



Energy Efficiency Optimization Based SWIPT in OFDM Relaying Systems

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Abstract. The rapid development of the information and communication industry has brought huge energy consumption, which also reduces the energy efficiency. In this article, we integrate the cooperative relaying technology into a SWIPT-OFDM system, and focus on the system energy efficiency maximization problem. More specifically, the relay node uses the DF protocol to forward information from the base station to the user. The objective function is to maximize the energy efficiency of the system, in which the system fixed circuit power consumption, target rate, and total system power limit are all considered. At first we derive a non-convex fractional expression, after a complex mathematical transformation, a new objective function is obtained, and then we propose an efficient policy to optimize the subcarrier and power allocation for obtaining the optimal energy efficiency. Simulation results show that the proposed algorithm can not only converge after several iterations, but also achieve higher energy efficiency.

Keywords: Energy efficiency · SWIPT · DF relay · OFDM · Resource allocation

1 Introduction

The artificial intelligence (AI) industry is developing rapidly now, AI technology has been applied in many fields [1], and the wireless communication industry is no exception. Applying AI technology to the wireless communications industry can bring better service to the users, however the power consumption has also increased dramatically, which leads to the low energy efficiency [2, 3]. Therefore, how to effectively improve energy efficiency has become a hard problem in wireless communication networks.

SWIPT technology is considered as an effective way to increase energy efficiency.

In [4], the authors applied SWIPT technology to multiple-input multiple-output (MIMO) system, and adopted the time-switching (TS) method to achieve SWIPT, and then found the optimal policy for power allocation and TS ratio which can maximize energy efficiency. Reference [5] considered the energy efficiency maximization problem in Cloud-Based cellular network, where the authors jointly optimized the sub-carrier and power allocation, and obtained the optimal energy efficiency.

Compared with wired channel, wireless channel has fading effect because of its open propagation space and time-varying characteristics [6]. The transmission signal has often undergone severe attenuation or distortion when it reaches the user. Cooperative relay technology can improve the reliability of information transmission and system capacity, and is widely used in wireless communication networks [7]. The two most common protocols of cooperative relay technology are the amplify-and-forward (AF) protocol and decode-and-forward (DF) protocol [8]. When the distance between base station and relay node is very close and the channel quality is good, the performance of DF protocol is better than that of AF protocol [9]. So in this article, we use the DF protocol at the relay node to forward information to the user.

Inspired by the above literature, in this article, we investigate the energy efficiency maximization problem based on SWIPT in DF relay OFDM systems, where the energy efficiency is maximized by optimizing subcarrier allocation and power allocation.

2 System Model and Problem Formulation

2.1 System Model

We consider a downlink OFDM system, which consists of one base station, one relay node, and one user, as shown in Fig. 1. The set of subcarriers can be expressed as $\mathbf{N} = \{1, 2, 3, \dots, N\}$, the total transmit power is set to P .

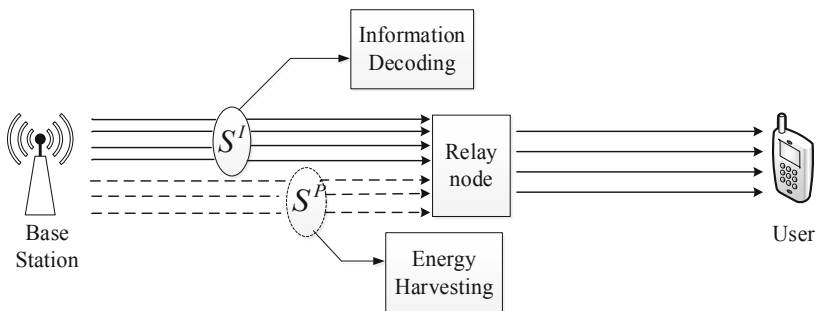


Fig. 1. System model

The transmission time from base station to user is equally divided into two time slots.

In the first time slot, the base station transmits information to the relay node, and the relay node utilizes a part of the subcarriers, which are denoted as S^I , for information decoding, and utilizes the rest of subcarriers, which are denoted as S^P , to perform energy harvesting. Let h_n represent the channel power gain on subcarrier n ($n \in \mathbf{N}$), and p_n denotes the power allocated on subcarrier n , the noise power is set as σ_n^2 .

