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Simultaneous Wireless Information and Power Transfer Based on Joint Subcarrier and Power Allocation in OFDM Systems

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ABSTRACT Energy harvesting (EH) is a prominent method to extend the operation time of energy-limited wireless networks. By integrating EH into wireless communications, the same spectrum is able to be used by simultaneous wireless information and power transfer (SWIPT) without affecting the quality of service. In this paper, we propose a joint subcarrier and power allocation-based SWIPT scheme in orthogonal frequency division multiplexing (OFDM) systems. Specifically, the received OFDM subcarriers are partitioned into two groups. A fraction of the received subcarriers are allocated to form one group, which is used for information decoding (ID), and the remaining subcarriers form the other group, which is used for energy harvesting. Thus, no splitter is needed at the receiver. A joint subcarrier and power allocation problem is formulated to maximize the harvested energy, subject to the ID constraint. By using the dual decomposition method, an efficient algorithm is proposed to solve this joint resource allocation problem.

INDEX TERMS Simultaneous wireless information and power transfer (SWIPT), subcarrier allocation, power allocation, orthogonal frequency division multiplexing (OFDM).

I. INTRODUCTION

In recent years, simultaneous wireless information and power transfer (SWIPT) has drawn a rising research interest as it can provide eternal energy for the energy limited wireless networks where the energy is supplied by finite batteries [1]. The SWIPT concept was first raised in [2], and the performance trade-off between information transmission rate and transferred power was characterized over flat fading channels [2] and frequency-selective channels [3], assuming that the receiver can harvest the energy and decode the information simultaneously from the same received signal.

However, this assumption is difficult to realize due to the limit of practical electronic circuits. The work in [4] proposed a practical receiver for SWIPT systems, in which the received RF signal is split into two streams, one is used to harvest the energy and the other is used to decode the information. Power splitting (PS) and time switching (TS) are two practical SWIPT schemes proposed in [5] and [6]. In PS scheme, the power spitter splits the received RF signal into two streams with different powers, which are respectively used for information decoding and energy harvesting. In TS scheme, the receiver switches into energy harvesting mode or information decoding mode within one transmission time. An original scheme based on receiver mode switching for multiple-input single-output (MISO) SWIPT networks is proposed in [7], where the transmitter equipped with multi-antenna uses conventional random beamforming techniques to send common information, which enables each single-antenna receiver to harvest more energy. Lagrangian relaxation method coupled with Dinkelbach method are used to address the energy efficiency optimization problem in the power splitting based MISO downlink systems [8], in which system energy efficiency is maximized under both the signal-to-interference-plus-noise ratio and energy harvesting constraints. Two different scenarios where the receivers used for information decoding and energy harvesting are separated or co-located are studied in multiple-input multiple-output (MIMO) broadcast SWIPT networks [1]. Reference [9] studied energy efficiency optimization problem in MIMO SWIPT systems with covariance channel state information feedback, in which the potential capacity obtained from the transferred energy is also considered.

Cooperative relay has been proposed as a powerful technique to improve system performance [10]. Integrating cooperative relay into SWIPT, energy limited relay nodes can be kept active through energy harvesting, also information-energy tradeoff can be fully utilizzed [11], [12]. Two SWIPT relaying protocols: PS based SWIPT and TS based SWIPT relaying protocols are studied in amplify-and-forward (AF) relay SWIPT networks [13], in which the relay node with energy constrained forwards the source signal to the destination by using the harvested energy from the received RF signal. The throughputs and ergodic capacity of PS based SWIPT and TS based SWIPT relaying protocols in decode-and-forward (DF) relay networks were derived in [14]. Power allocation for energy harvesting relay-assisted wireless networks with multiple transceiver pairs communicate with each other through one/multiple energy harvesting relays were studied in [15] and [16]. Outage probability and ergodic capacity are studied in SWIPT multiple antennas relay systems [17], where the multiple antennas relay harvest power either from the source signal or from the source signal and interference. Antenna selection, antenna switching and smart antenna application have been studied in MIMO relay-assisted SWIPT networks [18]–[20].

