Na *et al. EURASIP Journal on Wireless Communications and Networking* (2017) 2017:148
DOI 10.1186/s13638-017-0932-1

EURASIP Journal on Wireless Communications and Networking

RESEARCH

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Subcarrier allocation based simultaneous wireless information and power transfer for multiuser OFDM systems

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Abstract

Most existing algorithms of simultaneous wireless information and power transfer (SWIPT) for orthogonal frequency division multiplexing (OFDM) systems are studied based on power splitting or time splitting, which lead to time delay and the decrease of subcarrier utilization. In this paper, a multiuser OFDM system with multichannel is established and the subcarriers are divided into two parts. One part is used for information decoding and the other part is used for energy harvesting. We maximize the sum rate of the users under the constraint of energy harvesting by optimizing the channel allocation and power allocation. By means of iterative calculation, an efficient subcarrier allocation algorithm is proposed. Simulation results demonstrate that the proposed algorithm converges fast and can achieve higher sum rate than the conventional algorithm.

Keywords: Simultaneous wireless information and power transfer (SWIPT), OFDM, Subcarrier allocation, Power allocation

1 Introduction

Orthogonal frequency division multiplexing (OFDM) is the viable air interface for providing the high spectral efficiency and ubiquitous communication services because of its ability to combat frequency selective fading and flexibility in resource allocation. However, the power-hungry circuitries and the limited energy supplies in portable devices lead to the bottlenecks in prolonging the lifetime of networks and guaranteeing quality of service (QoS). As a result, the energy-efficient mobile communication has drawn much attention from both the industry and the academia [1–4].

Traditionally, the energy has been harvested from natural renewable energy sources, such as solar, wind and geothermal heat, thereby substantially reducing the reliance on the energy supply from conventional energy sources. In this context, simultaneous wireless information and power transfer (SWIPT) has emerged and attracted the widespread concern. Varshney put forward the concept of transmitting information and energy simultaneously and defined the capacity energy function for the first time [5]. Pulkit Grover proposed the model based on the electromagnetic induction principle and analyzed the noise coupling circuit with SWIPT [6–10] maximized the energy efficiency in spectrum sensing. Two transmission protocols based on power splitting relaying and mode adaptation were proposed in OFDM relaying SWIPT systems [11]. Liang Liu proposed a classical transmission solution [12]. Specifically, the received signal is divided into two circuits: one is used for information decoding, and the other one is used for energy harvesting. As two classical models, time switching (TS) model and power switching (PS) model were put forward in [13–15], respectively. In TS model, the receiver switches to energy harvesting mode or information mode within one transmission period. In PS model, the receiver splits the power into two parts with some ratios of which one part is used for information decoding and another part is used for energy harvesting. Javer Rubio combined SWIPT with multiple-input-single-output (MISO) in [16] where a transmitter with multi-antennas transmits the same information to several banks of single antenna simultaneously. Various types of SWIPT systems including two-user MIMO broadcast channels, two-way communication links, and point-to-point links assisted by passive relays have been formulated and optimized in [17–20] proposed an optimal algorithm of power splitting based on downlink

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OFDMA by means of iterative algorithm. A tradeoff between TS and PS was proposed in [21].

As the promising technology for improving spectrum efficiency, cognitive radio (CR) has been investigated a lot recently [22–24]. SWIPT in CR networks with multi-users was studied in [25]. Two SWIPT schemes were proposed [26] for CR networks with a single SU. The secure beamforming schemes for SWIPT in a MISO broadcast channel was investigated in [27].

Different from PS and TS models, we study a subcarrier allocation algorithm based on SWIPT for the OFDM system with multiusers which is without a splitter at the receiver. The subcarriers of each user are separated into the information decoding part and the energy harvesting part. On the basis, we address the problem of maximizing the sum rate of users under the condition of enough energy harvesting. The problem is non-convex, and an iterative algorithm is used to solve it.

