



Energy Efficiency Optimization Based SWIPT in Multiuser OFDM Systems

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Abstract. The research on wireless communication has been mainly focused on improving the system rate. However, while achieving the higher rate, it also consumes a lot of power, which leads to a reduction in energy efficiency. Therefore, in this paper, we propose a new algorithm to maximize energy efficiency in multiuser OFDM systems. More specifically, users can transfer information and collect energy simultaneously by using SWIPT technology, and the energy efficiency is maximized by optimizing the subcarrier allocation under some constraints. We formulate the proposed algorithm at first, and the initial optimization problem is non-convex, so we cannot get the optimal resource allocation directly. Later, by transforming the original objective function, the optimal solution is obtained. Finally, we validate the proposed algorithm with simulation results. The results show that the proposed algorithm can indeed improve energy efficiency. We also find that some variables have a huge impact on system energy efficiency.

Keywords: Multiuser system · OFDM · Energy efficiency · SWIPT

1 Introduction

In recent years, the rapid development of wireless networks has been bringing great convenience to our life, but it also brings new challenges, one of which is that the energy consumption is too large, which leads to a reduction in energy efficiency. Therefore, how to improve the energy efficiency of the system becomes very important in wireless networks.

SWIPT technology is an ideal way to improve energy efficiency. And TS (Time switching) and PS (Power splitting) are two most frequently used methods in SWIPT technology. And [1–5] used the PS method to improve energy efficiency. In [1], the authors optimized the PS ratio to achieve maximum secrecy energy efficiency

(SEE) where the artificial noise (AN) is also considered. [2] improved the energy efficiency of a MIMO system, in order to maintain the trade-off between the spectral efficiency and energy efficiency of the system, the authors also provided the Quality of Service (QoS) constraints. The authors in [3] studied how to improve energy efficiency of a two-way relay system. In [4], the authors applied SWIPT technology to the Internet of Things (IOT) and studied methods for improving energy efficiency under the case of single IOT device and multiple IOT devices. In [5], the authors used PS to harvest energy for forwarding information in clustered wireless sensor networks and then iterative optimize three variables, i.e., power, PS ratio, and relay selection, to maximize energy efficiency.

And [6, 7] used the TS method to improve energy efficiency. In [6], the authors gave optimal energy efficiency optimization schemes based on TS method. Then the authors also gave a suboptimal algorithm with lower complexity. Maximizing energy efficiency by optimizing time allocation factor and power is investigated in [7].

In the existing literature, PS method or TS method are mainly used for the energy efficiency maximization problem, but these two methods need to provide additional splitter or switcher. However, the method we give does not require splitter or switcher.

2 System Model and Problem Formulation

In this part, we introduce the multiuser OFDM system model and formulate the energy efficiency optimization problem of the system.

2.1 System Model

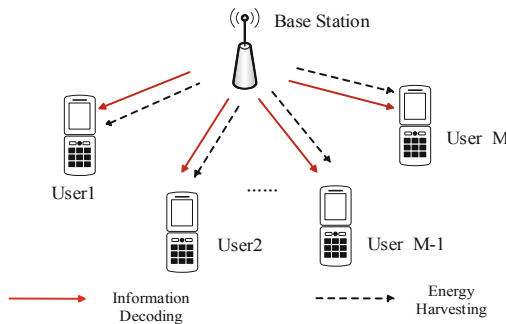


Fig. 1. System model

In a multiuser OFDM system, we consider there are M users and $\mathbf{N} = \{1, 2, \dots, N\}$ denotes the set of subcarriers, as shown in Fig. 1. User m can harvest energy while transmitting information. The set of subcarriers that user m uses to harvest energy can

be expressed as S_m^P , and S_m^I represents the subcarriers set for transmitting information. Let $p_{m,n}$ and $h_{m,n}$ denote the power and channel gain of user m on subcarrier n ($n \in \mathbf{N}$) respectively, and the total power transmitted by the base station is set to P . In multiuser systems, interference often occurs. To solve this problem, the subcarriers used for each user for information transmission cannot be the same. We stipulate that each user has a target rate R_m to maintain the trade-off between energy efficiency and system capacity. Thus, we can get the transmission rate of user m on subcarrier n ($n \in S_m^I$):

$$R_m = \sum_{n \in S_m^I} \log\left(1 + \frac{h_{m,n} p_{m,n}}{\sigma^2}\right) \quad (1)$$

where σ^2 is the variance of additive white Gaussian noise (AWGN). The throughput of the system is the sum of the rate transmitted by all users and is given by

$$E(S) = \sum_{m=1}^M \sum_{n \in S_m^I} \log\left(1 + \frac{h_{m,n} p_{m,n}}{\sigma^2}\right) \quad (2)$$