Orthogonal frequency division multiplexing (OFDM) can effectively enable high transmission rates, which is a widely used technology adopted in various standards [21]. Integrating OFDM into SWIPT, the advantages of SWIPT can be fully utilized with efficient wireless resource allocation schemes. The work in [22] studied the optimization of power control for different configurations in OFDM SWIPT systems. Power splitting in OFDMA SWIPT systems was studied in [23], where the non-convex wireless resource allocation problems were solved by using suboptimal iterative algorithms. Work [24] studied the optimal wireless resource allocation in a multiuser OFDM SWIPT system, where each user uses power splitting or time switching to coordinate information decoding and energy harvesting. [25] considered secure communications in a downlink OFDMA SWIPT system in which the power allocation optimization problem was investigated. Two transmission protocols based on power splitting relaying and mode adaptation were proposed in OFDM relaying SWIPT systems [26]. [27] studied power splitting-based relaying protocol and time switching-based relaying protocol in SWIPT MIMO-OFDM relay networks in which the resource allocation problems were studied.

Most of existing SWIPT works in OFDM systems are studied based on power splitting or time switching, where the receiver needs a power or time splitter to separate the received signal for energy harvesting and information decoding. In this paper, we propose a joint subcarrier and power allocation based SWIPT scheme in OFDM systems, in which no splitter is needed at the receiver. Specifically, the received OFDM subcarriers are partitioned into two groups. A fraction of the received subcarriers are allocated to one group which is used for information decoding, and the remaining subcarriers form the other group which is used for energy harvesting. Thus, the receiver only needs to know which group is allocated for information decoding, then the other group is allocated for energy harvesting. Thus, no splitter is needed any more at the receiver.

The main contributions of this paper are described as follows:

- Unlike the previous OFDM SWIPT scheme, no splitter is needed in our proposed OFDM SWIPT scheme, which can effectively reduce the complexity of the receiver.
- Joint subcarrier and power allocation is derived, such that the harvested energy is maximized, while guaranteeing the transmission rate achieving the target rate.
- Simulation results confirm the benefits of the proposed OFDM SWIPT scheme, and also demonstrate the superiority of the proposed resource allocation strategy over other strategies based on power splitting or water-filling power approach.

The remainder of this paper is organized as follows. In Section II, we introduce the system model and present the problem formulation. The joint optimal subcarrier and power allocation algorithm is presented in Section III. Simulation results are provided in Section IV to illustrate the performance of the proposed OFDM SWIPT scheme and resource allocation algorithm. Finally we conclude this paper in Section V.

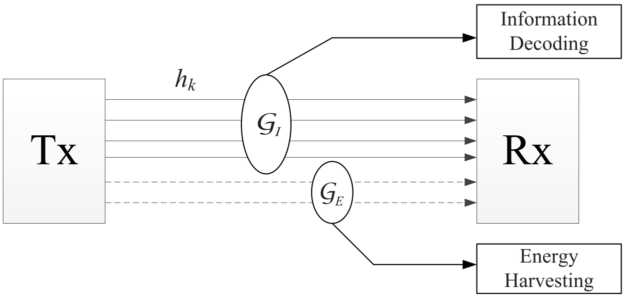

FIGURE 1. System model.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

We consider a wireless OFDM-based link, which consists of one transmitter (Tx) and one receiver (Rx), as shown in Fig. 1. Tx and Rx are equipped with a single antenna. The total system bandwidth is equally divided into K subcarriers. We denote the subcarriers set as $\mathcal{K} = \{1, \ldots, K\}$. The channel power gain over subcarrier k is denoted by h_k, which is assumed to be known at the transmitter. The power allocated over subcarrier k is denoted as p_k. The total transmission power over all the subcarriers is denoted as P.

We consider slow fading in which all the channel coefficients are assumed to be constant over multiple OFDM symbols. At Rx, the received signal on each subcarrier will be corrupted by noise n_k, which is modeled as an additive white Gaussian noise (AWGN) random variable with zero mean and variance σ_k^2, denoted by $n_k \sim \mathcal{CN}(0, \sigma_k^2)$. The receiver is assumed to adapt bandpass filters, which makes it possible to tap into different subcarriers [28].

B. PROBLEM FORMULATION

The received signal over all the OFDM subcarriers are divided into two groups, denoted as $\mathcal{G}_I$ and $\mathcal{G}_E$, where $\mathcal{G}_I \subseteq \mathcal{K}$, $\mathcal{G}_E \subseteq \mathcal{K}$ and $\mathcal{G}_I + \mathcal{G}_E = \mathcal{K}$. As shown in Fig.1, the subcarriers in $\mathcal{G}_I$ are used for information decoding and the subcarriers in $\mathcal{G}_E$ are used for energy harvesting.