2 System model

We consider a wireless OFDM downlink system consisting of one cognitive base station (CBS) and k users. As shown in Fig. 1, each user is only equipped with one antenna. Let K denote the set of k users. The OFDM system bandwidth is assumed to be equally divided into n ($n \ge k$) channels. The set of subcarriers is denoted as N ($N = \{1,2,\cdots n\}$). Each subcarrier must be allocated to only one user. Parts of subcarriers are used for energy harvesting, while the others are utilized for information decoding simultaneously. We suppose that the channel power gain on each subcarrier is always constant in one transmission period provided by the base station. Let $h_{k,n}$ represent the gain of the k-th user on the n-th subcarrier. Then, the noise power of each subcarrier is modeled as an additive white Gaussian noise (AWGN) random variable with zero mean and variance σ^2. The total transmission power is limited to the power budget P. Therefore, the power allocated on the n-th subcarrier is denoted as P_n. Let S^P represent the subcarriers used for energy harvesting to power transfer. Accordingly, the other subcarriers used for information decoding are denoted by S^I. Hence, S^I_K represents the subcarriers of K-th user for information transfer. Since one subcarrier cannot be used for energy harvesting and transfer information simultaneously, we have $S^I \cap S^P = \varnothing$and $S^I \cup S^P = N$.

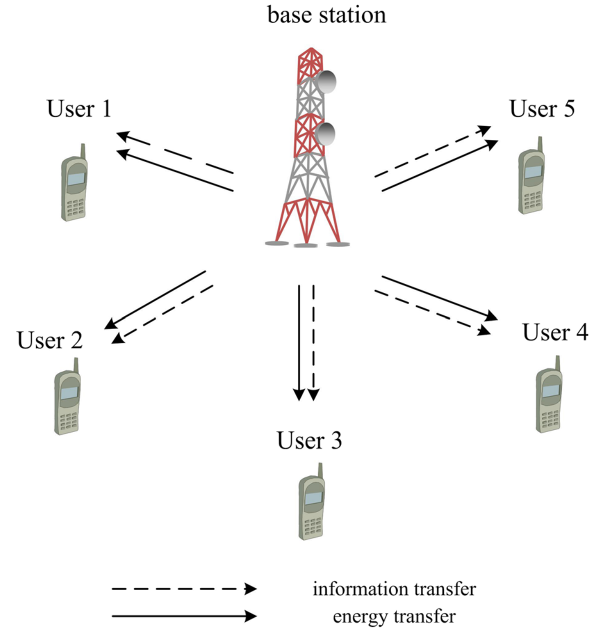

Fig. 1 System model

3 Problem formulation

Our aim is to maximize the sum rate of the OFDM downlink under the constraint of the minimum harvested energy for each user. Let B_k represent the minimum harvested energy of the k-th user. Since one subcarrier can only be allocated to one user, we use $\alpha_{n,k}$ to stand for a binary channel allocation index. In other words, $\alpha_{n,k} = 1$ means that the subcarrier n is only allocated to the user k, while $\alpha_{n,k} = 0$ is determined on other terms. Thus, it is written as:

$$\sum\nolimits_{k=1}^{K}\alpha_{k,n} = 1, \forall n\in N \tag{1}$$

The sum rate can be formulated as:

$$\sum\nolimits_{k=1}^{K}\sum\nolimits_{n\in S^I}\alpha_{k,n}\log\left(1+\frac{h_{k,n}P_n}{\sigma^2}\right) \tag{2}$$

Here, $n \in S^I$. With energy harvesting efficiency ε, the harvested energy during one transmission block for user k is determined by:

$$\sum\nolimits_{n\in S^P}\left(\varepsilon h_{k,n}P_n+\sigma^2\right) \tag{3}$$

For $\forall k \in K$. Therefore, the optimization model of maximum sum rate can be expressed as:

$$\begin{aligned}&\max_{\alpha_{n,k},\,S^I,\,P_n}\sum\nolimits_{k=1}^{K}\sum\nolimits_{n\in S^I}\alpha_{k,n}\log\left(1+\frac{h_{k,n}P_n}{\sigma^2}\right)\\&\quad\text{s.t. } \sum\nolimits_{n\in N}P_n\le P\ \ (P_n\ge 0)\\&\quad S^P\cup S^I=N\\&\quad S^P\cap S^I=\varnothing\\&\sum\nolimits_{k=1}^{K}\alpha_{k,n}=1,\quad \forall n\in N\\&\quad \alpha_{k,n}\in\{0,1\},\quad \forall k\in K,n\in N\end{aligned} \tag{4}$$

4 Optimal solution

Since the problem is non-convex, it is impossible to obtain the optimal solution directly. In this section, a sub-optimal algorithm is proposed for solving the non-convex problem.

