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Energy efficiency maximization for UAV-enabled amplify-and-forward relaying via joint power and trajectory optimization

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Abstract

This paper investigates an optimization problem corresponding to energy efficiency maximization of an unmanned aerial vehicle (UAV)-enabled relaying system, where a fixed-wing UAV acts as an amplify-and-forward mobile relay to assist data transmission between a source node and a destination node. On the premise of satisfying the speed and acceleration constraints of the UAV, the energy efficiency (EE) of the relaying system is maximized by jointly optimizing the UAV's trajectory and the individual transmit power levels of the source and the UAV relay. The initial joint optimization problem is non-convex and cannot be solved directly. Therefore, the joint optimization problem is decomposed into two sub-problems which are solved by applying the successive convex approximation technique and the Dinkelbach's algorithm. On this basis, an efficient iterative algorithm is proposed to tackle the joint optimization problem through the block coordinate descent technique. Simulation results demonstrated that by conducting the proposed algorithm, the flight trajectory of the UAV and the individual transmit power levels of the nodes can be flexibly adjusted according to the system conditions, and the proposed algorithm contributes to the higher EE compared with the benchmark schemes.

Keywords: UAV communication, Energy efficiency, Power control, Trajectory optimization, Amplify-and-forward

1 Introduction

In recent years, unmanned aerial vehicle (UAV) communication technologies have developed rapidly. Compared with traditional terrestrial communications, the advantages of UAV-assisted wireless communications can be summarized in the following three aspects. First, UAVs can be flexibly deployed on demand. In some emergency situations, such as terrestrial communication infrastructures are partially or completely disabled due to natural disasters, UAVs can be deployed as aerial platforms to effectively play the role of temporary communication facilities, with faster deployment speed than restoring the disabled communication infrastructures and lower deployment cost than employing high-altitude platforms (HAPs) or satellite communications [1]. Second, it is more likely for UAVs to establish line-of-sight (LoS) communication links with the ground base stations (BSs) or ground users (Gus) due to the flight height. For traditional terrestrial communications, however, the communication links often suffer from impairments such as shadowing and multipath fading in addition to the general path losses. By contrast, the UAV communication channels dominated by LoS links may improve the link capacity [2]. Third, UAVs can move quickly in the three-dimensional (3D) free space, providing degree of freedom for performance enhancement via trajectory design [3]. Due to the above advantages, UAV-assisted wireless communications have been used in a variety of scenarios, such as mobile relaying [4, 5], data collection and information dissemination [6–8].

As one of a promising application of UAV communications, UAV-enabled mobile relaying had been widely investigated in literature, where two main relaying protocols, i.e., decode-and-forward (DF) and amplify-and-forward (AF) protocols are applied. In [9], a UAV-enabled full-duplex DF relaying was investigated and a joint power and trajectory optimization problem was solved so as to minimize the system outage probability. In [10], a UAV-enabled relaying system with multiple pairs of users was investigated, and a total energy minimization problem was addressed, where the communication time, the UAV's transmit power level and trajectory were jointly optimized. In order to prolong the operating duration of UAV, multiple UAVs were applied in [11]. By jointly designing the trajectories of the UAVs and the transmit power levels of the source and the UAVs, the end-to-end throughput was maximized. For the purpose of achieving greater throughput with less energy consumption, [12] studied an energy-efficient UAV relaying, where the transmit power levels of the UAV and the BS, and the UAV's trajectory and flight speed were optimized for energy efficiency (EE). It should be noted that from a practical viewpoint, a DF UAV relay needs to decode and re-encode the received data before forwarding to a receiver, resulting in high implementation complexity and long time delay. In contrast, an AF UAV relay only needs to amplify the received signal and then forward to the receiver. Since no data decoded, it not only incurs low implementation complexity, but also ensures the privacy of the data. Therefore, AF relaying protocol has a priority to be used in UAV mobile relaying systems. Recently, the authors of [13] studied an AF UAV relaying system, and proposed a joint design for trajectory optimization and transmit power control of the UAV with the aim of minimizing the system outage probability. In [14], a power allocation and trajectory optimization scheme of a UAV-enabled AF relay network was proposed to maximize the end-to-end throughput, where the UAV was used to connect one pair of Gus. [15] extended the work of [14] to a network scenario with multiple pairs of Gus, and proposed an optimization scheme with power control and trajectory optimization together with time-slot allocation so as to maximize the minimum average information rate of all the pairs of Gus. In [16], a store-then-amplify-and-forward (SAF) relaying protocol was proposed for UAV-enabled relaying system, so that the source/UAV transmit power and the UAV's trajectory as well as the time-slot pairing were jointly optimized. The authors of [17] applied the aerial communication techniques to a vehicular network for the first time in which a ground BS serves two terrestrial vehicles with the aid of a UAV. In order to maximize the sum-rate or the min-rate of the considered two vehicles, optimal power allocation and trajectory planning of the vehicular network was developed. In [18], a UAV aided space-air-ground (SAG) network was considered, where the UAV served as a mobile relay to forward data of ground nodes to a satellite. By adopting the AF protocol, a sum rate maximization problem was solved via the joint optimization of time allocation, power control and UAV's trajectory.

As the increasingly important role of UAVs in relay communications, the limited onboard energy of UAVs has become a critical issue, since UAVs require a huge amount of propulsion energy to remain aloft in addition to communication related energy. Moreover, due to the current shortage of resources, green development is strongly advocated. Hence, how to obtain better throughput with less energy consumption deserves more attention, and it is of great significance to develop energy efficient UAV-enabled mobile relaying. To this end, we focus on the problem of energy efficiency maximization for a UAV-enabled AF relaying. As far as we know, this problem was only studied in [19] and [20]. In [19], an energy-efficient full-duplex UAV relaying was proposed, where the UAV relay employs the AF protocol and the flight speed was optimized by a genetic algorithm for EE. In [20], an EE maximization problem of a UAV-enabled Internet of things (IoT) system was studied, and the trajectory of the UAV was optimized to achieve green communications. Although EE maximization problem was studied in [19] and [20], only the flight speed or the trajectory of the UAV is optimized, and transmit power of the source and the UAV relay are not investigated, which could possibly contribute to EE enhancement in practice. To this end, with the aim of EE maximization, this paper studies a joint transmit power and flight trajectory optimization of a fixed-wing UAV-enabled mobile relaying by taking into consideration the maximum and average transmit power constraints at the source and the UAV relay, and the mobility constraints on the maximum and minimum velocity and the maximum acceleration as well as the initial and final positions of the UAV relay. Different from [19] and [20], our paper investigates a joint design of the UAV's trajectory optimization and the individual transmit power control of the source and the UAV relay with the aim of maximizing the EE of the system. It should be further pointed out that although the EE maximization problem was studied as well in [21], there are two major differences between it and our paper. On one hand, [21] considered a point-to-point wireless communication system consisting of a UAV and a ground terminal, whereas our paper considers a three-node mobile relaying system where a UAV provides relaying service for two ground nodes. On the other hand, only the trajectory of the UAV was optimized in [21], whereas we take both the trajectory and the transmit power of the UAV into consideration. The main contributions of the paper are summarized as follows.