The achievable rate (in Nats/OFDM symbol) for the Tx-Rx link is given by

$$R = \sum_{k \in \mathcal{G}_I} \ln\left(1 + \frac{p_k h_k}{\sigma_k^2}\right). \tag{1}$$

And the harvested energy at Rx is given by

$$Q = \xi \sum_{k \in \mathcal{G}_E} (p_k h_k + \sigma_k^2) \tag{2}$$

where ξ denotes the energy harvesting conversion efficiency at Rx.

With the objective of maximizing the harvested energy by joint subcarrier and power allocation, subject to a given target transmission rate constraint, the following optimization problem is formulated.

$$\max \xi \sum_{k \in \mathcal{G}_E} (p_k h_k + \sigma_k^2) \tag{3}$$

subject to

$$\sum_{k \in \mathcal{G}_I} \ln\left(1 + \frac{p_k h_k}{\sigma_k^2}\right) \geq R_T \tag{4}$$

$$\sum_{k \in \mathcal{G}_I} p_k + \sum_{k \in \mathcal{G}_E} p_k \leq P \tag{5}$$

III. OPTIMAL SOLUTION

In this section, we study the joint optimization of power allocation $\mathcal{P} = \{p_k\}$ and subcarrier set $\mathcal{G} = \{\mathcal{G}_I, \mathcal{G}_E\}$ to maximize the harvested energy Q, while guaranteeing the transmission rate achieving the target rate R_T.

The optimization problem in (3) is a mixed integer programming nonconvex problem. Directly finding the optimal $\mathcal{P}$ and $\mathcal{G}$ needs exhaustive search with very high complexity. However, the duality gap of a nonconvex optimization problem is zero, when it satisfies the "time-sharing" condition in multicarrier systems [29]. If the number of subcarriers is large, the "time-sharing" condition will always be satisfied [26]. As shown in Appendix, we can prove that our joint optimization problem satisfies the "time-sharing" condition. And then we can also prove that the time-sharing property implies zero duality gap. Therefore, the dual decomposition method can be used to solve the optimization problem in (3) through the following two steps.

A. OPTIMIZING DUAL VARIABLES

The Lagrange dual function of the optimization problem in (3) is given by

$$g(\boldsymbol{\beta}) = \max_{\{\mathcal{P}, \mathcal{G}\}} L(\mathcal{P}, \mathcal{G}) \tag{6}$$

where $L(\mathcal{P}, \mathcal{G})$ is given by (7) which is shown at the bottom of this page and $\boldsymbol{\beta} = (\beta_1, \beta_2)$ is the dual variables vector subject to the power and rate constraints. Then, the dual optimization problem can be given by

$$\min_{\boldsymbol{\beta}} \ g(\boldsymbol{\beta}) \tag{8}$$

subject to

$$\boldsymbol{\beta} \succeq 0$$

Since a dual function can be proved to be convex [29], we can use the subgradient-based method to minimize $g(\boldsymbol{\beta})$ with guaranteed convergence. The subgradient can be easily given as

$$\Delta\beta_1 = \sum_{k \in \mathcal{G}_I} \ln\left(1 + \frac{p_k h_k}{\sigma_k^2}\right) - R_T \tag{9}$$

$$\Delta\beta_2 = P - \sum_{k \in \mathcal{G}_I} p_k - \sum_{k \in \mathcal{G}_E} p_k \tag{10}$$

Letting $\Delta\boldsymbol{\beta} = (\Delta\beta_1, \Delta\beta_2)$, $\boldsymbol{\beta}$ is updated as $\boldsymbol{\beta}^{t+1} = \boldsymbol{\beta}^t + \nu^t \Delta\boldsymbol{\beta}$. With the step size ν^t following the diminishing step size policy in [29], this subgradient method is guaranteed to converge to the optimal $\boldsymbol{\beta}$. The computational complexity of this subgradient method can be given by $O(L^{\alpha})$ [30], where α is a nonnegative integer and L is the number of dual variables. As only two dual variables β_1 and β_2 are involved, thus the complexity can be given by $O(2^{\alpha}) = O(1)$.

B. OPTIMIZING $\mathcal{P}$ AND $\mathcal{G}$ WITH GIVEN DUAL VARIABLES

Calculating the Lagrange dual function $g(\boldsymbol{\beta})$ needs to obtain the optimal $\mathcal{P}$ and $\mathcal{G}$ at a given $\boldsymbol{\beta}$, which can be executed with the following two steps. Obtain the optimal $\mathcal{P}$ with a fixed $\mathcal{G}$ in the first step; then obtain the optimal $\mathcal{G}$ in the second step.