The optimization task can be decomposed into three steps: to optimize $\alpha_{k,n}$ with given P_n and $S^I(S^P)$, to optimize $P_n$with given $\alpha_{k,n}$ and $S^I(S^P)$, as well as to optimize $S^I(S^P)$ with given $\alpha_{k,n}$ and P_n.

Firstly, since P_n and $S^I(S^P)$ are determined, $\alpha_{k,n}$is optimized as follows:

$$\begin{gathered}\max_{\alpha_{n,k}} \sum\nolimits_{k=1}^{K} \alpha_{k,n} \log\left(1+\frac{h_{k,n}P_n}{\sigma^2}\right), \quad n \in S^I \\ \text{s.t.} \sum\nolimits_{k=1}^{K} \alpha_{k,n} = 1, \quad \forall n \in N \\ \alpha_{k,n} \in \{0,1\}, \quad \forall k \in K, n \in N\end{gathered} \tag{5}$$

The problem above is regarded as allocating the subcarrier n to the assigned user for obtaining the maximum sum rate. In other words, the subcarrier n ($n \in S^I$) is allocated to the user k which can get the maximum $h_{k,n}P_n$, i.e., $\alpha_{k^*,n} = 1$, $k^* = \arg\max_{k \in K} h_{k,n}P_n$ and $\alpha_{k,n} = 0, \forall k \neq k^*, k \in K$.

Secondly, P_n is optimized by $\alpha_{k,n}$ and $S^I(S^P)$. In this proposition, the problem can be rewritten as:

$$\begin{aligned}\max_{P_n} & \sum\nolimits_{n \in S_k^I} \log\left(1+\frac{h_{k^*,n}P_n}{\sigma^2}\right) \\ \text{s.t.} & \\ & \sum\nolimits_{n \in S^P} \left(\varepsilon h_{k^*,n}P_n + \sigma^2\right) \geq B_k \\ & \sum\nolimits_{n \in N} P_n \leq P \quad (P_n \geq 0)\end{aligned} \tag{6}$$

Note that $\alpha_{k^*,n} = 1, \alpha_{k,n} = 0, \forall k \neq k^*, k \in K$. The converted problem is satisfied with convex model. Therefore, the Lagrange dual decomposition is adopted to solve this problem. The Lagrange dual function is as follows:

$$g(\beta_1,,\beta_2) = \max_{\{P_n\}} L(P_n) \tag{7}$$

Where, β_1 and β_2 are the Lagrange multipliers and they are determined by the sub-gradient method. Meanwhile, $L(P_n)$ is expressed as:

$$\begin{aligned}L(P_n) = & \sum\nolimits_{n \in S_k^I} \log\left(1+\frac{h_{k^*,n}P_n}{\sigma^2}\right) \\ & + \beta_1 \left\{\sum\nolimits_{n \in S^P} \left(\varepsilon h_{k^*,n}P_n + \sigma^2\right) - B_k\right\} \\ & + \beta_2 \left(P - \sum\nolimits_{n \in N} P_n\right)\end{aligned} \tag{8}$$

Then, the dual problem can be simplified as follows:

$$\begin{aligned}& \min_{\beta_1,\beta_2} g(\beta_1,,\beta_2) \\ & \text{s.t} \quad \beta_1,\beta_2 \geq 0\end{aligned} \tag{9}$$

