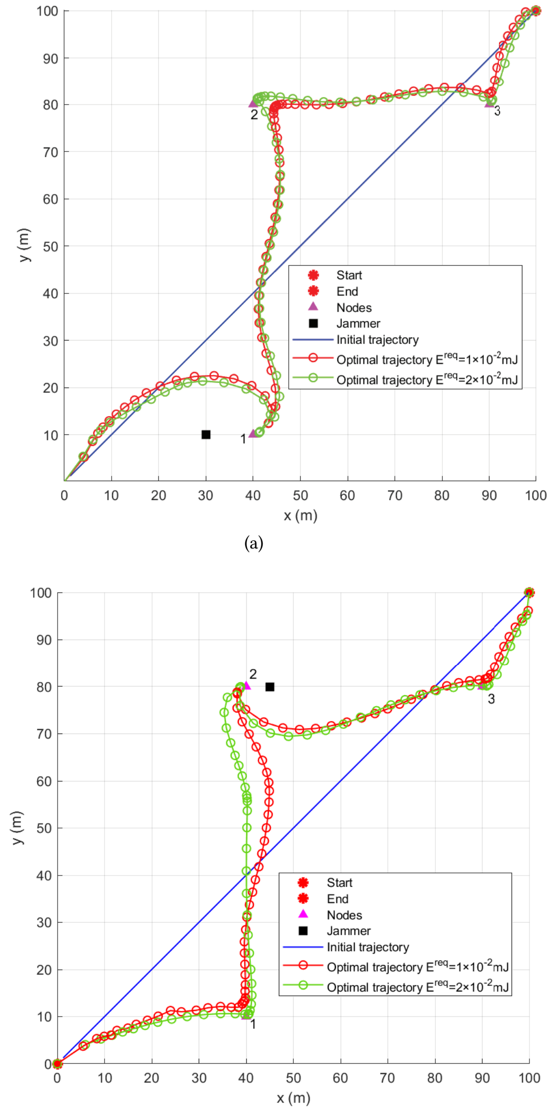
Based on the jammer's location, we set two scenarios:

Scene 1: the jammer's coordinate is $w_s = (30, 10, 0)$.

Scene 2: the jammer's coordinate is $w_s = (45, 80, 0)$.

4.2 System Performance

The Fig. 3 shows the convergence behavior of maximization of minimum throughput among all the three nodes in two different scenes, where the whole task time T = 40 seconds and the transmit power of the jammer p_s =100mW. Considering that the minimum energy demand of each node E^{req} will change in different task backgrounds, we investigate the performance in cases of E^{req} = 1×10^{-2}mJ and 2×10^{-2}mJ. It can be seen that the maximization



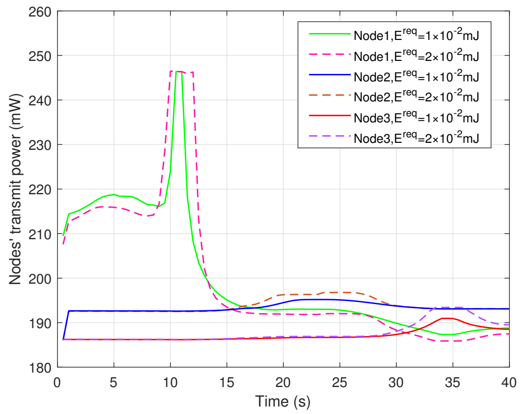
(a)

(b)

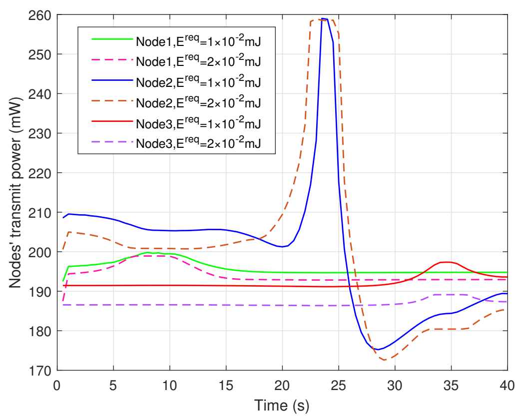
Figure 4: Optimal trajectory of UAV. (a) Scene 1. (b) Scene 2.

of minimum throughput can converge in the two scenarios, which verifies the convergence of our proposed algorithm. In addition, as E^{req} increases, the throughput decreases. The reason is that the system needs to make a trade-off between transferring energy and transmitting information. To meet the minimum energy needs of the nodes, the UAV has to fly to the position where suffering stronger jamming but can harvest more energy, resulting in the reduced throughput.

Fig. 4 shows the optimal trajectories of UAV in scene 1 and scene 2, respectively. Note that, in the LOS channel, the closer the UAV is to the node, the better the channel quality is between it and the node. In this case, in order to harvest as much energy as possible, the UAV need to fly as close to the node as possible. However, due

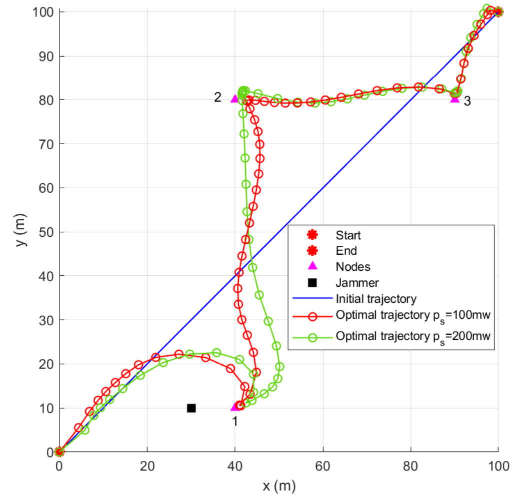


(a)

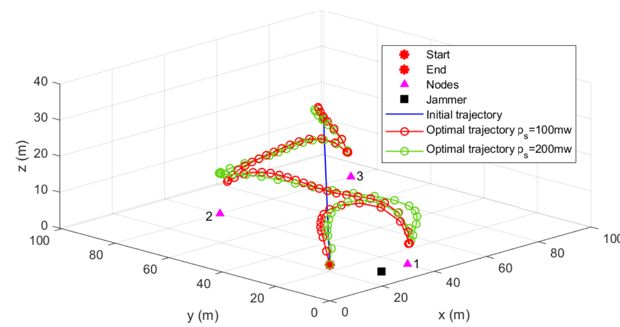


(b)

Figure 5: Optimal transmit power of nodes versus time. (a) Scene 1. (b) Scene 2.