1) OBTAINING THE OPTIMAL $\mathcal{P}$ FOR A FIXED $\mathcal{G}$

For a fixed $\mathcal{G}$, the partial derivatives of the Lagrangian in (7) with respective to the optimization variables p_k are

$$L(\mathcal{P}, \mathcal{G}) = \xi \sum_{k \in \mathcal{G}_E} (p_k h_k + \sigma_k^2) + \beta_1\Big(\sum_{k \in \mathcal{G}_I} \ln\left(1 + \frac{p_k h_k}{\sigma_k^2}\right) - R_T\Big) + \beta_2\Big(P - \sum_{k \in \mathcal{G}_I} p_k - \sum_{k \in \mathcal{G}_E} p_k\Big) \tag{7}$$

given by

$$\frac{\partial L(\mathcal{G},\boldsymbol{p})}{\partial p_k} = \frac{\beta_1 h_k}{\sigma_k^2 + p_k h_k} - \beta_2, \quad k \in \mathcal{G}_I \tag{11}$$

$$\frac{\partial L(\mathcal{G},\boldsymbol{p})}{\partial p_k} = h_k \xi - \beta_2, \quad k \in \mathcal{G}_E \tag{12}$$

By the Karush-Kuhn-Tucker conditions, the partial derivative of the Lagrangian is equal to zero at the optimal solution. Hence, the optimal p_k $(k \in \mathcal{G}_I)$ for a given $\boldsymbol{\beta}$ can be obtained as

$$p_k^* = \left(\frac{\beta_1}{\beta_2} - \frac{\sigma_k^2}{h_k}\right)^+. \tag{13}$$

And the optimal p_k $(k \in \mathcal{G}_E)$ can be obtained as

$$p_k^* = \begin{cases} P_{max} & h_k \xi > \beta_2 \\ P_{mim} & h_k \xi \leq \beta_2 \end{cases} \tag{14}$$

where P_{mim} and P_{max} denote the minimum and maximum power constraints on each subcarrier, respectively.[1]

2) OBTAINING THE OPTIMAL $\mathcal{G}$

Substituting (13) and (14) into (7), and adopting algebraic transformation, we can rewrite the Lagrangian in (7) as (15) which is shown at the bottom of this page.

Where

$$F_k^* = \beta_1 \ln\left(1 + \frac{p_k^* h_k}{\sigma_k^2}\right) - \xi(p_k^* h_k + \sigma_k^2). \tag{16}$$

In (15), we find that only the first part on the right-hand side, F_k^*, involves $\mathcal{G}_I$. Thus, we only need to work on F_k^* to obtain the optimal subcarrier set $\mathcal{G}_I$ that maximizes the Lagrangian. As a result, the optimal $\mathcal{G}_I$ can be found as

$$\mathcal{G}_I^* = \arg\max_{\mathcal{G}_I} \sum_{k \in \mathcal{G}_I} F_k^*. \tag{17}$$

$\mathcal{G}_I^*$ can be obtained by finding all the k's $(k \in \mathcal{K})$ which make F_k^* positive. Then, $\mathcal{G}_I^*$ is formed by all these k's. Clearly, the involved complexity is $O(K)$.

It follows that the optimal $\mathcal{G}_E$ can be given as

$$\mathcal{G}_E^* = \mathcal{K} - \mathcal{G}_I^*. \tag{18}$$

So far, the optimal primal variables $\boldsymbol{\mathcal{P}}$ and $\boldsymbol{\mathcal{G}}$ have been obtained with given dual variables. And the joint optimization problem in (3) can be finally solved by updating the dual variables, which involves an overall computational complexity of $O(1 \times K) = O(K)$. Based on the above discussions, the proposed solution for the joint optimization problem can be summarized in Algorithm 1.