Because the dual problem is differentiable, it can be solved by the classic sub-gradient method, which solves the optimal problem based on the gradient and the suitable step size [28]. The result is presented as below:

$$\Delta\beta_1 = \sum\nolimits_{n \in S^P} \varepsilon h_{k^*,n}P_n + \sigma^2 - B_k \tag{10}$$

$$\Delta\beta_2 = P - \sum\nolimits_{n \in N} P_n \tag{11}$$

For the given β_1 and β_2, the optimal power $P_n(n \in S^I)$ is obtained according to KKT conditions using mathematical manipulation:

$$P_n = \left(\frac{1}{\beta_2} - \frac{\sigma^2}{h_{k^*,n}}\right)^+ \tag{12}$$

Where, $(.)^+$denotes max(.,0).

Similarly, the allocated power P_n used for energy harvesting is determined as:

$$P_n = \begin{cases} P_{\max} \beta_1 h_{k^*,n} \varepsilon > \beta_2 \\ P_{\min} \beta_1 h_{k^*,n} \varepsilon \leq \beta_2 \end{cases} \tag{13}$$

Where, $P_{\max}$ and $P_{\min}$ represent the maximum and minimum power constraints on information decoding, respectively.

Algorithm 1: Proposed algorithm for the problem (6)

```
Initialize: $\beta_1(0), \beta_2(0), t = 0$.
Repeat
    Calculate$P_n(n \in S^I)$ according to (11)
    Calculate$P_n(n \in S^P)$ according to (12)
    $\beta_1(t+1) = \beta_1(t) - \text{stepsize1}(\sum_{n \in S^P} \varepsilon h_{k^*,n}P_n + \sigma^2 - B_k)$
    $\beta_2(t+1) = \beta_2(t) - \text{stepsize2}(P - \sum_{n \in N} P_n)$
    $t = t + 1$
Until $|\beta_1(t) - \beta_1(t-1)| \leq \varepsilon$ and $|\beta_2(t) - \beta_2(t-1)| \leq \varepsilon$
```

Where, ε(>0) denotes the error tolerance and t denotes the times of iteration.

According to P_n and $\alpha_{n,k}$, $S^I(S^P)$ can be obtained by substituting (11) and (12) into (8). Consequently, the Lagrange dual function can be rewritten as below:

$$\begin{aligned}L(S^P) = & \sum\nolimits_{k=1}{}^{K} \sum\nolimits_{n \in N} \alpha_{n,k} \log\left(1+\frac{h_{k,n}P_n}{\sigma^2}\right) \\ & - \sum\nolimits_{k=1}{}^{K} \sum\nolimits_{n \in S^P} \alpha_{n,k} \log\left(1+\frac{h_{k,n}P_n}{\sigma^2}\right) \\ & + \beta_1 \sum\nolimits_{n \in S^P} \left(\varepsilon h_{k,n}P_n + \sigma^2\right) - \beta_1 B_k + \beta_2 P - \beta_2 \sum\nolimits_{n \in N} P_n \\ = & \sum\nolimits_{n \in S^P} \left\{\beta_1 \left(\varepsilon h_{k,n}P_n + \sigma^2\right) - \sum\nolimits_{k=1}^{K} \alpha_{n,k} \log\left(1+\frac{h_{k,n}P_n}{\sigma^2}\right)\right\} \\ & + \sum\nolimits_{n \in N} \left\{\sum\nolimits_{k=1}^{K} \alpha_{n,k} \log\left(1+\frac{h_{k,n}P_n}{\sigma^2}\right) - \beta_2 P_n\right\} - \beta_1 B_k + \beta_2 P \\ = & \sum\nolimits_{n \in S^P} F_n + \sum\nolimits_{n \in N} \left\{\sum\nolimits_{k=1}^{K} \alpha_{n,k} \log\left(1+\frac{h_{k,n}P_n}{\sigma^2}\right) - \beta_2 P_n\right\} - \beta_1 B_k + \beta_2 P\end{aligned} \tag{14}$$

Where,

$$F_n = \beta_1\left(\varepsilon h_{k,n} P_n + \sigma^2\right) - \sum\nolimits_{k=1}^{K} \alpha_{n,k} \log\left(1 + \frac{h_{k,n} P_n}{\sigma^2}\right) \tag{15}$$

When we observe the formula (13), only the first item on the right side is about to S^P. Thus, the optimal S^P can be achieved by maximizing the item F_n, i.e.,

$$S^{P*} = \arg\ \max_{S^P} \sum\nolimits_{n \in S^P} F_n^* \tag{16}$$

S^{P*} can be easily obtained by substituting all the n into F_n to find the ones which make F_n positive. As a result, the rest of the set N belongs to S^{I*}.

