



Energy Efficiency Optimization for RF Energy Harvesting Relay System

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Abstract. This paper conducts research on the RF energy harvesting relay network, and proposes an improved energy harvesting relay protocol, which allows the energy harvesting source node to retransmit data to improve the system diversity gain, and constructs energy harvesting slot allocation, subcarrier pairing, and power Optimized model of distributed system energy efficiency. A resource allocation algorithm based on optimal energy efficiency is further proposed. The Dinkelbach method is used to transform the nonlinear programming problem into a linear programming problem. Then, the Hungarian algorithm and the sub-gradient method are used to obtain the iterative algorithm based on energy efficiency optimization. Simulation shows that the algorithm reduces the complexity of the algorithm and has good global convergence.

Keywords: RF energy harvesting · Energy efficiency · Power allocation · Subcarrier pairing

1 Introduction

Radio frequency energy harvesting (RF-EH) technology can extend the life of wireless networks, improve energy efficiency, and reduce the total greenhouse gas emissions of green wireless communications [1, 2].

Reference [3] applied RF energy harvesting technology to the cognitive radio (CR) network scenario earlier, considering a random geometric model of the

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homogeneous Poisson point process (HPPP) where the primary user and the secondary user are independent, the secondary user can obtain the environmental RF energy from the transmission, analyze the transmission probability and throughput of the secondary user, and get the best transmission power and user distribution density. Literature [5] conducts research on cognitive D2D communication based on energy harvesting in heterogeneous cellular networks. Cognitive D2D users can obtain energy from environmental interference, and analyzes two types of uplink or downlink for cellular communication Spectrum access strategy, namely random spectrum access (RSA) strategy and priority spectrum access (PSA) strategy. Literature [4] studies the transmission scheduling strategy in RF energy harvesting communication. In order to describe the actual environmental energy harvesting process more accurately, a nonlinear recursive model including the feedback loop of data transmission to the energy harvesting process is proposed, and a design based on The optimal transmission scheduling strategy of the recursive algorithm.

Literature [6,7] assumes that the secondary user node of the cognitive energy harvesting network satisfies the causal limitation of harvested energy. Literature [6] assumes that a system throughput optimization model of primary user interference limitation is constructed and proposes a system based on system Power allocation algorithm. Reference [7] considers the differences in energy acquisition capabilities, channel perception energy and channel quality of secondary users, and proposes a joint resource allocation algorithm for secondary user transmission channel selection, transmission power allocation, and transmission time assignment.

The collaborative communication technology represented by relays can significantly improve the average throughput of the system and expand the network coverage, and has received extensive attention from academia and industry. The literature [8–14] focuses on the application of energy harvesting technology in the field of collaborative communication the study.

Literature [8] studies a bidirectional relay scenario with energy harvesting nodes, proposes a dynamic selection relay strategy to improve throughput, and maximizes offline throughput through an iterative generalized water injection algorithm, and further gives a dynamic programming method Get the best online relay selection strategy. References [9,10] study the performance optimization scheme of the three-node energy harvesting bidirectional relay network (TWRN). Reference [9] assumes that energy transfer is allowed between nodes for energy collaboration. Under the constraints of energy harvesting (EH) and peak power, an optimal resource allocation scheme based on offline scheduling is proposed, and a dynamic programming-based Of the online scheduling scheme to approximate the offline optimal solution. Reference [10] assumes that the relay collects energy from the received information signal and co-channel interference signal, and then uses the collected energy to forward the correctly decoded signal to the receiver, and the receiver switches between decoding information and collecting energy Time switching scheme (TS), and power receiving scheme (PS), part of the received power is used for energy collection, and the

remaining power is used for information processing information, given the decoding and forwarding energy collection relay system traversal capacity and Analytical expression of interruption capacity. Reference [11] studies the maximum throughput of the end-to-end system of the energy harvesting two-hop relay communication network. Assuming that the energy arrival and channel state are known, the optimal offline time scheduling and power are obtained through the Karush-Kuhn-Tucker condition. Distribution, further proposed two sub-optimal low complexity online transmission strategies. Reference [12] studies the optimal design of bidirectional decoding and forwarding (DF) energy harvesting relay networks, and examines power split relay (PSR) and time switching relay (TSR) strategies, respectively, and applies the fairness max-min criterion and maximum According to the max-sum criterion of resource utilization, the optimal power allocation coefficient and the optimal time switching coefficient of the network based on PSR and TSR are obtained, and the maximum transmission rate is analyzed. Literature [13] studied the substrate-based energy harvesting cognitive relay scenario, assuming that the energy harvesting device has hardware damage, proposed a hardware damage-based substrate-based energy harvesting bidirectional cognitive relay network model, and deduced the secondary network in Sweden Closed solution of the probability of outage in a fading block fading channel. Reference [14] considers a two-way relay cooperative cognitive radio network for cooperative transmission of energy and information. The secondary user adopts two-way cooperative relay transmission. The relay adopts cooperative transmission of energy and information to derive the outage probability of the system and the traversal of secondary users. Closed solution of capacity.