Algorithm 1 Proposed Algorithm for the Joint Optimization Problem

```
1: initialize non-negative values $\{\beta_1, \beta_2\}$.
2: repeat
3:     Calculate the optimal power allocation $p_k^*$ defined in (13) and (14).
4:     Obtaining the optimal subcarrier allocation sets $\mathcal{G}_I^*$ and $\mathcal{G}_E^*$
5:     Update $\{\beta_1, \beta_2\}$ by the subgradient-based method with the subgradients defined in (9) and (10).
6: until $\{\beta_1, \beta_2\}$ converge.
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IV. SIMULATION RESULTS

In this section, the performance of the proposed joint subcarrier and power allocation based SWIPT scheme is demonstrated by simulation results in terms of harvested energy and power/subcarrier allocation ratio.

We consider a frequency-selective fading channel with six taps, where the central frequency is set to be 1.9 GHz. The line-of-sight (LOS) signal accounts for the primary role, then the channel is modeled as Ricean fading. Specifically, the channel over subcarrier k is modeled as $f(k) = \sqrt{\frac{M}{M+1}}\tilde{f} + \sqrt{\frac{1}{M+1}}\hat{f}(k)$, where $\tilde{f}$ is the LOS deterministic component,

$$\begin{aligned} L(\mathcal{G}) &= \xi \sum_{k=1}^{K}(p_k^* h_k + \sigma_k^2) - \xi \sum_{k \in \mathcal{G}_I}(p_k^* h_k + \sigma_k^2) + \beta_1 \sum_{k \in \mathcal{G}_I} \ln\left(1 + \frac{p_k^* h_k}{\sigma^2}\right) - \beta_1 R_T + \beta_2 P - \beta_2 \sum_{k \in \mathcal{G}_I} p_k^* \\ &\quad - \beta_2 (\sum_{k=1}^{K} p_k^* - \sum_{k \in \mathcal{G}_I} p_k^*) \\ &= \xi \sum_{k=1}^{K}(p_k^* h_k + \sigma_k^2) - \xi \sum_{k \in \mathcal{G}_I}(p_k^* h_k + \sigma_k^2) + \beta_1 \sum_{k \in \mathcal{G}_I} \ln\left(1 + \frac{p_k^* h_k}{\sigma^2}\right) - \beta_1 R_T + \beta_2 P - \beta_2 \sum_{k=1}^{K} p_k^* \\ &= \sum_{k \in \mathcal{G}_I}\left(\beta_1 \ln\left(1 + \frac{p_k^* h_k}{\sigma_k^2}\right) - \xi(p_k^* h_k + \sigma_k^2)\right) + \sum_{k=1}^{K}\left(\xi(p_k^* h_k + \sigma_k^2) - \beta_2 p_k^*\right) - \beta_1 R_T + \beta_2 P \\ &= \sum_{k \in \mathcal{G}_I} F_k^* + \sum_{k=1}^{K}\left(\xi(p_k^* h_k + \sigma_k^2) - \beta_2 p_k\right) - \beta_1 R_T + \beta_2 P \end{aligned} \tag{15}$$

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[1] They can be treated as "spectral masks" in OFDM systems, after considering the practical power amplifier limits as well as the restriction of the interference to neighboring users.

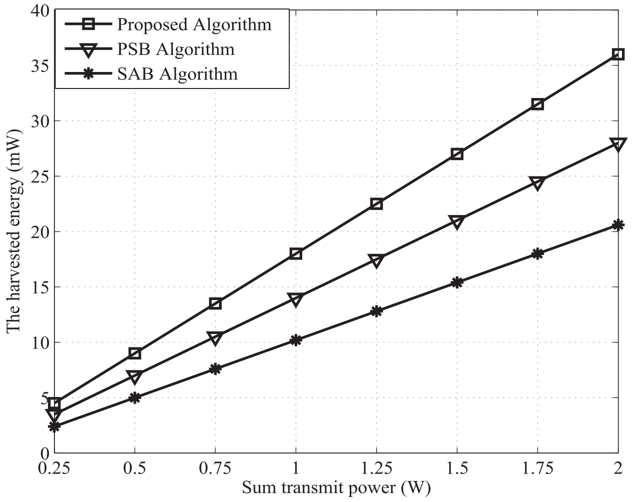

FIGURE 2. Harvested energy versus sum transmit power.

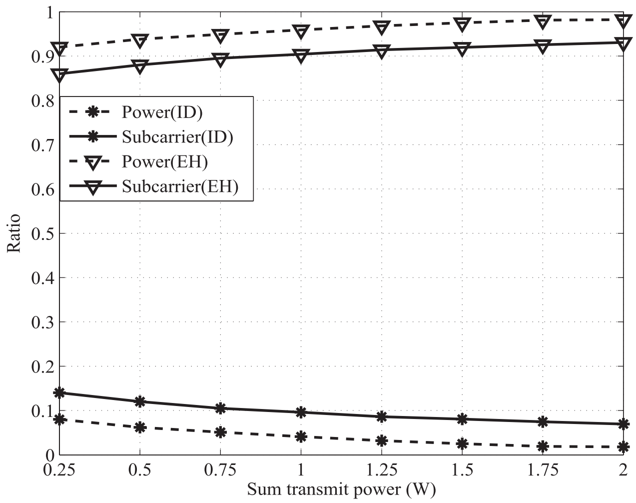

FIGURE 4. Power/subcarrier allocation ratio versus sum transmit power.

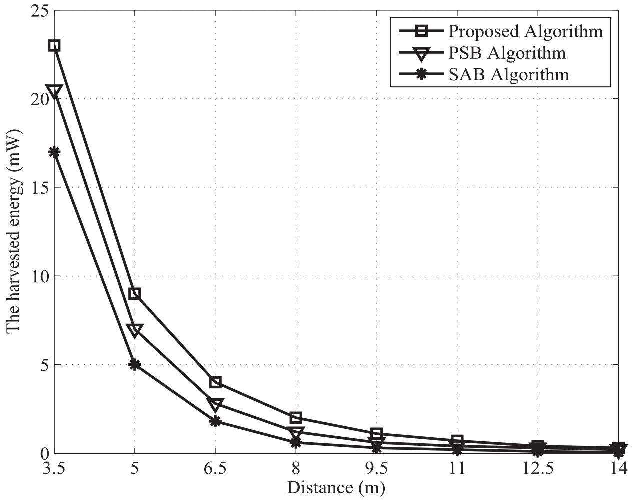