(1) We construct a mathematical model of a UAV-enabled AF relaying and formulate an optimization problem corresponding to EE maximization for the studied UAV relaying system, subject to transmit power and mobility constraints. To the best of our knowledge, there is no similar work in literature that jointly optimizes the transmit power and the UAV's trajectory for a UAV-enabled AF relaying system.
(2) The initial joint optimization problem is non-convex and cannot be solved directly. In order to deal with the non-convex optimization problem, we then decompose it into two sub-problems. One is the transmit power control at the source and the UAV relay, and the other is to optimize the UAV's trajectory. By applying the successive convex approximation (SCA) technique and the Dinkelbach's algorithm, the

two sub-problems are solved, leading to an iterative algorithm for the joint design of transmit power control and trajectory optimization.

(3) To verify the performance of the iterative algorithm, simulation results are provided, and show that the iterative algorithm can achieve convergence within a few iterations and the proposed joint optimization scheme performs better than the benchmark schemes in terms of EE.

The rest of this paper is organized as follows. Section 2 describes the methods used in this paper and introduces the mathematical model of the UAV relaying system under investigation and formulates an EE maximization problem. In Sect. 3, optimal transmit power control of the source and the UAV relay is handled with fixed relay trajectory and the UAV's trajectory is optimized with fixed transmit power, and next an iterative algorithm is proposed to jointly optimize the transmit power and the UAV's trajectory. Simulation results and discussion are presented in Sect. 4. Finally, Sect. 5 concludes the paper. In addition, the key mathematical notations are listed in Table 1 to facilitate the readers.

2 Methods

This paper mainly studies the EE maximization problem of a UAV-enabled AF relaying system. The research methodology in this paper involves system modeling, theoretical analysis and computer simulation. In this section, we construct a mathematical model of the UAV-enabled AF relaying system and formulate an optimization problem with the aim of EE maximization.

Table 1 Key notations used in this paper

Notation	Description
L	Distance between S and D
H	Flight altitude of UAV
T	Flight time of UAV
N	Number of time-slots
δ	Time-slot length
$\mathbf{q}(n)$	Horizontal coordinate of UAV in the n-th time-slot
$\mathbf{q}_S$ / $\mathbf{q}_D$	Horizontal coordinate of S/D
(x_0, y_0, H)/ (x_F, y_F, H)	Initial/Terminal position of UAV
h_{SR}/h_{RD}	Channel gain between S and R/R and D
$P_S(n)$/ $P_R(n)$	Transmit power of S/R in the n-th time-slot
σ^2	Noise power
$R_{RD}(n)$	Channel capacity between R and D
$\mathbf{v}(n)/\mathbf{a}(n)$	Flight speed/Acceleration of UAV in the n-th time-slot
$\overline{P}_S/\overline{P}_R$	Average transmit power of S/R
$P_{S\max}$/ $P_{R\max}$	Maximum transmit power of S/R
$v_{\max}$	Maximum velocity of UAV
$a_{\max}$	Maximum acceleration of UAV
B	Bandwidth
E	UAV flight related energy consumption

2.1 System model

As shown in Fig. 1, we consider a three-node mobile relaying system, where a fixed-wing UAV denoted by R is employed as a mobile relay to receive data from the source S and forward them to the destination D. The distance between S and D is L meters, and S and D are not able to communication with each other due to serve blockage or long distance. The UAV relay R operates in the time-division half-duplex style and adopts the AF relaying protocol. We assume that S, D and R are equipped with single antenna. During each time-slot, S first transmits data to R in the 1st hop, and the UAV relay R transmits a scaled version of the received signal to D in the 2nd hop. It is assumed that the UAV relay R flies at a fixed altitude of H meters, and H could be the minimum altitude for obstacles avoidance without frequent ascending and descending.

Suppose that S and D are located at $\mathbf{S} = (0, 0, 0)$ and $\mathbf{D} = (L, 0, 0)$, respectively. The UAV relay R starts from the initial position $\left(x_0, y_0, H\right)$ at the initial speed $\mathbf{v}_0$ and stops at the terminal position $\left(x_{\mathrm{F}}, y_{\mathrm{F}}, H\right)$ at the final speed $\mathbf{v}_{\mathrm{F}}$. This paper focuses on the UAV's flight stage, and ignores its take-off and landing phases. Suppose that the communication time of the UAV relaying system is T seconds. Here, T is divided into N time-slots, and the duration of each time-slot is denoted by δ, i.e.

$$\delta = \frac{T}{N} \tag{1}$$

For the case that δ is small enough, the position of the UAV in one time-slot can be considered to remain unchanged. Therefore, the system throughput at the beginning of each time-slot is regarded as the data rate of the whole time-slot in this paper. Denote by $\mathbf{q}_S = [0,\ 0]$ and $\mathbf{q}_D = [L,\ 0]$ the horizontal coordinates of S and D, respectively. In addition, $\mathbf{q}(n) = [x(n),\ y(n)]$ is used to represent the horizontal coordinate of the UAV relay R during the n th time-slot. Assume that R is at the initial position when $n = 1$ and is at the terminal position when $n = N + 1$, namely, $\mathbf{q}(1) = [x_0,\ y_0]$ and

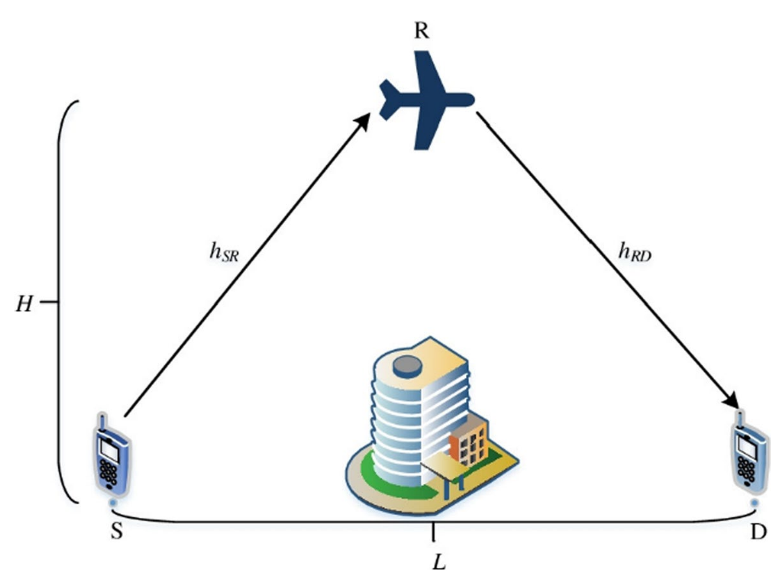

Fig. 1 The UAV relaying system under investigation

$\mathbf{q}(N+1) = [x_F, y_F]$. Therefore, during the n-th time-slot, the distance between R and S and that between R and D can be respectively expressed as

$$d_{SR}(n) = \sqrt{\|\mathbf{q}_S - \mathbf{q}(n)\|^2 + H^2} \tag{2}$$

$$d_{RD}(n) = \sqrt{\|\mathbf{q}(n) - \mathbf{q}_D\|^2 + H^2} \tag{3}$$

where $n = 1, 2, \cdots, N$.