And the energy harvested by user m on subcarrier n ($n \in S_m^P$) is given by

$$Q_m = \sum_{n \in S_m^P} (\varepsilon h_{m,n} p_{m,n} + \sigma^2) \quad (3)$$

where ε represents the conversion efficiency. The total power consumption is defined as the power consumed by the system minus the energy harvested by all users, and is shown as follows

$$E_{TP}(S) = P_B + MP_R + \sum_{m=1}^M \sum_{n \in \mathbf{N}} p_{m,n} - \sum_{m=1}^M \sum_{n \in S_m^P} (\varepsilon h_{m,n} p_{m,n} + \sigma^2) \quad (4)$$

where P_B, P_R represent the fixed power dissipation at base station and users, respectively.

So we can easily get the expression of the system energy efficiency [8]

$$E_{eff}(S) = \frac{E(S)}{E_{TP}(S)} \quad (5)$$

2.2 Problem Formulation

The optimization problem can be formulated as follows

$$\begin{aligned}
\mathbf{P1} : & \max_{S_m^l, S_m^p} E_{eff}(S) \\
s.t. \text{ C1} : & \sum_{n \in S_m^l} \log(1 + \frac{h_{m,n} p_{m,n}}{\sigma^2}) \geq R_m, \forall m = 1, 2, \dots, M \\
\text{C2} : & P_B + MP_R + \sum_{m=1}^M \sum_{n \in N} p_{m,n} \leq P \\
\text{C3} : & S_{m_1}^l \cap S_{m_2}^l = \emptyset, \forall m_1, m_2 = 1, 2, \dots, M, m_1 \neq m_2 \\
\text{C4} : & S_m^l \cap S_m^p = \emptyset
\end{aligned} \tag{6}$$

where C1 gives the target rate constraints for the users, C2 represents that the power consumed cannot exceed the total power, C3 and C4 are constraints of subcarrier set.

3 Optimal Solution

Since the objective function is a fraction, we cannot get the optimal solution directly. If we use the exhaustive method to solve this problem, the computational complexity is very large, so we apply another method to get the optimal solution. Without loss of generality, we define q^* as the maximum energy efficiency of the system, that is:

$$q^* = \frac{E(S^*)}{E_{TP}(S^*)} = \max_{S_m^l, S_m^p} \frac{E(S)}{E_{TP}(S)} \tag{7}$$

The maximum energy efficiency is obtained only when the following formula is achieved, the proof process can be found in [9, Appendix A].

$$\begin{aligned}
& \max_{S_m^l, S_m^p} E(S) - q^* E_{TP}(S) \\
& = E(S^*) - q^* E_{TP}(S^*) = 0
\end{aligned} \tag{8}$$

Inspired by (8), we transform (6) into the following formula.

$$\begin{aligned}
\mathbf{P2} : & \max_{S_m^l, S_m^p} E(S) - q E_{TP}(S) \\
s.t. & \text{ C1, C2, C3, C4}
\end{aligned} \tag{9}$$

Next we use the Lagrangian algorithm and the Dinkelbach iterative algorithm [10] to get the optimal subcarrier allocation scheme. First given q , and the Lagrange function of **P2** can be written as:

$$\begin{aligned}
 L(S, \beta) &= \sum_{m=1}^M \sum_{n \in S_m^I} \log\left(1 + \frac{h_{m,n} p_{m,n}}{\sigma^2}\right) \\
 &\quad - q[P_B + MP_R + \sum_{m=1}^M \sum_{n \in N} p_{m,n} - \sum_{m=1}^M \sum_{n \in S_m^P} (\varepsilon h_{m,n} p_{m,n} + \sigma^2)] \\
 &\quad + \sum_{m=1}^M \beta_{1,m} \left[\sum_{n \in S_m^I} \log\left(1 + \frac{h_{m,n} p_{m,n}}{\sigma^2}\right) - R_m \right] + \beta_2 \left[P - \sum_{m=1}^M \sum_{n \in N} p_{m,n} - P_B - MP_R \right]
 \end{aligned} \tag{10}$$