The proposed algorithm to solve the optimal problem is presented as below:

Algorithm 2: Proposed algorithm for the joint optimizationproblem

```
Initialize: $P_n(0) = 0$, $\alpha_{n,k^*}(0)$, $t = 0$
Given$P_n(0)$ and $\alpha_{n,k^*}(0)$, obtain $S^I(0)$ according to formula (16)
$R_k(0) = \sum_{k=1}^{K} \alpha_{n,k}(0) \log\left(1 + \frac{h_{k,n}P_n(0)}{\sigma^2}\right)$, $n \in S^I$
Repeat
    Given $P_n(0)$ and $S^I(t)$, set $\alpha_{n,k^*}(t) = 1$, $k^* = \arg\max_{k \in K}(h_{k,n}P_n)$ and $\alpha_{n,k^*}(t) = 0$, $\forall k \neq k^*$, $k \in K$
    Given $\alpha_{n,k^*}(t+1)$ and $S^I(t)$, obtain $P_n(t+1)$ for all $n \in N$, according to formulas (11) and (12)
    Given $\alpha_{n,k^*}(t+1)$ and $P_n(t+1)$, obtain $S^I(t+1)$
    $R_k(t+1) = \sum_{k=1}^{K} \alpha_{n,k}(t+1) \log\left(1 + \frac{h_{k,n}P_n(t+1)}{\sigma^2}\right)$, $n \in S^I$
    $t = t + 1$
Until $|R_k(t+1) - R_k(t)| \le \varepsilon$
```

Where, $\varepsilon(>0)$ denotes the error tolerance and t denotes the times of iteration.

5 Simulation results

In this section, the performance of the proposed subcarrier allocation algorithm based on SWIPT for the OFDM system with multiusers is demonstrated by simulation results.

We denote all the channels involved follow the Rayleigh distribution. For simplicity, we suppose that the minimum harvested energy limits for all the users are the same, i.e., $B_k = B$. In addition, we set $N = 16$, $K = 5$, $\sigma^2 = 1$, $P_{\max} = 3$ W, $P_{\min} = 0$, $\varepsilon = 1$, and the bandwidth is equal to 1 MHz.

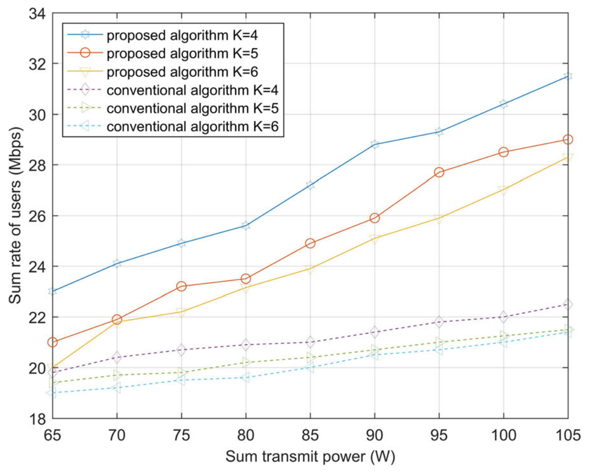

Fig. 3 Sum rate of users vs. sum transmission power

Figure 2 shows the convergence behavior of the proposed algorithm. It can be seen that the proposed algorithm converges fast. It indicates that the proposed algorithm can be implemented practically.

Figure 3 presents the comparison between the proposed optimization algorithm and the conventional algorithm of subcarrier allocation based on [29]. It can be observed that the proposed algorithm performs better compared with the conventional algorithm.