This article considers an RF-EH multi-relay scenario, which includes a base station BS, a source node, and relay nodes. The HTC relay mechanism is used in the network. The BS broadcasts energy to the source node and the relay node on the downlink channel, and receives signals from the source node and the relay node on its upstream channel. After the source node collects radio frequency energy from the BS, it uses the collected Energy transmission data. Taking the maximum energy efficiency of the system as the optimization goal, the transmission power of the entire network is restricted as the constraint condition, and then the energy efficiency optimal model of joint subcarrier pairing, power allocation and time slot assignment is concluded. The proposed optimization model is a mixed integer nonlinear programming problem, which can be simplified by the equivalent channel gain method and solved by the dual method. First, the Dinkelbach method is used to transform the nonlinear programming problem into a linear programming problem. Then, the Cauchy inequality and the Hungarian algorithm are used to solve the power allocation and subcarrier allocation problems of the current iteration. Finally, the sub-gradient method is used to obtain the iterative algorithm based on energy efficiency optimization.

The main contributions of this paper are summarized as follows:

- An improved HTC relay mechanism is proposed to allow the source node to retransmit the unsuccessful signal in the last time slot on another subcarrier.

Such a scheme can significantly improve the energy efficiency performance of the system.

- The proposed optimization model is a mixed integer nonlinear programming problem. The method of deriving the equivalent channel gain simplifies the objective function and reduces the computational complexity of the objective function.
- For an iterative process of energy efficiency optimization, a joint resource allocation algorithm is proposed. Joint allocation is based on the principle of energy efficiency optimization, power allocation, subcarrier pairing and time slot assignment.

The rest of this article is organized as follows. The second chapter is the system model and problem description, elaborating on the improved HTC protocol proposed in this paper, which comes down to the optimization problem. The third chapter is the energy efficiency optimization outer loop algorithm. Sect. 3 describes the energy efficiency optimization inner loop algorithm. Sect. 4 is the simulation results and analysis. Sect. 5 presents the conclusion of this study.

2 System Model and Problem Description

2.1 System Model

As shown in Fig. 1, this chapter studies the RF-EH multi-relay network scenario, including a base station BS, a source node S and K relay nodes, each relay works in AF half-duplex mode, the entire transmission bandwidth is divided equally into N sub-carriers. BS has a constant energy supply to ensure reliable communication. The source node S and all relays are equipped with rechargeable batteries without a stable energy supply device, and must rely on energy harvesting to complete data transmission.

Unlike the HTC relay mechanism in [16], it is assumed that the source node S and all K relay nodes can collect energy and use it to transmit data. The transmission process T of each data block is divided into two stages, an energy transmission stage $\tau_E T$ and a data transmission stage $\tau_I T$, and thus $\tau_E + \tau_I = 1$.

In the energy transmission phase $\tau_E T$, the BS broadcasts energy to the source node S and all K relay nodes in the downlink channel. After the source node S and the K relay nodes collect enough energy for the signal transmission of the next two time slots, the energy transmission phase ends.

In this paper, the subscript B indicates BS, the subscript S indicates the source node, and the subscript $R_k, k = 1, 2, \dots, K$ indicates each relay node. h^{BS} and h_k^{BR} represent the channel gain from BS to source node S and BS to relay node R_k on subcarrier i , respectively, and the channel gain follows the complex Gaussian distribution, defined as $h^{BS} \sim CN(0, \sigma_{BS}^2)$ and $h_k^{BR} \sim CN(0, \sigma_{BR,k}^2)$, where σ_{BS}^2 and $\sigma_{BR,k}^2$ represent the Gaussian white at the receiving end noise. P_B represents the transmission power of BS. In order to ensure that the relay and the source collect enough energy to work properly,