Here we equally distribute the power over all subcarriers, i.e., the power on each subcarrier is equal to each other. Next we can rewrite (10) as:

$$L(S, \beta) = \sum_{m=1}^M L_m - q(P_B + MP_R) - \sum_{m=1}^M \beta_{1,m} R_m + \beta_2(P - P_B - MP_R) \tag{11}$$

where

$$\begin{aligned}
 L_m &= \sum_{n \in S_m^I} \log\left(1 + \frac{h_{m,n} p_{m,n}}{\sigma^2}\right) - q \sum_{n \in N} p_{m,n} + q \sum_{n \in S_m^P} (\varepsilon h_{m,n} p_{m,n} + \sigma^2) \\
 &\quad + \beta_{1,m} \sum_{n \in S_m^I} \log\left(1 + \frac{h_{m,n} p_{m,n}}{\sigma^2}\right) - \beta_2 \sum_{n \in N} p_{m,n}
 \end{aligned} \tag{12}$$

Further, (12) can be also rewritten as:

$$L_m = q \sum_{n \in N} (\varepsilon h_{m,n} p_{m,n} + \sigma^2) + \sum_{n \in S_m^I} F_m - q \sum_{n \in N} p_{m,n} - \beta_2 \sum_{n \in N} p_{m,n} \tag{13}$$

where $F_m = \log\left(1 + \frac{h_{m,n} p_{m,n}}{\sigma^2}\right) + \beta_{1,m} \log\left(1 + \frac{h_{m,n} p_{m,n}}{\sigma^2}\right) - q(\varepsilon h_{m,n} p_{m,n} + \sigma^2)$

So we can get the optimal subcarrier set S_m^I from F_m , and is given by

$$S_m^I = \arg \max_{S_m^I} \sum_{n \in S_m^I} F_m \tag{14}$$

and the remaining subcarriers belong to S_m^P

$$S_m^P = \mathbf{N} - S_m^I \tag{15}$$

The optimal dual variable $\{\beta_{1,m}^*, \beta_2^*\}$ can be derived by the subgradient method [11]. The iterative algorithm we propose can be summarized as the following table.

Algorithm 1 The proposed iterative algorithm

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1 : initialize Fault tolerance range  $\tau$ 
2 : set  $q=0, i=1$ 
3 : repeat
4 : Given  $q$ , obtaining  $\{S_m^P, S_m^I\}$  in (14) and (15)
5 : if  $E(S_m^P, S_m^I) - qE_{TP}(S_m^P, S_m^I) < \tau$ 
6 : return  $\{S_m^{*P}, S_m^{*I}\} = \{S_m^P, S_m^I\}$  and  $q^* = \frac{E(S_m^P, S_m^I)}{E_{TP}(S_m^P, S_m^I)}$ 
7 : else
8 : set  $q = \frac{E(S_m^P, S_m^I)}{E_{TP}(S_m^P, S_m^I)}$  and  $i = i + 1$ 
9 : end if
10 : until  $E(S_m^P, S_m^I) - qE_{TP}(S_m^P, S_m^I) < \tau$  is true

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4 Simulation Results

In this section, we show the simulation results of the proposed algorithm. In the simulation process, we let $N = 32$, $M = 4$ and $\varepsilon = 1$. The fixed power consumption

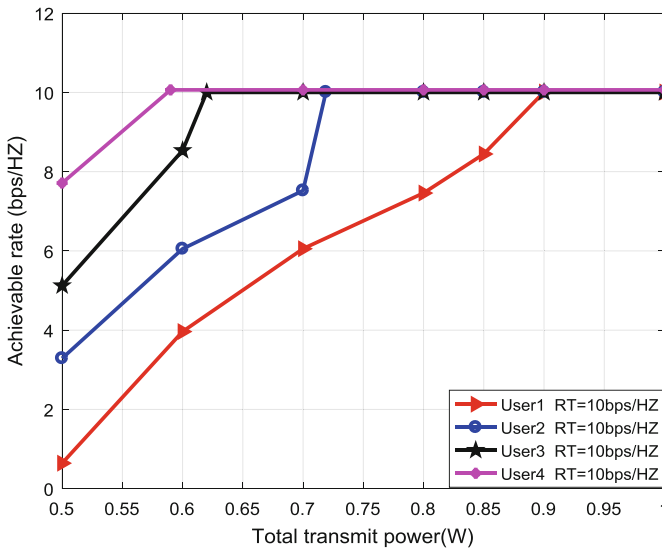


Fig. 2. Achievement rate versus total transmit power

of the transmitter and receiver is set to 0.05 W, i.e., $P_B = P_R = 0.05$ W. We noticed that the energy efficiency reaches its maximum after five iterations.