When the conventional algorithm allocates N subcarriers to K users, all the subcarriers are used for information decoding and the consumed energy comes from the system. Since the system can not produce energy by itself, the energy comes from the finite battery. Therefore, the constraint of minimum energy harvesting can not be

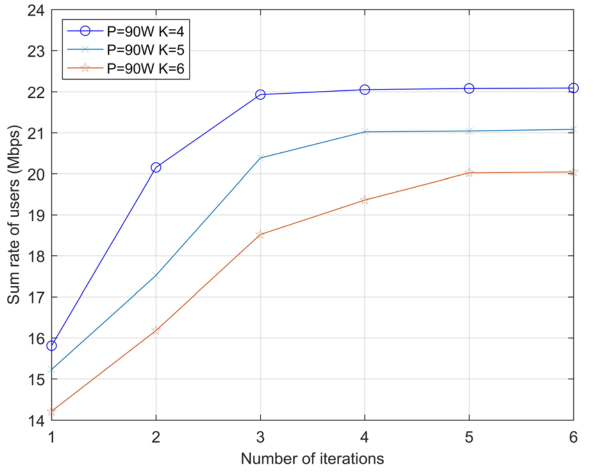

Fig. 2 Convergence behavior of the proposed algorithm

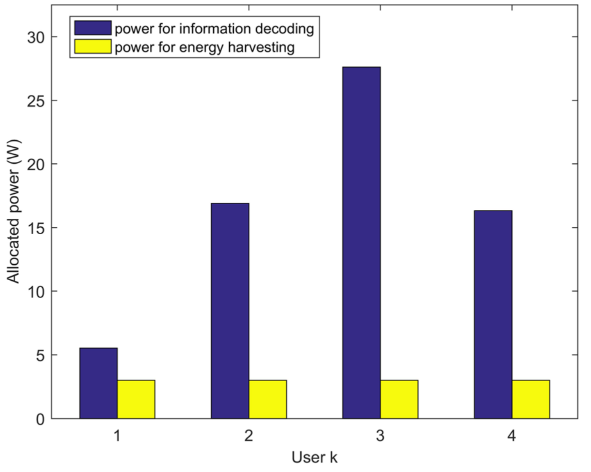

Fig. 4 The allocated power for user *k*

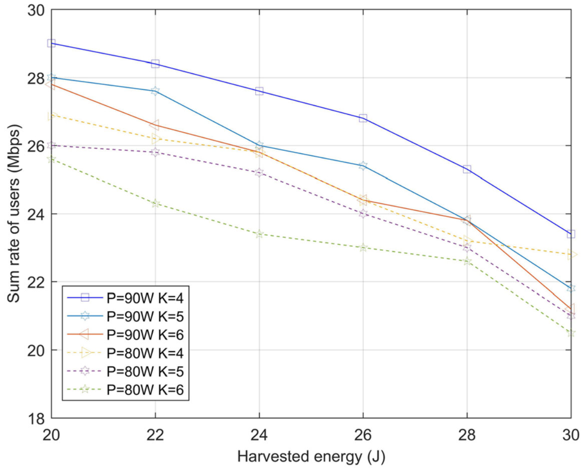

Fig. 5 Sum rate of users vs. harvested energy

satisfied more often than not. Since the water-filling approach is used for the power allocation of the conventional algorithm, it would cause some power waste. What is more, all the subcarriers allocated to information decoding lead to the energy consumption and less power is used for information decoding. Figure 2 also demonstrates that the sum rate of users increases with the increase of sum transmit power *P*. It can be interpreted as that the increase of sum transmit power brings about the more power allocated to information decoding with the same target harvested energy.

Figure 4 shows that the total transmit power used for information decoding of user *k*. It can be seen that the user 3 is allocated the most power, while the user 1 is the least. This is because, in our simulation, the user 3 has the best channel condition so that it can achieve higher sum rate.