2.2 Signal and channel model

According to [22], the probability of the existence of LoS links is 100% in rural environment when the flight altitude of UAV is higher than 40 m. Therefore, for simplicity of analysis, we assume that the S–R and R–D channels are dominated by LoS links. Furthermore, Doppler effect caused by the UAV mobility is assumed to be perfectly compensated [23]. Thus, during the n-th time-slot, the S-R and R-D channels follow the free-space path loss model and the channel gains can be respectively expressed as

$$h_{SR}(n) = \sqrt{\frac{\beta}{d_{SR}^{\alpha}(n)}}, n = 1, \cdots, N \tag{4}$$

$$h_{RD}(n) = \sqrt{\frac{\beta}{d_{RD}^{\alpha}(n)}}, n = 1, \cdots, N \tag{5}$$

where β denotes the channel power at the reference distance $d = 1$ m, α is the large-scale fading factor. Therefore, during the n-th time-slot, the signal received by the UAV can be written as

$$y_R(n) = \sqrt{P_S(n)}h_{SR}(n)x_S(n) + z_R(n), n = 1, \cdots, N \tag{6}$$

where $P_S(n)$ is the transmit power of S during the n-th time-slot, $x_S(n)$ is the transmit signal of S, $z_R(n)$ is the noise at R with power σ^2. According to the AF protocol, the UAV relay R amplifies the received signal $y_R(n)$ and forwards it to D. Here, the amplification coefficient is

$$G(n) = \sqrt{\frac{P_R(n)}{P_S(n)\left|h_{SR}(n)\right|^2 + \sigma^2}}, \tag{7}$$

where $P_R(n)$ is the transmit power of R. Therefore, during the n-th time-slot, the signal received by the destination node D is

$$\begin{aligned} y_D(n) &= G(n)y_R(n)h_{RD}(n) + z_D(n) \\ &= G(n)\sqrt{P_S(n)}h_{SR}(n)h_{RD}(n)x_S(n) + G(n)z_R(n)h_{RD}(n) + z_D(n) \end{aligned} \tag{8}$$

According to (7) and (8), the received signal to noise ratio (SNR) at D can be written as

$$\gamma_D(n) = \frac{P_S(n)P_R(n)\left|h_{SR}(n)\right|^2\left|h_{RD}(n)\right|^2}{(P_S(n)\left|h_{SR}(n)\right|^2 + P_R(n)\left|h_{RD}(n)\right|^2 + \sigma^2)\sigma^2} \tag{9}$$

Then, the instantaneous channel capacity of the link from R to D can be written as [24]

$$R_{RD}(n) = \frac{1}{2}\log_2\left[1 + \gamma_D(n)\right], n = 1, \cdots, N \tag{10}$$

2.3 UAV energy consumption model

Generally, the total energy consumption of a UAV relaying system consists of three parts, i.e., the UAV flight and the communication related energy consumption in addition to the static energy consumption of circuit. However, the latter two parts are usually much smaller than the UAV flight energy, and thus can be ignored. According to [21], for a fixed-wing UAV with level flight, its flight related energy consumption can be expressed as

$$E = \sum_{n=1}^{N}\delta\left(c_1\|\mathbf{v}(n)\|^3 + \frac{c_2}{\|\mathbf{v}(n)\|}\left\{1 + \frac{\|\mathbf{a}(n)\|^2 - \frac{\left[\mathbf{a}^{\mathrm{T}}(n)\mathbf{v}(n)\right]^2}{\|\mathbf{v}(n)\|^2}}{g^2}\right\}\right) + \frac{1}{2}m\left(\|\mathbf{v}_{\mathrm{F}}\|^2 - \|\mathbf{v}_0\|^2\right) \tag{11}$$

where $\mathbf{v}(n)$ and $\mathbf{a}(n)$ represent the flight speed and the acceleration of the UAV during the n-th time-slot, $\mathbf{v}_0$ and $\mathbf{v}_{\mathrm{F}}$ denote the initial and final velocities of the UAV, respectively, m is the UAV's mass, g stands for the gravitational acceleration, c_1 and c_2 are two parameters related to air density, aircraft's weight, wing area, etc. [24].

It should be noted that for the UAV relay R, the values of $\mathbf{q}(n)$, $\mathbf{v}(n)$ and $\mathbf{a}(n)$ in the n-th time-slot determine its velocity and position in the next time-slot, i.e., $\mathbf{v}(n+1)$ and $\mathbf{q}(n+1)$ which can be expressed as bellow.

$$\mathbf{v}(n+1) = \mathbf{v}(n) + \mathbf{a}(n)\delta \tag{12}$$

$$\mathbf{q}(n+1) = \mathbf{q}(n) + \mathbf{v}(n)\delta + \frac{1}{2}\mathbf{a}(n)\delta^2 \tag{13}$$

2.4 Problem formulation

With the aim of maximizing the EE of the UAV relaying system, the optimization problem corresponding to the joint design of transmit power control and flight trajectory optimization can be formulated as

$$\max_{\substack{\{\mathbf{a}(n)\},\\ \{P_S(n),P_R(n)\}}} \frac{\sum_{n=1}^{N} B\delta R_{RD}(n)}{E} \tag{14a}$$

$$\text{s.t. } 0 \le P_S(n) \le P_{S\max}, 0 \le P_R(n) \le P_{R\max}, \tag{14b}$$

$$\frac{1}{N}\sum_{n=1}^{N} P_S(n) \leq \overline{P}_S, \tag{14c}$$

$$\frac{1}{N}\sum_{n=1}^{N} P_R(n) \leq \overline{P}_R, \tag{14d}$$

$$\mathbf{v}(1) = \mathbf{v}_0, \mathbf{q}(1) = [x_0, y_0], \tag{14e}$$

$$\mathbf{v}(N+1) = \mathbf{v}_\mathrm{F}, \mathbf{q}(N+1) = [x_\mathrm{F}, y_\mathrm{F}], \tag{14f}$$

$$\mathbf{q}(n+1) = \mathbf{q}(n) + \mathbf{v}(n)\delta + \frac{1}{2}\mathbf{a}(n)\delta^2, \tag{14g}$$

$$\mathbf{v}(n+1) = \mathbf{v}(n) + \mathbf{a}(n)\delta, \tag{14h}$$

$$\|\mathbf{v}(n)\| \leq v_{\max}, \tag{14i}$$

$$\|\mathbf{v}(n)\| \geq v_{\min} \tag{14j}$$

$$\|\mathbf{a}(n)\| \leq a_{\max} \tag{14k}$$

where B is the bandwidth of the system, E is the UAV flight related energy consumption given by (11), (14b), (14c) and (14d) refer to the maximum and average transmit power constraints of S and R, (14e) gives the UAV's initial velocity and location, (14f) denotes the UAV's final velocity and location, and (14i), (14j) and (14k) are the velocity and acceleration limits of the UAV.