FIGURE 3. Harvested energy versus the distance between transmitter and receiver.

$\hat{f}(k)$ denotes the Rayleigh fading component, and M is the Rician factor specifying the power ratio between the LOS and fading components in $f(k)$. The channel power gain is denoted as $h(k) = |f(k)|^2$. We set $M = 3$. The noise spectrum density is set to be -50 dBm. The number of subcarriers $K = 32$, $\xi = 1$. The distance between the transmitter and receiver is set to be 5 meters and the target transmission rate $R_T = 4$ bps/Hz, unless otherwise specified.

In Figs. 2 and 3, the performance of the proposed joint optimization algorithm is compared with the following two benchmark algorithms.

Subcarrier allocation based (SAB) algorithm: certain subcarriers are allocated for information decoding, and the remaining subcarriers are used for energy harvesting. The subcarrier allocation is similar to our proposed algorithm, while the water-filling approach is used to allocate the power over subcarriers according to the Tx→Rx channel.

Power splitting based (PSB) algorithm: at receiver, each subcarrier is split into two streams with a fixed power ratio, where one stream is used to harvest the energy and the other one is used to decode the information [24].

Figs. 2 and 3 clearly show that the performance of our proposed joint optimization algorithm significantly outperforms the two benchmark algorithms while the performance of PSB algorithm is better than SAB algorithm. In PSB algorithm, the receiver does not adapt to the channel condition of each subcarrier and each subcarrier splits the same ratio of power for information decoding and energy harvesting. In SAB algorithm where the power is allocated based on the water-filling approach optimized for information decoding, this will cause some power waste for energy harvesting. Therefore, SAB is worse than PSB algorithm. Fig. 2 shows that when the sum transmit power increases, the harvested energy will also increase. This is because, with the same target transmission rate, there will be fewer subcarriers allocated for information decoding when the sum transmit power increases. Therefore, more subcarriers will be left for energy harvesting. In Fig. 3, we find that for our proposed algorithm the harvested energy decreases when the distance between transmitter and receiver increases. The reason is that with the same target ate, there will be more power allocated for information decoding when the distance becomes larger and therefore less energy will be harvested.