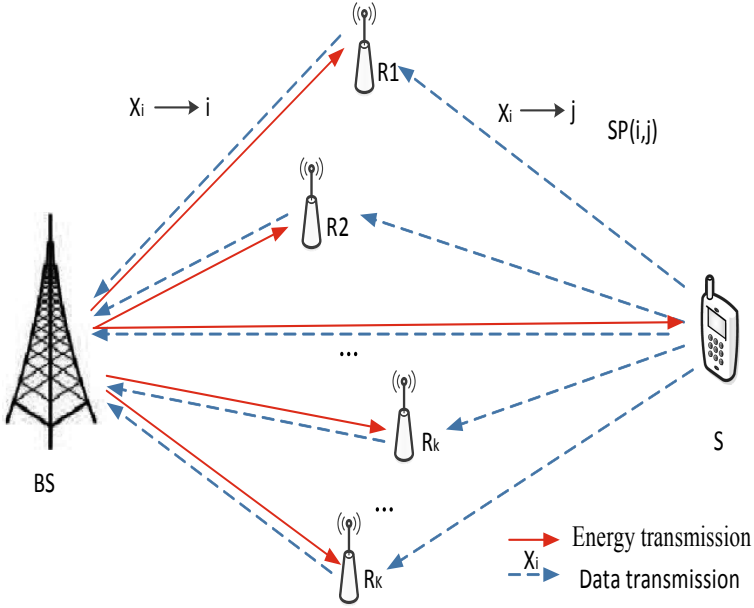


Fig. 1. RF-EH multi-relay network scenario.

the P_B needs to be large enough so that the energy collected from the noise can be ignored. In the energy transmission phase, the energy collected by the source node S and the relay node R_k and the total energy collected are expressed as

$$E^S = \zeta_S \tau_E T h^{BS} P_B \quad (1)$$

$$E_k^R = \zeta_k^R \tau_E T h_k^{BR} P_B, \quad k \in \{1, 2, \dots, K\} \quad (2)$$

$$E^{EH} = \tau_E T \left(\zeta_S h^{BS} + \sum_{k=1}^K \zeta_k^R h_k^{BR} \right) P_B \quad (3)$$

where ζ_S and ζ_k^R are the energy collection efficiency of the source node S and the relay node R_k , which meets $0 < \zeta_S < 1$, $0 < \zeta_k^R < 1$. Based on the AF relay protocol, a subcarrier pairing strategy is applied. Each relay receives the signal from the source node S on the subcarrier i , and then amplifies and forwards the signal on the subcarrier j in the next time slot. Define the $N \times N$ decision matrix $\Phi_{N \times N} = \{\phi_{i,j}\}$, where $\phi_{i,j}$ is the subcarrier pairing factor. $\phi_{i,j} = 1$ means that subcarrier i is paired with subcarrier j , denoted as $SP_{i,j}$, and conversely, $\phi_{i,j} = 0$ means that subcarrier i is not paired with subcarrier j . At the same time, it is stipulated that each subcarrier must be paired with only one subcarrier, so that $\phi_{i,j}$ meets the following

$$\phi_{i,j} \in \{0, 1\}, \forall i, j \quad (4)$$

$$\sum_{i=1}^N \phi_{i,j} = 1, \sum_{j=1}^N \phi_{i,j} = 1, \forall i, j \quad (5)$$

It is worth noting that the solution proposed in this chapter is suitable for indoor and outdoor application scenarios. For example, for indoor scenarios, intelligent terminals need to collect and process information about the indoor environment. The source node and relay node may have flexible locations and unstable power supplies. Power supply smart terminal, and BS stands for smart terminal with relatively fixed position and stable power supply. For outdoor scenes, this system model can also be a wireless sensor network with cooperative relay function, where the BS can be regarded as a gateway node of the wireless sensor network with a relatively fixed position, and the relay node and the source node can be regarded as wireless Sensor network nodes, with the help of EH technology, increase the energy endurance of sensor nodes, thereby increasing the stability and reliability of the network and reducing network maintenance costs.

2.2 Improve HTC Relay Protocol

As shown in Fig. 2, the transmission process T of each data block of the improved HTC relay protocol is divided into an energy transmission stage $\tau_E T$ and a data transmission stage $\tau_I T$. In the data transmission phase, $\tau_I T$ is used for uplink cooperative data communication and includes two time slots: information transmission time slot and information cooperation time slot. To simplify the expression, we assume that the two time slots in the data transmission phase are of equal length and are both $\tau_I T/2$ in length.