Figure 5 shows that the sum rate of users versus the minimum energy harvesting limit B_k under the fixed power budget. It is obvious that the sum rate varies with the constraint of the harvested energy. When B_k increases, the sum rate decreases. This is because when the constraint of energy harvesting increases, more subcarriers are allocated to satisfy the constraint of the harvested energy. It leads to less resources that are allocated to the information decoding. It can also be observed that, with regard to the same constraint of energy harvesting, the sum rate decreases as the number of users increases. That is expected due to the fact that under the same power budget, the increasing number of users causes the decrease of the average allocated power for each subcarrier. As a result, more subcarriers are allocated to energy harvesting in order to satisfy the same constraint of the required energy, as well as the sum rate of users increases.

Figure 6 shows the allocated power to each subcarrier under the condition of the power budget equal to 80 W. It also illustrates the average channel gain for each subcarrier. As shown in Fig. 6, when the subcarrier has the good channel condition, it is always used for energy harvesting. On the other hand, when the subcarrier has the bad channel condition, it is always used for information decoding and less power is allocated. The phenomenon appears because to allocate the good channel for energy harvesting leads to less subcarriers used for energy harvesting and more subcarriers used for information decoding to achieve maximum sum rate.

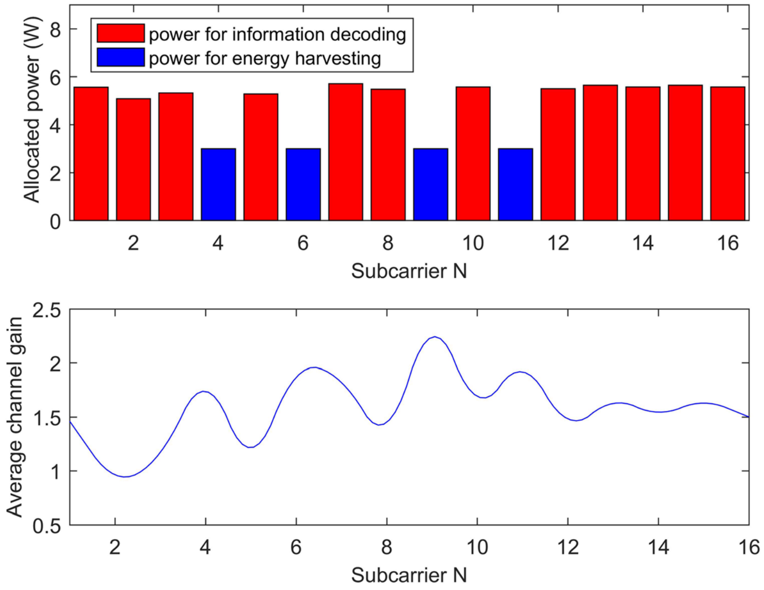

Fig. 6 The allocated power and channel condition of subcarrier *n*

6 Conclusions

A subcarrier allocation algorithm based on SWIPT for the OFDM system with multiusers was proposed in this paper. Traditionally, SWIPT is used for single user in OFDM systems more often than not. However, we proposed a joint optimization algorithm used for multiusers. Specifically, the OFDM subcarriers of each user are divided into two parts whose one part is used for information decoding and the other part is used for energy harvesting. Therefore, in contrast to the conventional time or power splitter at the receiver, the enough information rate can be obtained on the premise of the harvested energy we require. Simulation results show that the proposed algorithm converges fast and performs better than the conventional algorithm in the rate of information decoding.

Funding

This work was supported by the National Natural Science Foundations of China under Grant No. 61301131 and 61601221, the Natural Science Foundations of Jiangsu Province under Grant No. BK20140828, the China Postdoctoral Science Foundations under Grant No. 2015M580425 and the Fundamental Research Funds for the Central Universities under Grant No. 3132016347 and DUT16RC(3)045.

Authors' contributions

ZN designed the main body of the algorithm and completed the first simulation. XL gave the guidance on the ideas of the paper, optimized the parameters, and discussed the related problems with other authors. XL completed the remaining simulations, analyzed data, and processed simulation results. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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Received: 17 July 2017 Accepted: 17 August 2017

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