In Figs. 4-8, we focus on the performance of our proposed algorithm. Fig. 4 shows the power and subcarrier allocation ratio versus the sum transmit power. We find that with an increasing sum transmit power, more power will be used for energy harvesting. This is because, with a fixed target transmission rate, the power used for information decoding does not change and therefore more power will be left for energy harvesting. We also observe from the figure that more subcarriers are also allocated for energy harvesting when sum transmit power increases. This is because when transmit power increases, the power allocated to each subcarrier may

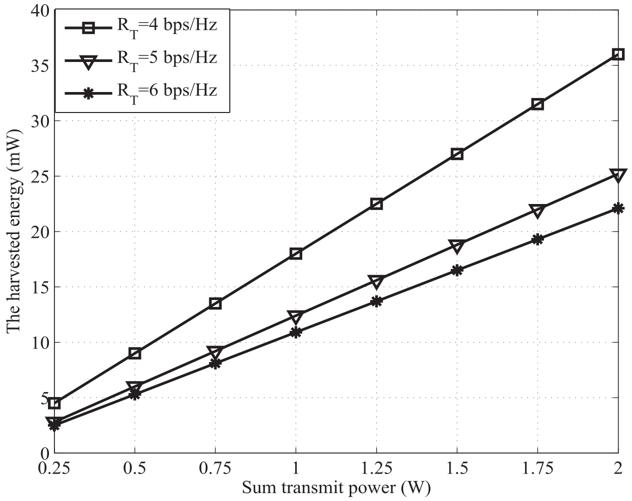

FIGURE 5. Harvested energy versus sum transmit power at different target rates.

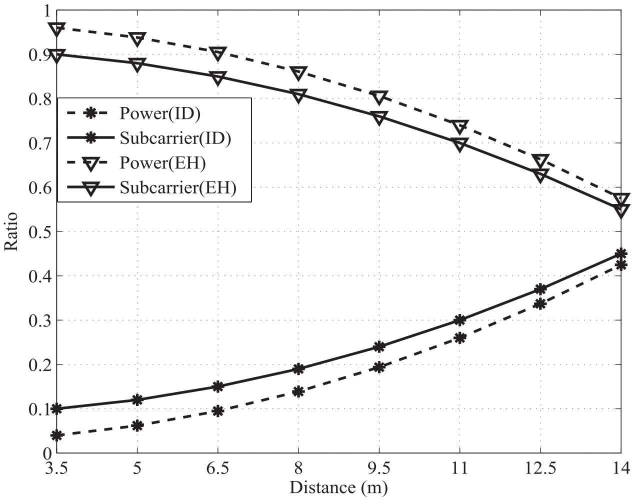

FIGURE 6. Power/subcarrier allocation ratio versus the distance between transmitter and receiver.

increase, especially for those subcarriers with good channel conditions. Therefore, with the same target transmission rate, there will be fewer subcarriers allocated for information decoding, and thus more subcarriers will be used for energy harvesting.

Fig. 5 shows the harvested energy versus the sum transmit power at different target rates. We find that with an increasing R_T, less energy will be harvested. This is because, with a fixed transmit power, more power will be needed for information decoding when the target rate becomes larger. Then, less power will be left for energy harvesting.

In Fig. 6, we display how the power/subcarrier allocation ratio varies according to the distance between the transmitter and receiver, where the sum transmit power $P = 0.5$ W. In Fig. 6, we find that when the distance increases, more power and more subcarriers will be used for information decoding. When the distance becomes larger, the channel between the transmitter and receiver becomes worse, then more power and more subcarriers are needed for information decoding to satisfy the fixed target transmission rate. Therefore, less power and fewer subcarriers will be left for energy harvesting.

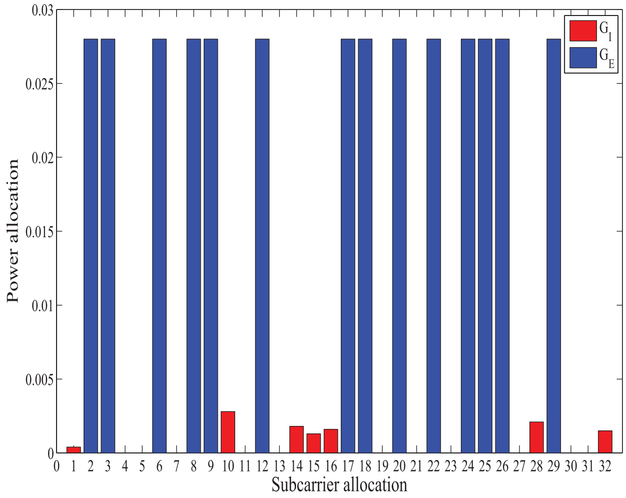

FIGURE 7. Power and subcarrier allocation in first transmission slot when $R_T = 4bps/Hz$.

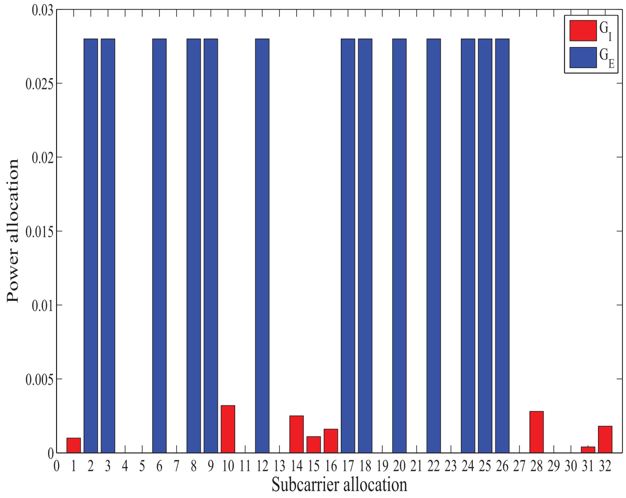

FIGURE 8. Power and subcarrier allocation in first transmission slot when $R_T = 5bps/Hz$.

The proposed joint subcarrier and power allocation with different target transmission rates are shown in Fig. 7 and Fig. 8 when $d_1 = 0.5m$ and $P = 0.5W$. We can observe that a large portion of the power and subcarriers are allocated to harvest energy. This is because the target transmission rates are small, only a few power and subcarriers are required to decode the information. Comparing with Fig. 7 and Fig. 8, we can find that when the target transmission rates becomes larger, more power and more subcarriers are needed needed for information decoding to satisfy the larger target transmission rate.