In the first time slot of $\tau_I T$ in the data transmission phase, the source node S broadcasts the signal to the relay node and the base station BS simultaneously. $g_{i,1}^{SB}$ and $g_{i,k}^{SR}$ represent the channel gains on the subcarrier i from the source node S to BS and from the source node S to the relay node R_k respectively. The channel gains follow the complex Gaussian distribution and are defined as $g_{i,1}^{SB} \sim CN(0, \sigma_{SB,1}^2)$ and $g_{i,k}^{SR} \sim CN(0, \sigma_{SR,k}^2)$, respectively, where $\sigma_{SB,1}^2$ and $\sigma_{SR,k}^2$ represent the receiving end Gaussian white noise.

On the subcarrier i , the signals received by the k -th relay and BS are represented as $y_{i,k}^R$ and y_i^B , respectively.

$$y_{i,k}^R = g_{i,k}^{SR} \sqrt{P_i^{S1}} x_i + n_{i,k}^{SR} \quad \forall i, k \quad (6)$$

$$y_i^B = g_{i,1}^{SB} \sqrt{P_i^{S1}} x_i + n_{i,1}^{SB} \quad \forall i \quad (7)$$

where P_i^{S1} , x_i , $n_{i,1}^{SB}$ and $n_{i,k}^{SR}$ represent the power allocated to the source node S in the first time slot, the transmission signal from the source node S to the BS, the source node S and the k -th relay on the subcarrier i of the first time slot Gaussian white noise.

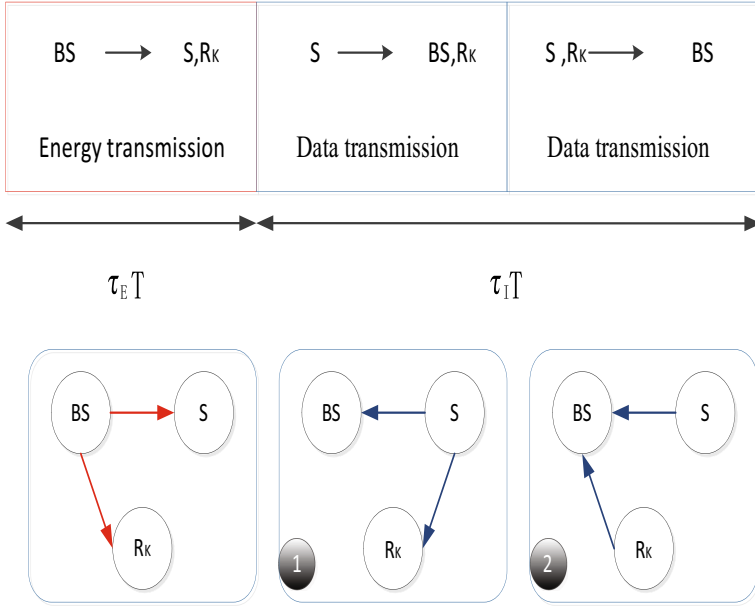


Fig. 2. Proposed improved HTC relay protocol.

In the second time slot of $\tau_I T$ during data transmission, all relays forward the signal received in the first time slot to the BS. Different from the HTC relay mechanism in [15], the signal of the previous time slot is retransmitted by S on another subcarrier which can further improve system performance. For the $SP_{i,j}$, the joint signal received from the source node S and all relays received at the BS can be expressed as

$$y_{(i,j)}^B = g_{j,2}^{SB} \sqrt{P_{i,j}^{S2}} x_i + \sum_{k=1}^K g_{j,k}^{RB} \alpha_{i,k}^R y_{i,k}^R + n_{j,2}^{SB} \quad (8)$$

where $P_{i,j}^{S2}$, $\alpha_{i,k}^R$ and $n_{j,2}^{SB}$ represent the power allocated by the second time slot source node S on the subcarrier pair $SP_{i,j}$, the amplification factor of the k -th relay and the Gaussian white noise of the source node S on the j -th subcarrier, $\alpha_{i,k}^R$ can be expressed as

$$\alpha_{i,k}^R = \sqrt{P_{i,j,k}^R / \left(|g_{i,k}^{SR}|^2 P_i^{S1} + \sigma_{R,k}^2 \right)} \quad (9)$$

where $P_{i,j,k}^R$ represents the power allocated to the k -th relay by the second time slot on the j -th subcarrier.