Figure 2 shows total transmit power versus achievement rate of different users, and we set $R_m = 10(\text{bps}/\text{HZ})$. Due to the different channels, the rate trends of different users are also different. And we can see from the figure that the channel of user 4 is the best, while the user 1 has the worst channel.

From Fig. 3, we can see that the energy efficiency increases with the increase of the total transmission power, and then it does not change any more. That means that the system energy efficiency has reached its maximum. Moreover, the noise power also has a significant effect on energy efficiency. If the noise power is increased, the system energy efficiency will be reduced.

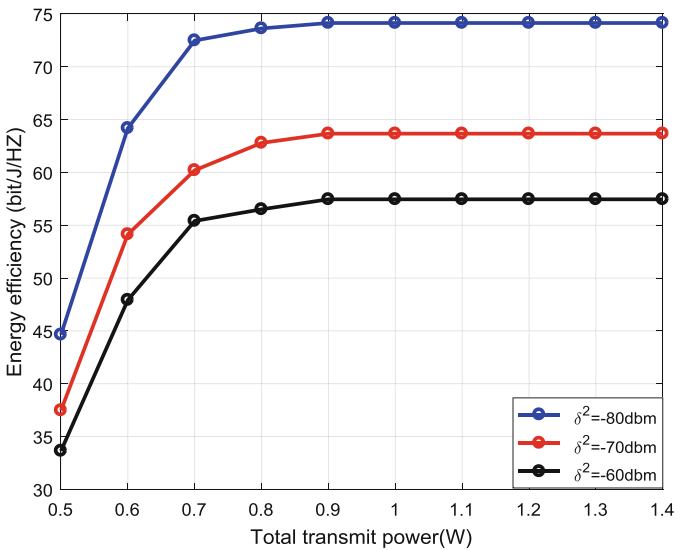


Fig. 3. Energy efficiency versus total transmit power

We compare the proposed algorithm with other algorithms, as shown in Fig. 4.

Baseline algorithm: We maximize the system throughput, while the constraints of **P2** remain unchanged.

It can be clearly seen that the change trend of energy efficiency is similar under different noise power. The difference is that the energy efficiency is lower when the noise power is high. This also validates the conclusion of Fig. 3. We can also see in Fig. 4 that the baseline algorithm is very close to the proposed algorithm when the transmit power is small. The reason why the energy efficiency of baseline algorithm increases first and then decreases is that the baseline algorithm sacrifices energy efficiency for the sake of achieving a higher rate.

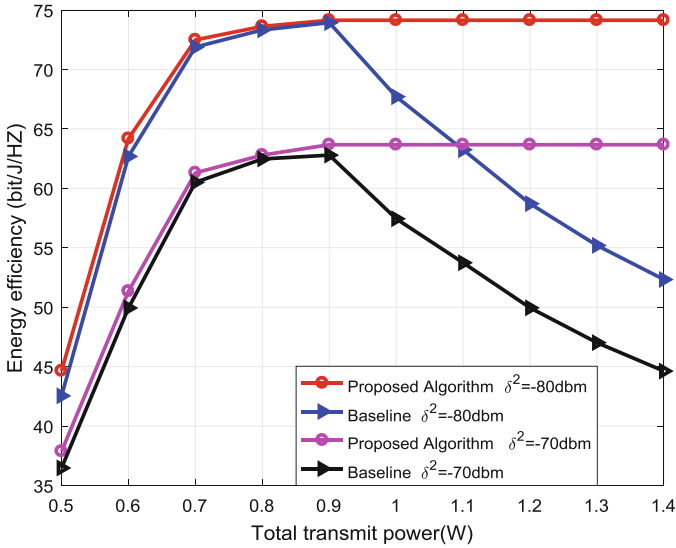


Fig. 4. Energy efficiency versus total transmit power

5 Conclusions

In this paper, we get the optimal subcarrier set to maximize the energy efficiency of multiuser systems. The initial optimization problem is difficult to solve, then we obtain the optimal solution by transforming the objective function. Simulation results show that our proposed algorithm can achieve higher energy efficiency, and we also find that the noise power has an obvious influence on the energy efficiency of the system.

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