In the second time slot, the relay node forwards the information to the user by using the energy harvested in the first time slot. The channel power gain on subcarrier n' is denoted by $g_{n'}$, and the power on the subcarrier n' is $p_{n'}$, and the noise power is $\sigma_{n'}^2$.

Therefore, the rate received by the relay node in the first time slot can be expressed as

$$R_1 = \frac{1}{2} \sum_{n \in S^I} \ln\left(1 + \frac{h_n p_n}{\sigma_n^2}\right) \quad (1)$$

And the energy harvested by the relay node can be written as

$$Q = \zeta \sum_{n \in S^P} (h_n p_n + \sigma_n^2) \quad (2)$$

where ζ denotes the energy harvesting conversion efficiency.

In the second time slot, the rate from relay node to user can be expressed as

$$R_2 = \frac{1}{2} \sum_{n'=1}^N \ln\left(1 + \frac{g_{n'} p_{n'}}{\sigma_{n'}^2}\right) \quad (3)$$

After two time slots, the achievable rate from base station to user with the help of relay node can be given as

$$R(P, S) = \min(R_1, R_2) \quad (4)$$

where $P = \{p_{n'}\}$ and $S = \{S^I, S^P\}$.

For convenience, we let $R(P, S) = \alpha R_1 + (1 - \alpha) R_2$, and $\alpha \in \{0, 1\}$.

And the sum of power consumption of the considered system in two time slots is expressed as

$$U_{TP}(P, S) = P_B + P_R + P_u + \sum_{n=1}^N p_n + \sum_{n'=1}^N p_{n'} - Q \quad (5)$$

where P_B , P_R and P_u represent the fixed circuit power consumption at base station, relay node and user, respectively.

So we can easily get the mathematical formula of the system energy efficiency, where the energy efficiency is the ratio of system rate to the total power consumption [10], as shown below

$$E_{\text{eff}}(P, S) = \frac{R(P, S)}{U_{TP}(P, S)} \quad (6)$$

2.2 Problem Formulation

With the goal of maximizing energy efficiency under some constraints, and this is formulated as

$$\begin{aligned}
\mathbf{P1} : & \max_{p_n, S^P, S^I} E_{eff}(P, S) \\
s.t. \ C1 : & R_1 = \frac{1}{2} \sum_{n \in S^I} \ln\left(1 + \frac{h_n p_n}{\sigma_n^2}\right) \geq R_T \\
\ C2 : & R_2 = \frac{1}{2} \sum_{n'=1}^N \ln\left(1 + \frac{g_{n'} p_{n'}}{\sigma_{n'}^2}\right) \geq R_T \\
\ C3 : & P_B + P_R + P_u + \sum_{n=1}^N p_n \leq P, (p_n \geq 0) \\
\ C4 : & \zeta \sum_{n \in S^P} (h_n p_n + \sigma_n^2) \geq \sum_{n'=1}^N p_{n'} \\
\ C5 : & S^I + S^P = \mathbf{N} \\
\ C6 : & S^I \cap S^P = \emptyset
\end{aligned} \tag{7}$$

where R_T is the target rate of the system, C1 and C2 give the target rate constraints, C3 represents the total power limit of the system. C4 indicates that the energy required for relay node to forward information to the user comes from Q . C5 and C6 are constraints of subcarrier set.

3 Optimal Solution

In this part, we maximize energy efficiency $E_{eff}(P, S)$ by optimizing the power p_n and the subcarrier allocation (S^I, S^P) .

We define the maximum energy efficiency of the system as q^* , i.e.,

$$q^* = \frac{R(P^*, S^*)}{U_{TP}(P^*, S^*)} = \max_{p_n, S^P, S^I} \frac{R(P, S)}{U_{TP}(P, S)} \tag{8}$$

The maximum energy efficiency q^* is obtained only when the following formula is established [11]:

$$\begin{aligned}
& \max_{p_n, S^P, S^I} R(P, S) - q^* U_{TP}(P, S) \\
& = R(P^*, S^*) - q^* U_{TP}(P^*, S^*) = 0
\end{aligned} \tag{9}$$

Inspired by (9), we convert the original objective function into the following formula by introducing a parameter q .

$$\begin{aligned} \mathbf{P2} : \max_{p_n, S^p, S^l} & R(P, S) - qU_{TP}(P, S) \\ \text{s.t. } & C1, C2, C3, C4, C5, C6 \end{aligned} \quad (10)$$