3 Joint optimization of transmit power and trajectory

It can be observed that the objective function of problem (14) is a fractional function with a non-concave numerator over a non-convex denominator and that the minimum speed constraint (14j) is non-convex. It means that problem (14) cannot be directly solved with a standard convex optimization technique. In order to solve this issue, problem (14) is decomposed into two sub-problems, namely, (1) transmit power control of S and R with fixed relay's trajectory; (2) UAV's trajectory optimization with fixed transmit power of S and R. By solving the two sub-problems, an iterative algorithm is developed to achieve a suboptimal solution of problem (14), leading to a joint design of transmit power control and UAV's trajectory optimization.

3.1 Optimal transmit power control with fixed relay's trajectory

Here, the first sub-problem is addressed. Since the UAV relay's trajectory is assumed to be fixed, the values of $\mathbf{a}(n)$, $\mathbf{v}(n)$ and $\mathbf{q}(n)$ are known. In addition, according to (4), (5) and (11), $h_{SR}(n)$, $h_{RD}(n)$ and E are also fixed in this situation. Therefore, the optimization problem of transmit power control of S and R with fixed relay trajectory can be formulated as

$$\max_{\{P_S(n),P_R(n)\}} \quad \sum_{n=1}^{N} R_{RD}(n) \tag{15a}$$

$$\text{s.t.}(14\text{b}),\ (14\text{c}),\ (14\text{d}) \tag{15b}$$

Since $R_{RD}(n)$ is non-concave with respect to $\{P_S(n), P_R(n)\}$, problem (15) is still a non-convex optimization problem. To this end, the SCA technique is employed so as to maximize a lower-bound of problem (15).

It can be observed by (10) that $R_{RD}(n)$ is convex with respect to $\frac{1}{\gamma_D(n)}$. Due to the fact that the first-order Taylor expansion of a convex function is its global under-estimator [25], for the $(j+1)$-th iteration, we can find a lower-bound of $R_{RD}^{j+1}(n)$ by using its first-order Taylor expansion at $\frac{1}{\gamma_D^j(n)}$ as follows

$$\begin{aligned} R_{RD}^{j+1}(n) \geq \frac{1}{2}\log_2\left[1+\frac{1}{1\Big/\gamma_D^j(n)}\right] - \frac{[\gamma_D^j(n)]^2\cdot\log_2 e}{2(\gamma_D^j(n)+1)}\left[\frac{1}{\gamma_D^{j+1}(n)}-\frac{1}{\gamma_D^j(n)}\right] \\ = R_{RDlb}^{j+1}(n) \end{aligned} \tag{16}$$

where

$$\frac{1}{\gamma_D^{j+1}(n)} = \frac{\frac{|h_{SR}(n)|^2\sigma^2}{P_R^{j+1}(n)} + \frac{|h_{RD}(n)|^2\sigma^2}{P_S^{j+1}(n)} + \frac{\sigma^4}{P_S^{j+1}(n)P_R^{j+1}(n)}}{|h_{SR}(n)|^2|h_{RD}(n)|^2}, \tag{17}$$

Since the Hessian matrix is positive definite, $\frac{1}{\gamma_D^{j+1}(n)}$ is convex with respect to $\left\{P_S^{j+1}(n), P_R^{j+1}(n)\right\}$. Therefore, in (16), $R_{RDlb}^{j+1}(n)$ is jointly concave with respect to $\left\{P_S^{j+1}(n), P_R^{j+1}(n)\right\}$. Consequently, for the $(j+1)$-th iteration, problem (15) can be transformed into

$$\max_{\{P_S^{j+1}(n),P_R^{j+1}(n)\}} \quad \sum_{n=1}^{N} R_{RDlb}^{j+1}(n) \tag{18a}$$

$$\text{s.t. } 0 \leq P_S^{j+1}(n) \leq P_{S\max}, 0 \leq P_R^{j+1}(n) \leq P_{R\max}, \tag{18b}$$

$$\frac{1}{N}\sum_{n=1}^{N} P_S^{j+1}(n) \leq \overline{P}_S, \tag{18c}$$

$$\frac{1}{N}\sum_{n=1}^{N} P_R^{j+1}(n) \leq \overline{P}_R, \tag{18d}$$

The objective function of problem (18) is concave and all its constraints are convex. Thus, (18) is a convex optimization problem which can be solved by standard convex optimization techniques such as the interior-point method [25]. Then, problem (15) can be approximately figured out by successively updating the transmit power of S and

R which can be achieved by solving problem (18). An iterative algorithm is presented below so as to acquire the solution of (15).

Algorithm 1 The Iterative Process of Solving Problem (15)

1: Initialize $\left\{P_S^j(n), P_R^j(n)\right\}$, so that all the constraints of (15) can be satisfied. Let $j=0$.
2: **repeat**
3: Solve problem (18) to obtain $\left\{P_S^{j+1}(n), P_R^{j+1}(n)\right\}$ according to the interior-point method.
4: Update $j=j+1$.
5: **until** $\left|\sum_{n=1}^{N} R_{RDlb}^{j}(n) - \sum_{n=1}^{N} R_{RDlb}^{j-1}(n)\right| \le \varepsilon$.
6: Output $\left\{P_S^*(n)=P_S^j(n), P_R^*(n)=P_R^j(n)\right\}$.

3.2 Trajectory optimization with fixed transmit power

Here, the second sub-problem is investigated, i.e., the UAV relay's trajectory optimization with fixed transmit power of S and R. Suppose that $\mathbf{v}_0 = \mathbf{v}_F$, then, the trajectory optimization with fixed transmit power can be formulated as

$$\max_{\{\mathbf{a}(n)\}} \frac{\sum\limits_{n=1}^{N} B\delta R_{RD}(n)}{E} \tag{19a}$$

$$\text{s.t.}(14e) \sim (14k). \tag{19b}$$

It is noticed that the denominator of (19a) can be upper-bounded as

$$\begin{aligned} E &\le \sum_{n=1}^{N} \delta\left(c_1\|\mathbf{v}(n)\|^3 + \frac{c_2}{\|\mathbf{v}(n)\|}\left\{1 + \frac{\|\mathbf{a}(n)\|^2}{g^2}\right\}\right) \\ &= E_{ub} \end{aligned} \tag{20}$$

where the term $[\mathbf{a}^{\mathrm{T}}(n)\mathbf{v}(n)]^2 / \|\mathbf{v}(n)\|^2$ is omitted. With this simplification, E_{ub} can be readily processed as a convex function, which will facilitate the solution of the optimization problem. For the case that the UAV flies at a constant speed, $\mathbf{a}^{\mathrm{T}}(n)\mathbf{v}(n)=0$ and $E=E_{ub}$ holds; for the case that the UAV flies at a variable speed, $E<E_{ub}$ holds. Replacing E with E_{ub} will actually leads to a lower-bound of EE.

