OFDM Based SWIPT in a Two-Way Relaying Network

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Abstract. We consider a simultaneous wireless transfer of information and power in a two-way relaying network, a decode-and-forward protocol and OFDM modulation is employed. Subcarriers are divided into a couple of groups, one is for information decoding, and another is for energy harvesting. With total rate maximized, subcarrier grouping optimization is performed. And the power of subcarriers is optimized according to channel state. The performance of the optimal design is performed on different transmit conditions.

Keywords: SWIPT · DF · TWR network · OFDM subcarrier grouping

1 Introduction

Simultaneous wireless transfer of information and power (SWIPT) technology is a frontier direction of the cross-integration of wireless information transmission technology and energy harvesting technology, aiming to realize the parallel transmission of energy and information. Consequently, receiver requires information processing and energy harvesting. The splitting is achieved by time switching (TS) and power splitting (PS) as been put forward in [1, 2]. With multiple receiving antennas, antenna selection (AS) also has been proposed [1].

In addition, cooperation and relaying has been identified as an efficient solution for lengthening the distance of transmission as well as increasing stability in wireless communications [3, 4]. Combined with SWIPT, relay node could collect the energy in the RF signal sent by the source node for information collaboration, instead of consuming its own energy. There are various forms, for example, the OWR [5, 6] and TWR protocols [7, 8]. Amplify-and-Forward (AF) or Decode-and-forward (DF) relay is also an option [9].

In this paper, we address the SWIPT in a two-phase wireless network, where a relay decodes and forwarding the signals of two sources with the energy powered from them. Noting that the relay in the first phase existing interference caused by two sources using the same bandwidth to send information simultaneously. Therefore, we use interference elimination and OFDM modulation method. As a kind of mature modulation technique, OFDM technology can resist inter-symbol interference caused by channel selective fading and can flexibly allocate subcarriers and control transmission power on

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subcarriers. And we assumed the relay node knows the subcarrier grouping condition of source node when receives information and energy, so that the relay does not need a splitter as PS protocol.

The rest of this paper is organized as follows. In Sect. 2, we introduce the system model. The problem formulation and optimal solution is depicted in Sects. 3 and 4, respectively. In Sect. 5, simulation results are proposed to illustrate the performance of the proposed OFDM based SWIPT scheme and subcarrier grouping allocation algorithm. Finally, we draw the conclusion of this paper in Sect. 6.

2 System Model

Relaying network system model can be seen in Fig. 1, which consists of two source nodes S1, S2, and one relay node R. The signal is OFDM modulated over K subcarriers.

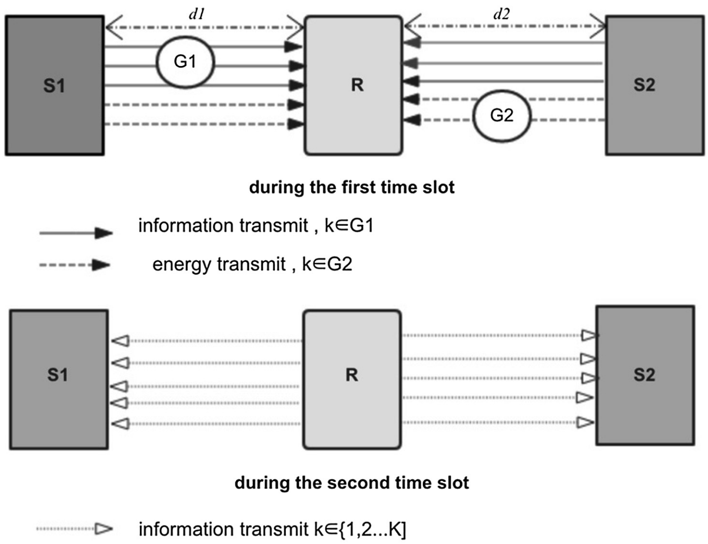

Fig. 1. System model

In our model, a completed transmission is composed of two time slots. During the first time slot, both source nodes transmit its signal $x_{1,k}, x_{2,k}$ over all the subcarriers. We use k $\in \{1, \ldots, K\}$ to denote the subcarriers. And $h_{1,k}$ and $h_{2,k}$ are the channel coefficient of the S1 $\rightarrow$ R link and S2 $\rightarrow$ R link, respectively. The received signal on subcarrier k at R is corrupted by noise $n_{R,k}$, which are complex Gaussian random variables, denoted by $n_{R,k} \sim CN(0, \sigma_k^2)$. The total transmit power of S1 is denoted as p_{s1}, and so is p_{s2}. The signal at DF relay can be given as:

$$y_{R,k} = h_{1,k}\sqrt{p_{s1,k}}x_{1,k} + h_{2,k}\sqrt{p_{s2,k}}x_{2,k} + n_{R,k} \tag{1}$$