(a)



(b)

Figure 6: Optimal trajectory of UAV with different transmit power of jammer. (a) Vertical view. (b) Lateral view.

to the presence of the jammer, the closer the UAV is to the jammer, the larger the interference generated by the jammer is, and the less data can be collected from the node. To increase the throughput of the node, the UAV has to fly further away from the node to avoid the interference. Thus, UAV needs to strike a balance between the optimal data collection point and the optimal energy transfer point. We can see that in both scene 1 and scene 2, UAV flies more closely to each node in the case of $E^{req} = 2 \times 10^{-2}$mJ than that in the case of $E^{req} = 1 \times 10^{-2}$mJ. This is because that UAV can transfer more energy in this way in spite of interference from the jammer. That is also the reason that the throughput decreases as the energy requirement increase, as shown in the Fig. 3.

Fig. 5 shows the transmit power variation trend of different nodes after transmit power optimization in the two scenes. As we can see that, when UAV hovers near a node, the transmit power of the node increases, and it can take advantage of the better channel condition to transmit more data. Moreover, the transmit power fluctuations of node 1 in scene 1 and node 2 in scene 2 are obvious. This is due to the fact that the two nodes are closest to the jammer and suffer the strongest interference. Therefore, more transmit power is required to increase the throughput. Furthermore, as the minimum energy demand of the node increases, the hovering time of the UAV increases accordingly, which ensures that the node can have enough time to obtain energy from the UAV.

In order to evaluate the impact of jammer's transmit power on the node with the maximum minimum throughput, we simulate the trajectory of UAV in two cases, where jammer's power $p_s = 100$mW and $p_s = 200$mW, respectively. The task time is $T = 30$ seconds, and the minimum energy requirement is $E^{req} = 2 \times 10^{-2}$mJ. In Fig.6 , the UAV's trajectory in scene 1 is shown.

It can be seen from the Fig. 6, the trajectory of UAV is optimized to different degrees in two different jamming power. The higher the jamming power is, the more obviously UAV flies further from the jammer. From Fig. 6(a), we can find that the trajectory projection of the UAV is offset to the other side of the jammer. From Fig. 6(b), we can see that the UAV raises its trajectory altitude to stay away from the jammer. When the UAV flies above the node, it drops to the lowest altitude again to satisfy the nodes' energy requirements.

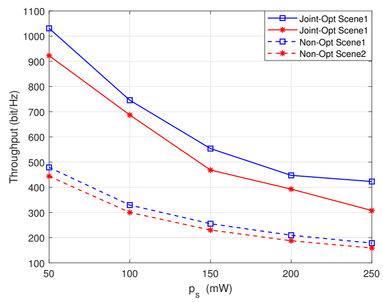


Figure 7: Throughput versus transmit power of jammer.

Fig. 8 depicts the throughput versus the task time in different optimization methods. As can be seen from the Fig. 8, the throughput in the three schemes continues to increase with the increase of task time. The longer the task time, more obvious the gap is between the three schemes. Furthermore, the performance improvement of the joint optimization algorithm is significantly higher than the other two schemes. The reason is that, as the mission time increases, the UAV has enough time to optimize its trajectory. To this end, nodes can harvest energy and transmit data under better channel conditions both in scene 1 and 2. To sum up, that the proposed algorithm can improve performance obviously in different scenarios and different task time.

Fig. 7 represents the relationship between the throughout and the transmit power of jammer in the two scenes. We can obverse that the throughput decreases monotonically as the jammer's transmit power increases. This is because that larger interference introduced by the jammer results in the lower throughput of each node. In addition, the throughput obtained based on the joint optimization algorithm is more than twice as high as that based on the non-optimization algorithm.

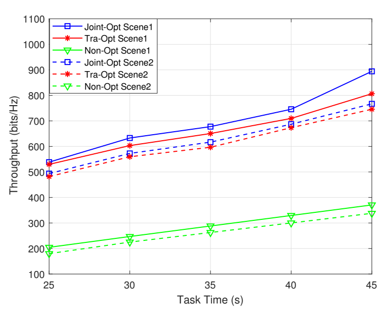


Figure 8: Throughput versus task time in different optimization methods.

5 CONCLUSION

In this paper, we consider a scenario of UAV-assisted SWIPT in jamming environment. Then, we design an iterative algorithm called Joint Power and Trajectory Optimization for Anti-jamming and verify the effectiveness of the algorithm by a set of simulations. Simulation results show that the joint optimization algorithm proposed can improve the data throughput of nodes and satisfy energy requirements of all nodes at the same time in various scenarios. In addition, the algorithm we proposed can perform better comparing with existing methods. Also, we can observe that the UAV will hover or slow down nearby the nodes and fly away from the jammer to improve channel quality. Meanwhile, the nodes will increase transmit power when the UAV fly closely. In the following research, we will consider multiple UAVs and more jammers.

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