Therefore, (19a) can be lower-bounded as

$$\begin{aligned} EE &\ge \frac{\sum\limits_{n=1}^{N} B\delta R_{RD}(n)}{E_{ub}} \\ &= \frac{\sum\limits_{n=1}^{N} B\delta R_{RD}(n)}{\sum\limits_{n=1}^{N} \delta\left(c_1\|\mathbf{v}(n)\|^3 + \frac{c_2}{\|\mathbf{v}(n)\|}\left\{1 + \frac{\|\mathbf{a}(n)\|^2}{g^2}\right\}\right)} \\ &= EE_{lb} \end{aligned} \tag{21}$$

Thus, problem (19) can be approximately solved by maximizing its lower-bound, giving

$$\max_{\{\mathbf{a}(n)\}} \quad EE_{lb} \tag{22a}$$

$$\text{s.t.}(14e) \sim (14k) \tag{22b}$$

Obviously, problem (22) is not a convex problem. In order to solve it, slack variable $\tau(n)$ is introduced so that the following constraints should be satisfied.

$$\tau^2(n) \leq \|\mathbf{v}(n)\|^2 \tag{23}$$

$$\tau(n) \geq v_{\min} \tag{24}$$

Then, problem (22) can be rewritten as

$$\max_{\{\mathbf{a}(n),\tau(n)\}} \quad \frac{\sum_{n=1}^{N} B\delta R_{RD}(n)}{\sum_{n=1}^{N} \delta\left(c_1\|\mathbf{v}(n)\|^3 + \frac{c_2}{\tau(n)}\left\{1 + \frac{\|\mathbf{a}(n)\|^2}{g^2}\right\}\right)} \tag{25a}$$

$$\text{s.t.}(14e) \sim (14k), (23), (24). \tag{25b}$$

It can be observed that when the optimal solution is obtained, $\tau(n) = ||\mathbf{v}(n)||$ must hold, otherwise, there must exist a better target value by increasing the value of $\tau(n)$. Therefore, problem (25) is equivalent to problem (22).

Note that although the denominator of (25a) is jointly convex with respect to $\{\mathbf{a}(n), \mathbf{v}(n), \tau(n)\}$, the numerator of it is non-concave and the constraint (23) is non-convex, and hence problem (25) is neither a convex nor quasi-convex problem. To tackle the non-convex constraint (23), the SCA technique is used. Owing to the fact that $||\mathbf{v}(n)||^2$ is convex with respect to $\mathbf{v}(n)$, for the $(j+1)$-th iteration, a lower-bound of $||\mathbf{v}_{j+1}(n)||^2$ can be achieved by using its first-order Taylor expansion at $\mathbf{v}_j(n)$, which can be given bellow

$$\left\|\mathbf{v}_{j+1}(n)\right\|^2 \geq \left\|\mathbf{v}_j(n)\right\|^2 + 2\mathbf{v}_j^T(n)\left[\mathbf{v}_{j+1}(n) - \mathbf{v}_j(n)\right] \tag{26}$$

Thus, (23) can be transformed into

$$\tau_{j+1}^2(n) \leq \left\|\mathbf{v}_j(n)\right\|^2 + 2\mathbf{v}_j^T(n)\left[\mathbf{v}_{j+1}(n) - \mathbf{v}_j(n)\right] \tag{27}$$

Next, we deal with the non-concavity of the numerator of the objective function in (25a). Define

$$A(n) = \frac{1}{P_S(n)\left|h_{SR}(n)\right|^2} = \frac{\|\mathbf{q}_S - \mathbf{q}(n)\|^2 + H^2}{P_S(n)\beta} \tag{28}$$

$$C(n) = \frac{1}{P_R(n)\left|h_{RD}(n)\right|^2} = \frac{\|\mathbf{q}(n) - \mathbf{q}_D\|^2 + H^2}{P_R(n)\beta} \tag{29}$$

The SNR at the node D can be expressed as

$$\gamma_D(n) = \frac{1}{[A(n) + C(n) + A(n)C(n)\sigma^2]\sigma^2} \tag{30}$$

Since the Hessian matrix is positive definite, $R_{RD}(n) = \frac{1}{2}\log_2[1 + \gamma_D(n)]$ is convex with respect to $\{A(n), C(n)\}$. As mentioned earlier, the first-order Taylor expansion of a convex function is its lower-bound. For the $(j+1)$-th iteration, a lower-bound of $R_{RD}^{j+1}(n)$ can be obtained by using its first-order Taylor expansion at $\{A_j(n), C_j(n)\}$, which is presented in (31).

$$\begin{aligned} R_{RD}^{j+1}(n) \geq \frac{1}{2}\log_2\left[1 + \frac{1}{[A_j(n) + C_j(n) + A_j(n)C_j(n)\sigma^2]\sigma^2}\right] \\ -D_j(n)\left[A_{j+1}(n) - A_j(n)\right] - E_j(n)\left[C_{j+1}(n) - C_j(n)\right] \\ = R_{RDlb'}^{j+1}(n) \end{aligned} \tag{31}$$

where

$$D_j(n) = \frac{(1 + C_j(n)\sigma^2)\log_2 e}{2[1 + (A_j(n) + C_j(n) + A_j(n)C_j(n)\sigma^2)\sigma^2][A_j(n) + C_j(n) + A_j(n)C_j(n)\sigma^2]} \tag{32}$$

$$E_j(n) = \frac{(1 + A_j(n)\sigma^2)\log_2 e}{2[1 + (A_j(n) + C_j(n) + A_j(n)C_j(n)\sigma^2)\sigma^2][A_j(n) + C_j(n) + A_j(n)C_j(n)\sigma^2]} \tag{33}$$

Since $A_{j+1}(n)$ and $C_{j+1}(n)$ are both convex with respect to $\mathbf{q}_{j+1}(n)$, $R_{RDlb'}^{j+1}(n)$ in (31) is concave with respect to $\mathbf{q}_{j+1}(n)$. Therefore, for the $(j+1)$-th iteration, problem (25) can be transformed into

$$\max_{\{\mathbf{a}_{j+1}(n), \tau_{j+1}(n)\}} \frac{\sum_{n=1}^{N} BR_{RDlb'}^{j+1}(n)}{\sum_{n=1}^{N}\left(c_1\|\mathbf{v}_{j+1}(n)\|^3 + \frac{c_2}{\tau_{j+1}(n)}\left\{1 + \frac{\|\mathbf{a}_{j+1}(n)\|^2}{g^2}\right\}\right)} \tag{34a}$$

$$\text{s.t.}\mathbf{v}_{j+1}(1) = \mathbf{v}_0, \mathbf{q}_{j+1}(1) = [x_0, y_0] \tag{34b}$$

$$\mathbf{v}_{j+1}(N+1) = \mathbf{v}_F, \mathbf{q}_{j+1}(N+1) = [x_F, y_F] \tag{34c}$$

$$\mathbf{q}_{j+1}(n+1) = \mathbf{q}_{j+1}(n) + \mathbf{v}_{j+1}(n)\delta + \frac{1}{2}\mathbf{a}_{j+1}(n)\delta^2 \tag{34d}$$

$$\mathbf{v}_{j+1}(n+1) = \mathbf{v}_{j+1}(n) + \mathbf{a}_{j+1}(n)\delta \tag{34e}$$