Using the improved HTC relay mechanism, the signal-to-interference and noise ratio of the first and second time slots on the subcarrier pair $SP_{i,j}$ are

expressed as SNR_i^{TS1} and $SNR_{(i,j)}^{TS2}$, respectively, which can be expressed as follows

$$SNR_i^{TS1} = |g_{i,1}^{SB}|^2 P_i^{S1} / \sigma_{SB,1}^2 \quad (10)$$

$$SNR_{(i,j)}^{TS2} = \frac{\left(\sum_{k=1}^K \frac{|g_{j,k}^{SR} g_{j,k}^{RB}| \sqrt{P_i^{S1} P_{i,j,k}^R}}{\sqrt{P_i^{S1} |g_{j,k}^{SR}|^2 + \sigma_{SR,k}^2}} + |g_{j,2}^{SB}| \sqrt{P_{i,j}^{S2}} \right)^2}{\sigma_{SB,2}^2 + \sum_{k=1}^K \left(\frac{|g_{j,k}^{RB}| \sqrt{P_{i,j,k}^R}}{\sqrt{P_i^{S1} |g_{j,k}^{SR}|^2 + \sigma_{SR,k}^2}} \right)^2 \sigma_{SR,k}^2} \quad (11)$$

2.3 Problem Description

Using the maximum ratio combining method to combine the received signals from two time slots, the end-to-end transmission rate of the subcarrier pair $SP_{i,j}$ can be expressed as

$$R_{(i,j)} = \frac{\tau I}{2} \log(1 + SNR_i^{TS1} + SNR_{(i,j)}^{TS2}) \quad (12)$$

Therefore, the total reachable rate of the system can be expressed as

$$R_{total}(\Phi, \mathbf{P}) = \sum_{i=1}^N \sum_{j=1}^N \phi_{i,j} R_{(i,j)} \quad (13)$$

where $\Phi = \{\phi_{i,j}\}$, $\mathbf{P} = \{P_{i,j}\}$.

In order to better characterize the energy consumption of the system, the energy consumption of the system is divided into two parts: transmission power consumption and inherent power consumption of the circuit, the former mainly refers to the energy overhead caused by the transmission data of users and relays, expressed as

$$P_{trans}(\Phi, \mathbf{P}) = \sum_{i=1}^N \sum_{j=1}^N (P_i^{S1} + P_{i,j}^{S2}) + \sum_{i=1}^N \sum_{j=1}^N P_{i,j,k}^R = \sum_{i=1}^N \sum_{j=1}^N \phi_{i,j} P_{(i,j)} \quad (14)$$

The latter's inherent power consumption of the circuit is positioned as P_C , which mainly includes system overhead such as digital-to-analog converters and power amplifiers. This chapter considers it as a constant and specifies that $\frac{1}{\varsigma}$ represents power conversion efficiency. For example, when $\varsigma = 2$, the efficiency of the system power amplifier is 50%. Summing the energy consumption of the two parts, the total energy expenditure of the system is obtained as follows

$$P_{total}(\Phi, \mathbf{P}) = P_C + \varsigma P_{trans}(\Phi, \mathbf{P}) \quad (15)$$

This article considers joint subcarrier pairing and power allocation on different subcarriers and terminals, and the following constraints must be met

$$\sum_{i=1}^N \sum_{j=1}^N (P_i^{S1} + P_{i,j}^{S2}) \leq P^S = \frac{1 - \tau_I}{\tau_I} 2\zeta_S h^{BS} P_B \quad (16)$$

$$\sum_{i=1}^N \sum_{j=1}^N \sum_{k=1}^K P_{i,j,k}^R \leq \sum_{k=1}^K P_k^R = \frac{1 - \tau_I}{\tau_I} 2\zeta_k^R P_B \sum_{k=1}^K h_k^{BR} \quad (17)$$

where Among them, P^S and P_k^R represent the sum of the transmission power of the source node S and the k -th relay in the two time slots, respectively. According to (4)–(5), the total transmit power consumed by the sub-carriers for $SP_{i,j}$ in the first and second time slots is expressed as $P_{i,j}$, thus giving the limitation of the total transmission power P_T

$$\sum_{i=1}^N \sum_{j=1}^N \phi_{i,j} P_{i,j} = P^S + \sum_{k=1}^K P_k^R \leq P_T \quad (18)$$