The received signal is separated into a couple of groups depending on different subcarriers, information decoding group G1 and energy harvesting group G2, respectively. Where $G1 \in K$, $G2 \in K$ and $G1 \cup G2 = K$. When R uses the subcarriers in G1 to decode information, there exits interference for R receives the signal come from S1 and S2 simultaneously. To reduce the interference, when $p^I_{s1,k}\gamma_{1,k} > p^I_{s2,k}\gamma_{2,k}$, $x_{1,k}$ will be decoded priority, meanwhile, $x_{2,k}$ will be regarded as noise. $x_{2,k}$ will be decoded later, we define $\gamma_{1,k} = \frac{|h_{1,k}|^2}{\sigma_k^2}$, $\gamma_{2,k} = \frac{|h_{2,k}|^2}{\sigma_k^2}$. For simplicity, the condition $p^I_{s1,k}\gamma_{1,k} > p^I_{s2,k}\gamma_{2,k}$ could be defined as $G11$, and the condition $p^I_{s1,k}\gamma_{1,k} < p^I_{s2,k}\gamma_{2,k}$ could be defined as G12, $G11 \cup G12 = G1$. Therefore, achievable rate on every subcarrier k can be expressed as

$$R_{s1R,k}\begin{cases} \frac{1}{2}\ln\left(1 + \frac{p^I_{s1,k}\gamma_{1,k}}{1 + p^I_{s2k}\gamma_{2,k}}\right), k \in G11 \\ \frac{1}{2}\ln\left(1 + p^I_{s1,k}\gamma_{1,k}\right), k \in G12 \end{cases} \tag{2}$$

$$R_{s2R,k} = \begin{cases} \frac{1}{2}\ln\left(1 + p^I_{s2,k}\gamma_{2,k}\right), k \in G11 \\ \frac{1}{2}\ln\left(1 + \frac{p^I_{s2,k}\gamma_{2,k}}{1 + p^I_{s1,k}\gamma_{1,k}}\right), k \in G12 \end{cases} \tag{3}$$

Sum achievable rate in the first phase:

$$R_{s1R} = \sum_{k\in G1} R_{s1R,k} = \sum_{k\in G11}\frac{1}{2}\ln\left(1 + \frac{p^I_{s1,k}\gamma_{1,k}}{1 + p^I_{s2,k}\gamma_{2,k}}\right) + \sum_{k\in G12}\frac{1}{2}\ln\left(1 + p^I_{s1,k}\gamma_{1,k}\right) \tag{4}$$

$$R_{s2R} = \sum_{k\in G1} R_{s2R,k} = \sum_{k\in G11}\frac{1}{2}\ln\left(1 + \frac{p^I_{s2,k}\gamma_{2,k}}{1 + p^I_{s1,k}\gamma_{1,k}}\right) + \sum_{k\in G12}\frac{1}{2}\ln\left(1 + p^I_{s2,k}\gamma_{2,k}\right) \tag{5}$$

And energy harvested at relay R can be given as

$$Q = \sum_{k\in G2} Q_k = \sum_{k\in G_2} \zeta(p^E_{s1,k}|h_{1,k}|^2 + p^E_{s2,k}|h_{2,k}|^2 + \sigma_k^2) \tag{6}$$

ζ denotes the energy conversion efficiency at Relay R.

During the second time slot, R uses all the subcarriers $k' \in \{1, \ldots, \mathrm{K}\}$ to forward signal, which is also called broadcast phase. Similarly, $h_{1,k'}$ and $h_{2,k'}$ are the channel coefficient of the link R $\rightarrow$ S1, R $\rightarrow$ S2 over subcarriers k', $p_{r,k'}$ representing the transmit power of R on subcarrier k$'$. Therefore, sum achievable rate here can be seen as (7) and (8). It is worth noting that both the source node could decode the signal from the other source node since it could identify its own signal.

$$R_{Rs1} = \sum_{k'=1}^{K} \frac{1}{2} \ln\left(1 + p_{r,k'}\gamma_{1,k'}\right) \tag{7}$$

$$R_{Rs2} = \sum_{k'=1}^{K} \frac{1}{2} \ln\left(1 + p_{r,k'}\gamma_{2,k'}\right) \tag{8}$$

Through two time slots of transmission, the transmission rate of S1 to S2 through relay R can be expressed as R_{s1}, whose value is determined by the smaller value of R_{s1R}, R_{Rs2} in DF relay network. Corresponding, R_{s2} representing the transmission rate of S2 to S1. And *Rs* representing the system total rate, as the following formula

$$R_{s1} = \min(R_{s1R}, R_{Rs2}) \tag{9}$$

$$R_{s2} = \min(R_{s2R}, R_{Rs1}) \tag{10}$$

$$Rs = R_{s1} + R_{s2} \tag{11}$$

3 Problem Formulation

In this article, our target is to maximize the system total transmission rate. Power allocation in the first time slot is determined by water-filling algorithm with minimum power limit, whose value is p_{min}, and $p_{r,k'}$ in the second time slot uses average power allocation as (14), which satisfies the energy constrain in relay node R.