$$\|\mathbf{v}_{j+1}(n)\| \leq v_{\max} \tag{34f}$$

$$\|\mathbf{a}_{j+1}(n)\| \leq a_{\max} \tag{34g}$$

$$\tau_{j+1}(n) \geq v_{\min} \tag{34h}$$

$$(27) \tag{34i}$$

According to the discussions above, the objective value of problem (34) gives a lower-bound to that of problem (25). In addition, problem (34) is a fractional maximization problem with a concave numerator and a convex denominator, and all the constraints are convex. Thus, it can be efficiently solved via the standard Dinkelbach's algorithm [26] which transforms the fraction maximization problem into a subtractive optimization problem. For the j-th iteration, let

$$\omega_j = \frac{\sum_{n=1}^{N} BR^j_{RDlb'}(n)}{\sum_{n=1}^{N}\left(c_1||\mathbf{v}_j(n)||^3 + \frac{c_2}{\tau_j(n)}\left\{1 + \frac{||\mathbf{a}(n)||^2}{g^2}\right\}\right)} \tag{35}$$

For the $(j+1)$-th iteration, let

$$F(\{\mathbf{a}_{j+1}(n), \tau_{j+1}(n)\}) = \sum_{n=1}^{N} BR^{j+1}_{RDlb'}(n) - \omega_j\left(\sum_{n=1}^{N}\left(c_1||\mathbf{v}_{j+1}(n)||^3 + \frac{c_2}{\tau_{j+1}(n)}\left\{1 + \frac{||\mathbf{a}_{j+1}(n)||^2}{g^2}\right\}\right)\right) \tag{36}$$

Then, problem (34) can be transformed into

$$\max_{\{\mathbf{a}_{j+1}(n), \tau_{j+1}(n)\}} \ F(\{\mathbf{a}_{j+1}(n), \tau_{j+1}(n)\}) \tag{37a}$$

$$\text{s.t.}(34\text{b}) - (34\text{i})$$

With a given ω_j, problem (37) is a convex optimization problem which can be solved via convex optimization tools. Then problem (34) can be solved by iteratively optimizing problem (37) with updated ω_j.

Therefore, the original non-convex problem (25) can be solved by an iterative optimization, which is summarized in Algorithm 2.

Algorithm 2 The Iterative Process of Solving Problem (25)

1: Initialize $\{\mathbf{a}_j(n), \tau_j(n)\}$ so that all the constraints of (25) can be satisfied. Let j=0.
2: **repeat**
3: Let l=0, $\mathbf{a}_l(n) = \mathbf{a}_j(n)$, $\tau_l(n) = \tau_j(n), \forall\, n$.
4: **repeat**
5: Compute ω_l based on (35).
6: Solve problem (37) to obtain $\{\mathbf{a}_{l+1}(n), \tau_{l+1}(n)\}$.
7: Update l=l+1.
8: **until** $|F(\{\mathbf{a}_l(n), \tau_l(n)\}) - F(\{\mathbf{a}_{l-1}(n), \tau_{l-1}(n)\})| \leq \varepsilon$.
9: Update j=j+1.
10: $\mathbf{a}_j(n) = \mathbf{a}_l(n)$, $\tau_j(n) = \tau_l(n)$, $\forall\, n$.
11: **until** the increment of the objective value of problem (25) is below a threshold ε.
12: Output $\{\mathbf{a}^*(n) = \mathbf{a}_j(n), \tau^*(n) = \tau_j(n)\}$.

3.3 Joint power and trajectory optimization

According to Algorithms 1 and 2, an iterative algorithm is proposed to jointly optimize the transmit power and the trajectory based on the block coordinate descent (BCD) technique, which finally solves problem (14). The iterative algorithm is summarized in Algorithm 3. It is noted that, each iteration in Algorithm 3 only needs to solve convex optimization problems, and thus the worse case complexity of Algorithm 3 is polynomial [25, 27], which is within the scope of the affordability of the UAV-enabled relaying systems.

Algorithm 3 Joint Power and Trajectory Optimization

1: Initialize the UAV's acceleration $\{\mathbf{a}(n)\}$, so that all the constraints of (14) can be satisfied. Let j=0.
2: **repeat**
3: Fix the UAV's trajectory, and find the transmit power of S and R $\{P_S^j(n), P_R^j(n)\}$ using Algorithm 1.
4: With $\{P_S^j(n), P_R^j(n)\}$, obtain the UAV's optimal acceleration $\{\mathbf{a}_j(n)\}$ using Algorithm 2.
5: Update $j = j+1$.
6: **until** the increment of the objective value of problem (14) is below a threshold ε.
7: Output $\{\mathbf{a}^*(n), P_S^*(n), P_R^*(n)\}$ corresponding to $\mathbf{a}^*(n)=\mathbf{a}_j(n)$, $P_S^*(n)=P_S^j(n)$, $P_R^*(n)=P_R^j(n)$.

4 Simulation results

In this section, simulation results are provided to validate the proposed optimization scheme. According to [14] and [16], the distance L between S and D is set to 2000 m. The flight altitude of the UAV is fixed at $H=200$ m, and the UAV is assumed to fly from the initial position (700, 200, 200) to the final position (1300, 200, 200). The initial and final velocities of the UAV $\mathbf{v}_0$ and $\mathbf{v}_F$ are assumed to be [5; 0]. The maximum and minimum speeds of the UAV are set to $v_{\max}=50$ m/s and $v_{\min}=5$ m/s, respectively, and the maximum UAV's acceleration is set to $a_{\max}=5$ m/s^2 [21]. The communication bandwidth is $B=1$MHz, and the power spectrum density of noise at the UAV and D is assumed to be $N_0=$-120dBm/Hz. Furthermore, $c_1=0.000926$ and $c_2=2250$ are assumed [21]. Unless otherwise stated, the average transmit power is set to $\overline{P}_S=\overline{P}_R=0.02$W, and the maximum transmit power is assumed to be $P_{S\max}=P_{R\max}=0.04$W.

Figure 2 presents the convergence of Algorithm 3 and the effect of time-slot length on EE of the system, where three different time-slot lengths $\delta=3$ s, $\delta=6$ s and $\delta=12$ s are include. The UAV flight time T is 120 s and the terminating threshold of Algorithm 3 is set to 0.1%. EE_{exact} and EE_{lb} represent the exact EE and the lower-bound of EE. Our simulation results show that EE_{lb} is less than and close to EE_{exact}, confirming the correctness of our investigations. It is observed from Fig. 2 that Algorithm 3 converges quickly, indicating the effectiveness of the algorithm. When the time-slot length decreases, the EE of the system increases. This is due to the assumption in Sect. 2.1 that the speed and the position of the UAV in each time-slot can be considered to remain constant. When the flight time of the UAV is fixed, according to $\delta=T/N$, decreasing the time-slot length means that the UAV has more time-slots to adjust its speed, leading to a reduction of energy consumption of the system, and an enhancement of EE.