In summary, the energy efficiency optimization problem of the energy harvesting multi-relay system is expressed as follows

$$\begin{aligned} P1 : \quad & \max_{\tau_I, P_i^{S1}, P_{i,j}^{S2}, P_{i,j,k}^R, \phi_{i,j}} \frac{R_{total}(\Phi, \mathbf{P})}{P_{total}(\Phi, \mathbf{P})} \\ \text{s.t. } & \phi_{i,j} \in \{0, 1\}, \forall i, j \quad 19A \\ & \sum_{i=1}^N \phi_{i,j} = 1, \sum_{j=1}^N \phi_{i,j} = 1, \forall i, j \quad 19B \\ & \sum_{i=1}^N \sum_{j=1}^N (P_i^{S1} + P_{i,j}^{S2}) \leq P^S = \frac{1 - \tau_I}{\tau_I} 2\zeta_S h^{BS} P_B \quad 19C \\ & \sum_{i=1}^N \sum_{j=1}^N \sum_{k=1}^K P_{i,j,k}^R \leq \sum_{k=1}^K P_k^R = \frac{1 - \tau_I}{\tau_I} 2P_B \sum_{k=1}^K \zeta_k^R h_k^{BR} \quad 19D \\ & \sum_{i=1}^N \sum_{j=1}^N \phi_{i,j} P_{i,j} = P^S + \sum_{k=1}^K P_k^R \leq P_T \quad 19E \end{aligned} \quad (19)$$

The objective function of P1 is to maximize $\sum_{i=1}^N \sum_{j=1}^N \phi_{i,j} R_{(i,j)}$, where $R_{(i,j)}$ and $\phi_{i,j}$ respectively represent the end-to-end transmission rate and the subcarrier pairing factor on the subcarrier pair $SP_{i,j}$. Constraints (19A)–(19B) indicate that each subcarrier must be paired with only one subcarrier. Constraints (19C)–(19E) represent constraints on the source node S , relay, and total transmit power, respectively. Generally speaking, P1 is a mixed integer nonlinear programming problem with high computational complexity, which is usually solved by the dual method.

In the following content, we will transform the optimization problem P1 into other forms and use the Dinkelbach method to solve the optimal energy efficiency.

3 Energy Efficiency Optimization Algorithm

3.1 Continuous Relaxation of Optimization Problem

The optimization problem P1 gives an optimization model that maximizes the average energy efficiency of the system. It is easy to find that the optimization problem P1 is a Mixed-Integer Nonlinear Programming (MINLP) problem. Such problems can usually be solved by branch and bound methods [16] Solution, but the computational complexity is extremely large, it is difficult to be applied in the actual system. In order to reduce the computational complexity, this section proposes a low complexity optimization method that can find the optimal solution in polynomial time.

First, ignore the physical meaning of formula (4), in order to convert the optimization problem P1 into a quasi-convex function form, we will relax the binary integer constraint to the real number constraint and rewrite Eq. (4) as

$$\phi_{i,j} \in [0, 1], \forall i, j \quad (20)$$

So we can get the relaxation problem of the original problem P1

$$\begin{aligned}
 P2 : \quad & \max_{\tau_I, P_i^{S1}, P_{i,j}^{S2}, P_{i,j,k}^R, \phi_{i,j}} \frac{R_{total}(\Phi, \mathbf{P})}{P_{total}(\Phi, \mathbf{P})} \\
 s.t. \quad & \phi_{i,j} \in [0, 1], \forall i, j \\
 & \sum_{i=1}^N \phi_{i,j} = 1, \sum_{j=1}^N \phi_{i,j} = 1, \forall i, j \\
 & \sum_{i=1}^N \sum_{j=1}^N (P_i^{S2} + P_{i,j}^{S3}) \leq P^S = \frac{1-\tau_I}{\tau_I} 2\zeta_S h^{BS} P_B \\
 & \sum_{i=1}^N \sum_{j=1}^N \sum_{k=1}^K P_{i,j,k}^R \leq \sum_{k=1}^K P_k^R = \frac{1-\tau_I}{\tau_I} 2P_B \sum_{k=1}^K \zeta_k^R h_k^{BR} \\
 & \sum_{i=1}^N \sum_{j=1}^N \phi_{i,j} P_{i,j} = P^S + \sum_{k=1}^K P_k^R \leq P_T
 \end{aligned} \quad (21)$$

Note that the traditional convex optimization software package can be used to solve the relaxation problem P2 to obtain the solution to the original problem P1, but the solution efficiency is very low, because it is not guaranteed that the $\Phi^*(\alpha, \beta)$ returned by the iteration is binary. Since there is no available method to convert the real $\Phi^*(\alpha, \beta)$ into a binary solution, the Hungarian algorithm based on the equivalent channel gain $A_{i,j}$ is usually used to perform subcarrier pairing $\phi_{i,j}$. The use of the improved HTC protocol in this paper will lead to more complicated derivation based on equivalent channel gain, which will be explained in detail in the next section.