$$p_{s1,k} = \max\{p_{min}, \frac{1}{\beta_1} - \frac{1}{\gamma_{1,k}}\}, k \in \{1, 2, \ldots K\} \tag{12}$$

$$p_{s2,k} = \max\{p_{min}, \frac{1}{\beta_2} - \frac{1}{\gamma_{2,k}}\}, k \in \{1, 2, \ldots K\} \tag{13}$$

$$\mathrm{p_{r,k'}} = \frac{1}{\mathrm{K}}\mathrm{Q} \tag{14}$$

β_1, β_2 meet the power constraints $\sum_{k=1}^{K} p_{s1,k} = P_s$, $\sum_{k=1}^{K} p_{s2,k} = P_s$, respectively. The problem can be transferred into determining subcarrier grouping, and can be formulated as

$$Max \;\; Rs = R_{s1} + R_{s2} \tag{15}$$

$$s.t. Q \geq \sum_{k'=1}^{K} p_{r,k'} \tag{16}$$

4 Optimal Solution

The optimization problem in (15–16) is a non-convex problem, using exhaustive search would be rather difficult. We assumed that the "time-sharing" condition [10] is meet, which will be always satisfied when the number of subcarriers is larger. In our scenario, the dual decomposition method can be used to solve the problem in (15–16) using the following two steps.

Step 1: Constructing a Lagrangian function

$$min(\alpha)g(\alpha) = max\, L(G1, G2) \tag{17}$$

While

$$g(\alpha) = g(\alpha_1, \alpha_{11}, \alpha_2, \alpha_{21}, \alpha_3) = \alpha_1(R_{s1R} - R_{s1}) + \alpha_{11}(R_{Rs2} - R_{s1}) + R_{s1} + \alpha_2(R_{s2R} - R_{s2}) + \alpha_{21}(R_{Rs1} - R_{s2}) + R_{s2} + \alpha_3\left(Q - \sum_{k'=1}^{K} p_{r,k'}\right) \tag{18}$$

$\alpha = \{\alpha_1, \alpha_{11}, \alpha_2, \alpha_{21}\}$ are binary parameters, $\alpha \in \{0, 1\}$, satisfying $\alpha_{11} + \alpha_1 = 1$, $\alpha_{21} + \alpha_2 = 1$. If $R_{s1R} > R_{Rs2}$, $R_{s1} = R_{Rs2}$, α_1 is supposed to be 0, and α_{11} is supposed to be 1. In order to get the optimal value, we relax $\alpha_1, \alpha_{11}, \alpha_2, \alpha_{21}$ to be real values in the interval [0, 1], instead of binary. Substituting it into (18), the dual function can be rewritten as (19)

$$g(\alpha_1, \alpha_2, \alpha_3) = \alpha_1 R_{s1R} + (1 - \alpha_1)R_{Rs2} + \alpha_2 R_{s2R} + (1 - \alpha_2)R_{Rs1} + \alpha_3\left(Q - \sum_{k'=1}^{K} p_{r,k'}\right) \tag{19}$$

Using the sub-gradient based methods. The sub-gradient can be easily given as:

$$\triangle\alpha_1 = R_{s1R} - R_{Rs2} \tag{20}$$

$$\triangle\alpha_2 = R_{s2R} - R_{Rs2} \tag{21}$$

α_1, α_2, is updated by $\alpha^{t+1} = \alpha^t - \xi^t \triangle\alpha$, ξ^t is the step size satisfying the diminishing policy [11]. Thus, the optimal dual variable of convergence can be obtained. And α_3 is nearly equal constrain, so its value could be adjusted first.

Step 2: Assumed that we had already know $\{p^*_{s1,k}, p^*_{s2,k}, p^*_{r,k'}\}$. Substituting (12)–(14) into (19), and having mathematic transformation, we can rewrite the formula as (22). And only the first part on the right side, F_k, involves $G1$. Therefore, the optimal subcarrier group for information decoding $G1$ can be obtained by (24), finding all the $k \in \{1, \ldots, K\}$ makes F_k positive.

$$g(\alpha_1,\alpha_2,\alpha_3) = \sum_{k\in G1} F_k^* + (1-\alpha_1)R_{Rs2}^* + (1-\alpha_2)R_{Rs1}^* + \alpha_3(\sum_{k=1}^{K} Q_k^* - \sum_{k'=1}^{K} p_{r,k'}^*) \quad (22)$$

Where

$$F_k^* = \alpha_1 R_{s1R,k} + \alpha_2 R_{s2R,k}^* - \alpha_3 Q_k^* \quad (23)$$

$$G_1^* = \arg\max F_k^* \quad (24)$$

$$G_2^* = \mathrm{K} - G_1^* \quad (25)$$

5 Simulation Results

In our article, we set the distance between two sources nodes to be 4 m. Relay R locates between S1 and S2, and the distance between R and S1 is represented as d1, as can be seen in Fig. 1. Both the total power of S1 and S2 is represented as Ps. The number of subcarriers K is 32. The harvesting conversion efficiency is set to be 1.