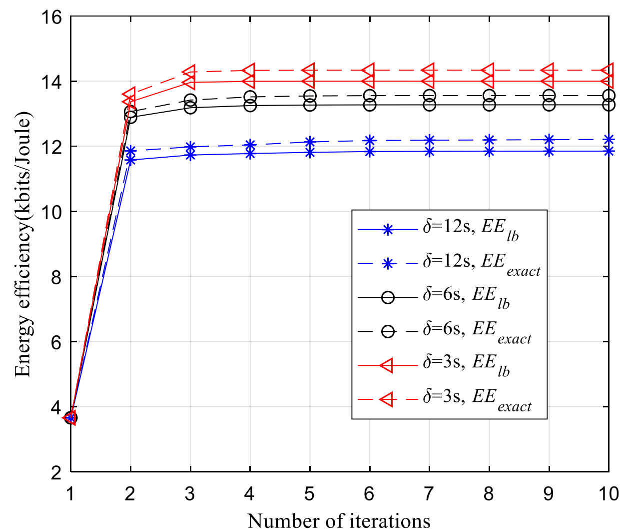

Fig. 2 Convergence of Algorithm 3 and the effect of time-slot length on energy efficiency

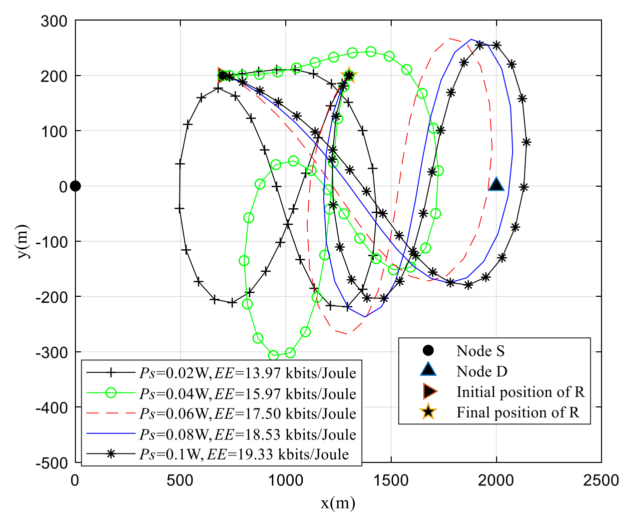

Fig. 3 Optimized trajectories of the UAV with fixed transmit power

A simple case is analyzed in Fig. 3, where only the flight trajectory of the UAV is optimized. The transmit power of the UAV is fixed at 0.02W, while the transmit power of S is set to five different values. The purpose is to explore the influence of the transmit power of S on the trajectory of the UAV and the EE of the system. It can be observed that the UAV hovers around between its initial and final positions following an approximate "8" shape path. When the transmit power of S increases, the trajectory of the UAV becomes closer to D. The reason is that when the transmit power of S increases, more data can be collected by the UAV from S. In order for the UAV to complete the data transfer, it should close to D. Therefore, with increasing the transmit power of S, the throughput of the system increases. Moreover, the optimized trajectory enables the UAV to fly without excessive energy consumption, hence the EE of the system is improved.

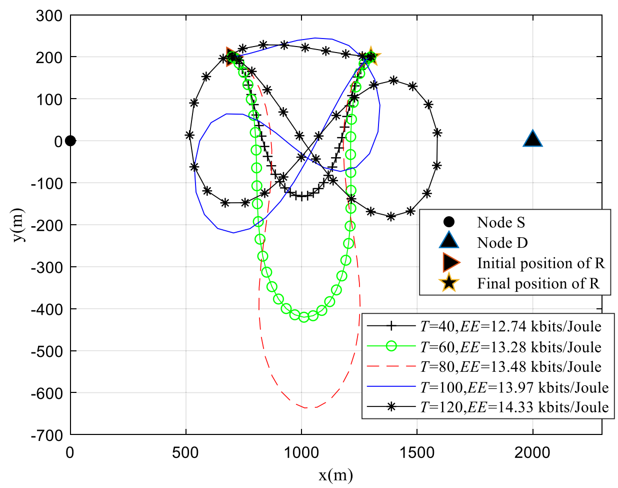

Fig. 4 Trajectories of the UAV of the joint optimization scheme

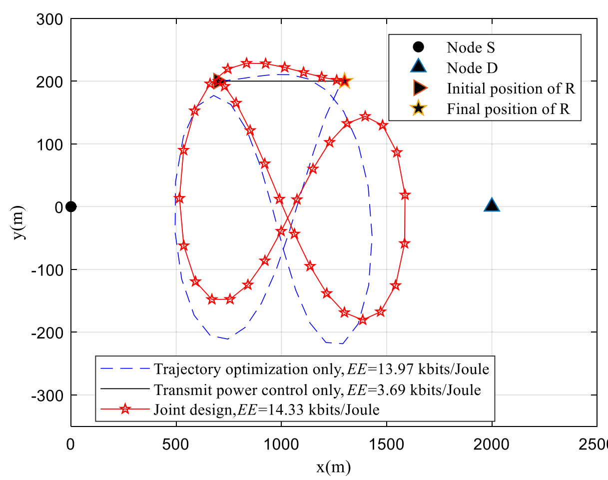

Fig. 5 Trajectories of the UAV of the three compared schemes

Figure 4 plots the flight trajectories of the UAV using the proposed joint optimization scheme, where five different flight time, i.e., $T=40$ s, $T=60$ s, $T=80$ s, $T=100$ s and $T=120$ s, are considered. It can be seen that the trajectories of the UAV vary with the variant of flight time. When the flight time T is short, the UAV flies in approximately symmetric "U" shape and in the direction of the vertical connection between S and D. The reason is that if the UAV flies in the direction of S or D, it cannot well forward the data received from S to D or cannot collect more data from S. Therefore, flying in symmetric shape and in the direction of the vertical connection between S and D can receive as much data as possible from S and forward as much data as possible to D. The "U" shape is because the fixed-wing UAV cannot change its flight direction instantaneously and thus needs radian to change directions. With the increasing of flight time, the UAV hovers around following an approximate "8" shape path, so as to maintain a sufficiently good communication channel yet without excessive energy consumption. It can also be seen from Fig. 4 that the EE increases with the increasing of flight time. This is because the UAV has more time to adjust its flight trajectory and transmit power.

Figure 5 presents the flight trajectories of the UAV of the three compared schemes, i.e., (1) trajectory optimization with fixed transmit power, (2) transmit power control with fixed trajectory, and (3) joint optimization of transmit power and flight trajectory, where $T = 120$ s is assumed. Here, the scheme of trajectory optimization with fixed transmit power (i.e. the scheme of trajectory optimization only) corresponds to the scheme proposed in [20]. For the flight speed optimization scheme proposed in [19], the UAV's trajectory is deduced according to the optimized flight speed. Therefore, the optimization scheme in [19] can be considered to be equivalent to the trajectory optimization scheme in [20]. For the scheme of trajectory optimization with fixed transmit power, the transmit power of S and R are fixed and set to 0.02W. For the scheme of transmit power control with fixed trajectory, the UAV is assumed to fly straight from the initial position to the final position at the initial speed. Figure 5 demonstrates that the UAV's trajectory of the scheme of trajectory optimization with fixed transmit power follows an approximate "8" shape path as that of the joint optimization scheme. Compared with the scheme of trajectory optimization with fixed transmit power, the UAV is closer to D, leading to the higher EE of the system when the joint optimization scheme is employed.