3.2 Energy Efficiency Optimization Iterative Algorithm

Analyze the optimization problem P2, define the optimal value of energy efficiency as η^* , and its feasible region is as \mathbf{T} , adopt Dinkelbach method [24]

$$\eta^* = \max_{\Phi, \mathbf{P}} \frac{R_{total}(\Phi, \mathbf{P})}{P_{total}(\Phi, \mathbf{P})} = \frac{R_{total}(\Phi^*, \mathbf{P}^*)}{P_{total}(\Phi^*, \mathbf{P}^*)}, \forall \{\Phi, \mathbf{P}\} \in \mathbf{T} \quad (22)$$

$$F(\eta) = \max_{\Phi, \mathbf{P}} [R_{total}(\Phi, \mathbf{P}) - \eta P_{total}(\Phi, \mathbf{P})] \quad (23)$$

The Dinkelbach fractional planning method can obtain the optimal energy efficiency value η^* through the iterative method under the premise of given power allocation \mathbf{P} and subcarrier assignment Φ to users. The detailed algorithm flow is shown in Table 1.

Table 1. Energy efficiency optimization iterative algorithm.

Algorithm 1 Energy efficiency optimization iterative algorithm.

1. **Initialize.**

2. Set the iteration termination times N_{outer}^{max} , iteration termination accuracy ϖ_{outer} , and the initial iteration value $\eta_0 = 0$ and $n = 0$.

3. **Loop body**

4. Update iteration index $n = n + 1$.

5. Solving the Optimization Problem $F(\eta_{n-1}) = \max_{\Phi, \mathbf{P}} [R_{total}(\Phi, \mathbf{P}) - \eta_{n-1} P_{total}(\Phi, \mathbf{P})]$

gain $\{\Phi^*, \mathbf{P}^*\}$

6. Calculate the energy efficiency under the current iterative index using $\{\Phi^*, \mathbf{P}^*\}$,

$\eta_n = R_{total}(\Phi^*, \mathbf{P}^*) / P_{total}(\Phi^*, \mathbf{P}^*)$.

7. **End Condition:** $|\eta_n - \eta_{n-1}| < \varpi_{outer}$ or $n > N_{outer}^{max}$.

8. Output optimal solution $\{\eta^*, \Phi^*, \mathbf{P}^*\}$.

4 Simulation and Analysis Results

In this section, we compare the performance of the proposed energy efficiency-based joint resource allocation algorithm with other resource allocation schemes. The channel gain of each subcarrier is modeled as a complex Gaussian distribution with a mean value of 0 and a variance of $c \cdot d_{i,j}^{-\nu}$, satisfying the $h_{i,j} \sim CN(0, c \cdot d_{i,j}^{-\nu})$. The hypothetical scenario is a circular region with a relay node centered at 500m radius. As shown in Fig. 1, the base station BS is distributed in the left semicircle, the source node is S distributed in the right semicircle, the K relays are randomly distributed in the circle, and the number of subcarriers of the OFDM system is $N=16$. AWGNs variance $\sigma_r^2 = \sigma_k^2 = N_0 = -131$ dBm, circuit power consumption set to $P_C = 30$ dBm.

Compare the proposed EE optimization algorithm with the literature [6, 17, 18] algorithm's spectral efficiency performance, as shown in Fig. 3. The purpose of the resource allocation algorithm proposed in [6, 17, 18] is to maximize the SE of the system, so as the P_B increases, the performance curve increases monotonously. It can be seen from the figure that the EE optimization algorithm is proposed in this paper. When $P_B \leq 18$ dBm, the spectrum efficiency

continues to increase, and when $P_B > 18$ dBm the curve tends to be stable, this is because the proposed EE maximization resource optimization algorithm does not sacrifice energy consumption for spectrum Increased efficiency. In addition, at $P_B \leq 18$ dBm, the proposed algorithm has higher SE performance than the algorithms in [17,18], and [6], and can achieve performance gains of approximately 3.0 dB, 2.0 dB, and 1.6 dB, respectively.