V. CONCLUSION

In this paper, we propose a joint subcarrier and power allocation based SWIPT scheme in OFDM systems, in which no time or power splitter is needed at the receiver. Specifically, the received OFDM subcarriers are partitioned into two groups. A group of the received subcarriers are used for information decoding, and the remaining subcarriers are grouped to form the other group which is used for energy harvesting. The receiver only needs to know which group is allocated for information decoding, then the other group is allocated for energy harvesting. Therefore, no splitter is needed any more at the receiver. Joint subcarrier and power allocation is investigated to maximize the harvested energy subject to the information detection constraint.

APPENDIX

Let $\boldsymbol{x}$ and $\boldsymbol{y}$ be the optimal solutions to the joint optimization problem with rate constraints R_{Tx} and R_{Ty}, respectively. For any $0 \leq \nu \leq 1$, there always exists a feasible solution $\boldsymbol{z}$, such that $R_{Tz} \geq \nu R_{Tx} + (1-\nu)R_{Ty}$ and $f(\boldsymbol{z}) \geq \nu f(\boldsymbol{x}) + (1-\nu)f(\boldsymbol{y})$, where $f(.)$ is the objective function of the joint optimization problem in (3). Thus our joint optimization problem satisfies the "time-sharing" condition.

To prove the time-sharing property implies zero duality gap, we first need to prove that the objective function of our joint optimization problem is a concave function of R_T. Let R_{Tx}, R_{Ty} and R_{Tz} be the rate constraints with $R_{Tz} \geq \nu R_{Tx} + (1-\nu)R_{Ty}$ for some $0 \leq \nu \leq 1$. Let $\boldsymbol{x}$, $\boldsymbol{y}$ and $\boldsymbol{z'}$ be the optimal solutions to the joint optimization problem with rate constraints R_{Tx}, R_{Ty} and R_{Tz}, respectively. Since $R_{Tz} \geq \nu R_{Tx} + (1-\nu)R_{Ty}$, the time-sharing property implies that there exists a $\boldsymbol{z'}$ such that $R_{Tz'} \geq \nu R_{Tx} + (1-\nu)R_{Ty}$ and $f(\boldsymbol{z'}) \geq \nu f(\boldsymbol{x}) + (1-\nu)f(\boldsymbol{y})$. Since $\boldsymbol{z'}$ is a feasible solution for the optimization problem, this means that $f(\boldsymbol{z}) \geq f(\boldsymbol{z'}) \geq \nu R_{Tx} + (1-\nu)R_{Ty}$, thus proving that our joint optimization problem is a concave function of R_T. Then we can prove that duality gap is zero by using the similar methods used in [29].

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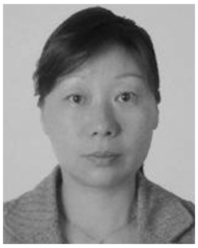

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