Figures 6 and 7 give the transmit power of S and the UAV versus the UAV's flight time under the three compared schemes, where all the parameters are the same as those in Fig. 5. For the scheme of trajectory optimization with fixed transmit power, the transmit power of S and R are set to their average transmit power. For the scheme of transmit power control with fixed trajectory, the UAV is assumed to fly straight from the initial position to the final position at the initial speed. Figures 6 and 7 show that for the scheme of transmit power control with fixed trajectory, the UAV flights far away from S when the flight time increases. In order for the UAV to collect more data from S, the transmit power of S increases monotonically. In this situation, the distance between the UAV and D gets close, and thus the transmit power of the UAV gradually decreases. For

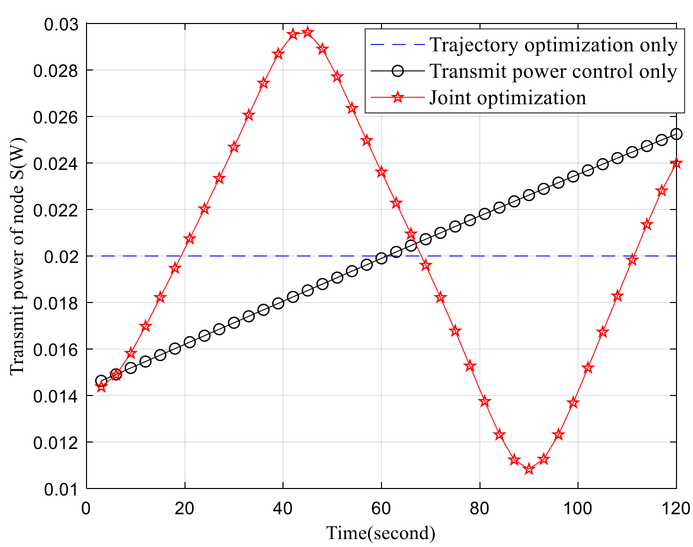

Fig. 6 Transmit power of S under the three compared schemes

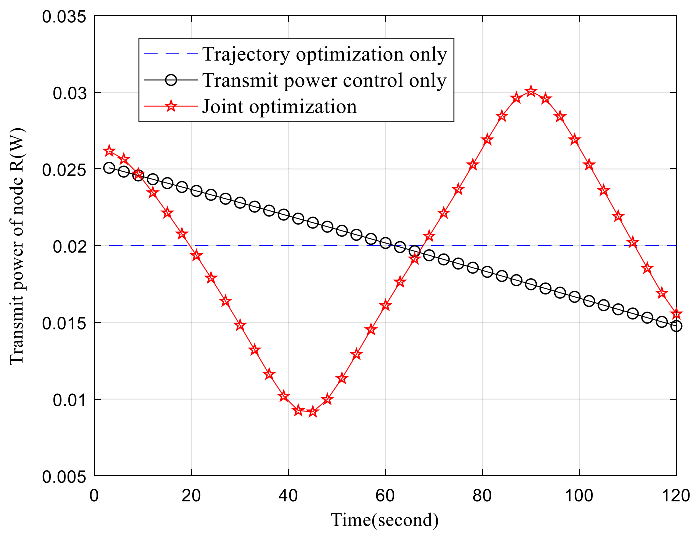

Fig. 7 Transmit power of the UAV under the three compared schemes

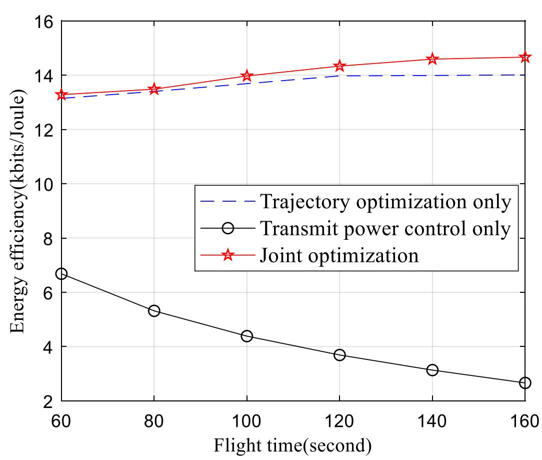

Fig. 8 Energy efficiency of the three compared schemes

the joint optimization scheme, the transmit power of S and the UAV is related to the distance between S and R, and that between R and D. It can be observed that at the beginning, the UAV flies away from S, resulting in a long distance between them. Therefore, in order to send more data to the UAV, the transmit power of S gradually increases. Then, as the UAV flies to S, the UAV and S get close and thus the channel condition becomes better, then the transmit power of S gradually decreases. At the final phase, the UAV flies away from S again, and the distance between S and R increases accordingly. As a result, S increases its transmit power again. The transmit power of the UAV has a similar rule. Due to the space limitation, it is omitted.

Figure 8 plots the achieved system EE of the three compared schemes versus the flight time T. It is observed that for the scheme of transmit power control with fixed trajectory, the EE decreases with the increasing of flight time of the UAV. This is because the energy consumption of the UAV increases with the increasing of flight time. By conducting the scheme of transmit power control with fixed trajectory, however, the improvement of the UAV's throughput is very limited. Therefore, the EE of the scheme of transmit power control only decreases. Compared with the scheme of transmit power control only, the scheme of trajectory optimization only improves the EE to a large extent, however, it is still not the optimal solution. The proposed joint optimization scheme can achieve the highest EE. With the increasing of the flight time, the improvement of EE of the joint optimization scheme becomes more evident. This is because the longer the flight time, the more degrees of freedom can be used by the UAV to adjust its flight path and transmit power flexibly, which leads to the greatest EE.

5 Conclusions

This paper developed a joint optimization scheme for a UAV-enabled AF relaying system. The objective is to maximize the EE of the system over a finite time horizon via optimizing both the source and the UAV's transmit power as well as the UAV's trajectory. To solve the initial non-convex optimization problem, the transmit power and the trajectory are first optimized separately, and then an iterative algorithm is proposed to joint optimize the transmit power and the flight trajectory based on the BCD technique. Numerical results showed that the EE of the system of the proposed joint optimization scheme is the best compared to the benchmark schemes. The longer the flight time, the more degrees of freedom can be used by the UAV to adjust its flight path flexibly and thus leads to greater EE.

Abbreviations

UAV Unmanned aerial vehicle
AF Amplify and forward
EE Energy efficiency
HAP High altitude platform
LoS Line of sight
BS Base station
Gu Ground user
3D Three dimensional
DF Decode and forward
SAF Store then amplify and forward
SAG Space air ground
IoT Internet of things
SCA Successive convex approximation
SNR Signal to noise ratio
BCD Block coordinate technique

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Author contributions
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Availability of data and materials
Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Competing interests
The authors declare that they have no competing interests.

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