Therefore, the Lagrangian function of (10) can be written as

$$\begin{aligned} L(P, S) = & \left\{ \frac{\alpha}{2} \sum_{n \in S^l} \ln\left(1 + \frac{h_n p_n}{\sigma_n^2}\right) + \frac{(1-\alpha)}{2} \sum_{n'=1}^N \ln\left(1 + \frac{g_{n'} p_{n'}}{\sigma_{n'}^2}\right) \right. \\ & \left. - q[P_B + P_R + P_u + \sum_{n=1}^N p_n + \sum_{n'=1}^N p_{n'} - \zeta \sum_{n \in S^p} (h_n p_n + \sigma_n^2)] \right\} \\ & + \beta_1 \left[\frac{1}{2} \sum_{n \in S^l} \ln\left(1 + \frac{h_n p_n}{\sigma_n^2}\right) - R_T \right] + \beta_2 \left[\frac{1}{2} \sum_{n'=1}^N \ln\left(1 + \frac{g_{n'} p_{n'}}{\sigma_{n'}^2}\right) - R_T \right] \\ & + \beta_3 \left[P - \sum_{n=1}^N p_n - P_B - P_R - P_u \right] + \beta_4 \left[\zeta \sum_{n \in S^p} (h_n p_n + \sigma_n^2) - \sum_{n'=1}^N p_{n'} \right] \end{aligned} \quad (11)$$

First, subgradient method is applied to obtain the optimal dual variable $\{\beta_1^*, \beta_2^*, \beta_3^*, \beta_4^*\}$.

$$\Delta\beta_1 = \frac{1}{2} \sum_{n \in S^l} \ln\left(1 + \frac{h_n p_n}{\sigma_n^2}\right) - R_T \quad (12)$$

$$\Delta\beta_2 = \frac{1}{2} \sum_{n'=1}^N \ln\left(1 + \frac{g_{n'} p_{n'}}{\sigma_{n'}^2}\right) - R_T \quad (13)$$

$$\Delta\beta_3 = P - \sum_{n=1}^N p_n - P_B - P_R - P_u \quad (14)$$

$$\Delta\beta_4 = \zeta \sum_{n \in S^p} (h_n p_n + \sigma_n^2) - \sum_{n'=1}^N p_{n'} \quad (15)$$

Then we are divided into two steps to get the optimal solution and we rewrite (11) as

$$L(P, S) = L - (q + \beta_3)(P_B + P_R + P_u) - \beta_1 R_T - \beta_2 R_T + \beta_3 P \quad (16)$$

where

$$\begin{aligned}
L = & \frac{\alpha}{2} \sum_{n \in S^I} \ln\left(1 + \frac{h_n p_n}{\sigma_n^2}\right) + \frac{(1-\alpha)}{2} \sum_{n'=1}^N \ln\left(1 + \frac{g_{n'} p_{n'}}{\sigma_{n'}^2}\right) - q \sum_{n=1}^N p_n - q \sum_{n'=1}^N p_{n'} \\
& + q \zeta \sum_{n \in S^P} (h_n p_n + \sigma_n^2) + \frac{\beta_1}{2} \sum_{n \in S^I} \ln\left(1 + \frac{h_n p_n}{\sigma_n^2}\right) + \frac{\beta_2}{2} \sum_{n'=1}^N \ln\left(1 + \frac{g_{n'} p_{n'}}{\sigma_{n'}^2}\right) \\
& - \beta_3 \sum_{n=1}^N p_n + \beta_4 \zeta \sum_{n \in S^P} (h_n p_n + \sigma_n^2) - \beta_4 \sum_{n'=1}^N p_{n'}
\end{aligned} \tag{17}$$

In this paper, we equally allocate power in the first time slot, and optimize the power in the second time slot. So we get the derivative of L with respect to $p_{n'}$

$$\frac{\partial L}{\partial p_{n'}} = (1 - \alpha + \beta_2) \frac{g_{n'}}{2(\sigma_{n'}^2 + g_{n'} p_{n'})} - q - \beta_4 \tag{18}$$

Let (18) be equal to 0, and we can get the optimal $p_{n'}^*$

$$p_{n'}^* = \left[\frac{(1 - \alpha + \beta_2)}{2(q + \beta_4)} - \frac{\sigma_{n'}^2}{g_{n'}} \right]^+ \tag{19}$$

Next substituting (19) into (17), and we can get the optimal subcarrier set (S^{I*}, S^{P*}) in the first time slot.