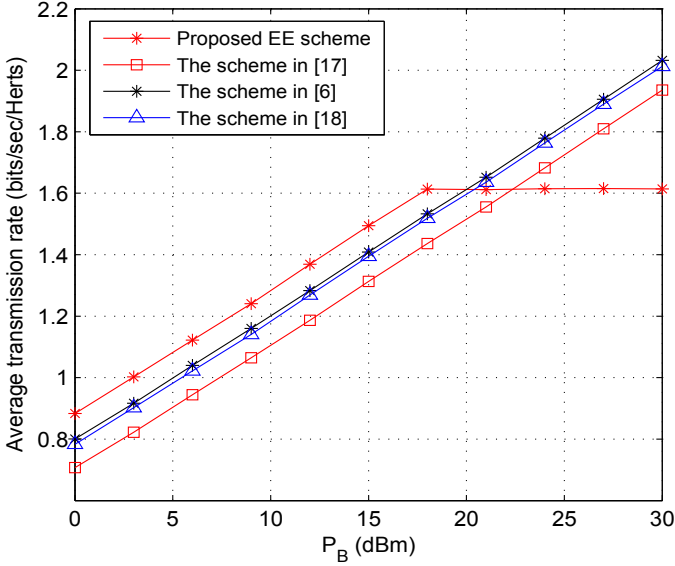


Fig. 3. Comparison of spectrum efficiency performance of different resource allocation algorithms.

Figure 4 shows the energy efficiency performance comparison between the proposed EE optimization algorithm and the literature [6,17,18] algorithm. Due to the optimization goal of literature [6] and literature [17], the spectrum efficiency is maximized, so when $P_B \leq 18$ dBm, the energy efficiency curve increases monotonously, and when $P_B > 18$ dBm decreases monotonously. However, the algorithm proposed in this chapter and the algorithm proposed in [18] both pursue the maximization of EE, and increase monotonously when $P_B \leq 18$ dBm, and remain stable until $P_B > 18$ dBm. In particular, when $P_B > 18$ dBm, the algorithm proposed in this chapter keeps the average EE unchanged and reaches the optimal value, which is about 5.6 bit/J/Hz. This is because once the maximum EE value of the system is reached, the source node and the relay node will not consume extra energy for useless data transmission. As can also be seen in Figs. 3 and 4, due to the use of joint channel-user assignment and a new relay strategy, when $P_B \leq 18$ dBm, the EE scheme proposed in this chapter can achieve better EE and SE performance, literature [18] Although the algorithm

also considers joint channel user assignment, it does not consider the improvement of the relay strategy, so its EE performance is lower than the algorithm proposed in this chapter.

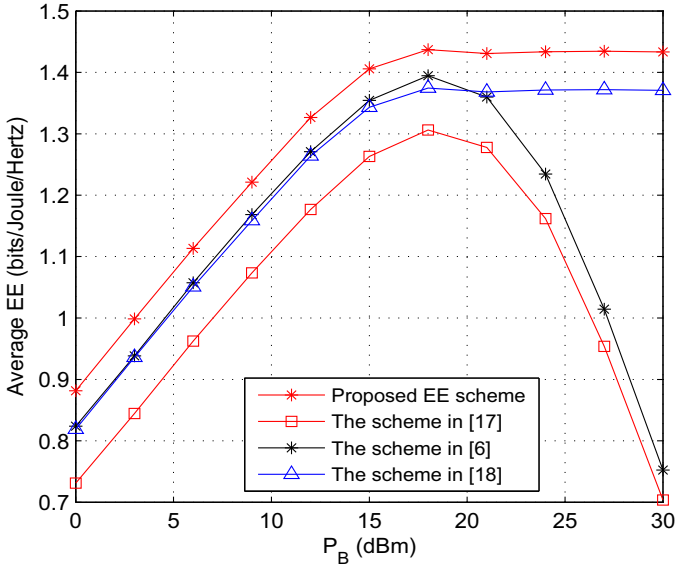


Fig. 4. Comparison of energy efficiency performance of different resource allocation algorithms.

5 Conclusions

Aiming at the RF energy harvesting relay network scenario, this paper proposes a resource allocation algorithm based on optimal energy efficiency, and constructs a system energy efficiency optimization model including energy harvesting time slot allocation, subcarrier pairing, and power allocation. Dinkelbach method, Cauchy inequality and Hungarian algorithm are used to solve the problem of time slot assignment, power allocation and subcarrier allocation based on energy efficiency. Simulation shows that the algorithm reduces the complexity of the algorithm and has good global convergence.

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