$$\begin{aligned}
L = & \sum_{n'=1}^N \left\{ \frac{(1-\alpha)}{2} \ln\left(1 + \frac{g_{n'} p_{n'}^*}{\sigma_{n'}^2}\right) + \frac{\beta_2}{2} \ln\left(1 + \frac{g_{n'} p_{n'}^*}{\sigma_{n'}^2}\right) - q p_{n'}^* - \beta_4 p_{n'}^* \right\} \\
& + \sum_{n \in S^I} F + \sum_{n=1}^N \left\{ \zeta (q + \beta_4) (h_n p_n + \sigma_n^2) - q p_n - \beta_3 p_n \right\}
\end{aligned} \tag{20}$$

where

$$F = \frac{\alpha}{2} \ln\left(1 + \frac{h_n p_n}{\sigma_n^2}\right) + \frac{\beta_1}{2} \ln\left(1 + \frac{h_n p_n}{\sigma_n^2}\right) - \zeta (q + \beta_4) (h_n p_n + \sigma_n^2) \tag{21}$$

From the above equation, we can know that S^I can be obtained by finding all subcarrier which can make F positive, as shown below

$$S^{I*} = \arg \max_{S^I} \sum_{n \in S^I} F \tag{22}$$

$$S^{P*} = \mathbf{N} - S^{I*} \tag{23}$$

Thus we get the optimal resource allocation of an iterative process, and the maximum energy efficiency can be obtained by multiple iterations of q .

4 Simulation Results

In the simulation, we set the initial value of q to 0, the total number of subcarriers $N = 32$, the fixed circuit power consumption $P_B = P_R = P_u = 0.02$ W, and R_T is set to 8 bps/Hz. For convenience, we let $\xi = 1$, and the noise power of the two time slots are equal to -80 dbm. Both the distance from the base station to the relay node and the distance from the relay node to the user are set to 1 m.

Figure 2 shows that our proposed algorithm can achieve maximum energy efficiency after four iterations. After each iteration, the value of energy efficiency will increase, and eventually it will not change after reaching the maximum value. Moreover, the trend of energy efficiency is also different with different total transmission power P .

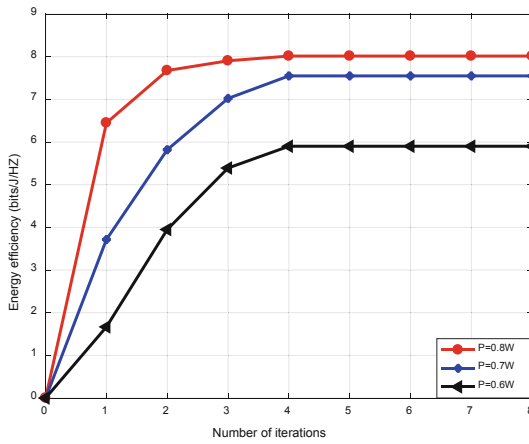


Fig. 2. Energy efficiency versus the number of iterations

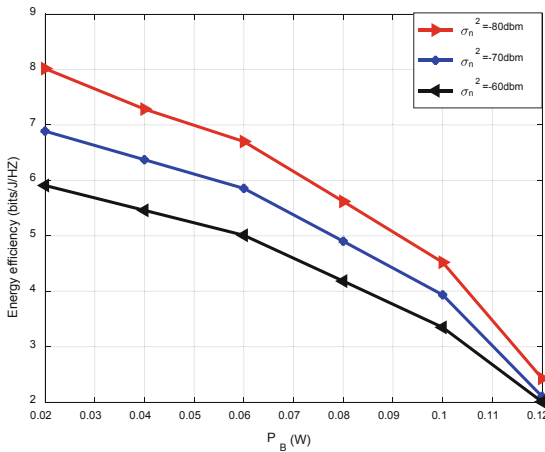


Fig. 3. P_B versus energy efficiency

Figure 3 depicts the fixed circuit power consumption at base station P_B versus energy efficiency. Obviously, the energy efficiency decreases with the increase of P_B . The reason is that the increase of P_B will lead to the increase of total power consumption.

5 Conclusion

In this paper, we formulate the energy efficiency maximization problem in SWIPT-OFDM system with DF protocol, in which the system target rate and fixed power consumption are taken into consideration. By using dual method and iterative method, the optimization problem is solved. Our simulation results demonstrate the effectiveness of the proposed algorithm.

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