The channel is as Rice fading, and line-of-sight signal plays a primary role in this simulation. Channel coefficient h_k could be depicted as (26). Where $\mathrm{g1}(k)$ and $\mathrm{g2}(k)$ denotes LOS deterministic component and the Rayleigh fading, respectively, and M is the Rice factor set to be 3.

$$\mathrm{h}_k = \sqrt{\frac{M}{M+1}}\mathrm{g1}(k) + \sqrt{\frac{1}{M+1}}\mathrm{g2}(k) \quad (26)$$

$$|\mathrm{g1}|^2 = -40\mathrm{dB} \quad (27)$$

$$g2(k) \in CN(0, d^{(-v)}) \quad (28)$$

v is the path-loss index, which is set to be 2, and the variance of noise is set to be-50 dBm.

Figures 2 and 3 show the power allocation of source nodes S1 and S2, respectively, when Ps = 2 w, p_{min} = 0.02 w, and d1 = 1.5 m. As can be seen, subcarrier index number 7 is allocated as energy transmission, and the other subcarriers are used for information decoding. Due to the interference cancellation technique, one side will inevitably have a relatively poor SINR. Therefore, the total rate in this paper does not require the minimum decoding SINR, and the results show that the number of subcarriers used for energy is not very large.

Figure 4 shows the total rate versus relay location d1 when Ps = 2 w and 4 w. The curve is approximately axisymmetric with d1 = 2 m. The total rate reaches the lowest value when d1 is 2 m, when R is exactly at the middle of S1 and S2. When d1 is 2 m,

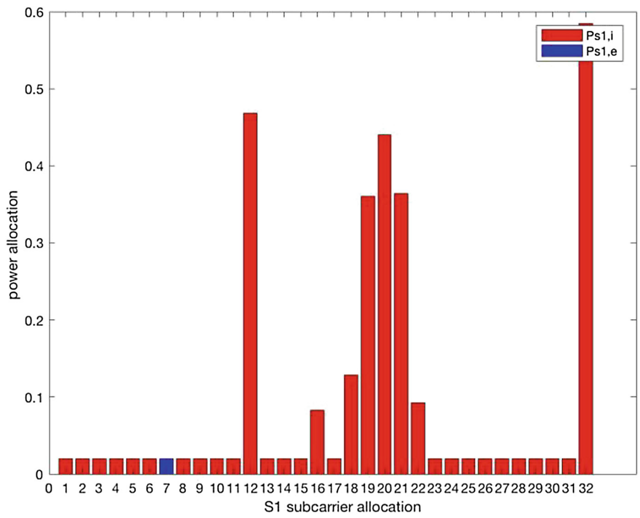

Fig. 2. Power allocation of S1

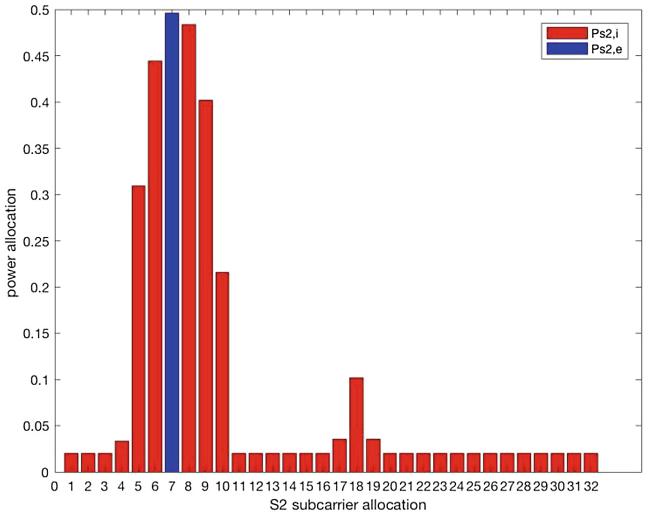

Fig. 3. Power allocation of S2

the two channels are similar, which is not conducive to interference cancellation. We can see that the relay location has a clear influence on the total rate.

When the transmission power becomes larger, the total rate increases, as can be seen in Fig. 5. While d1 is set as 1.3 m and 2.0 m, respectively. Both curves show an upward trend and conform to the law of Fig. 4.

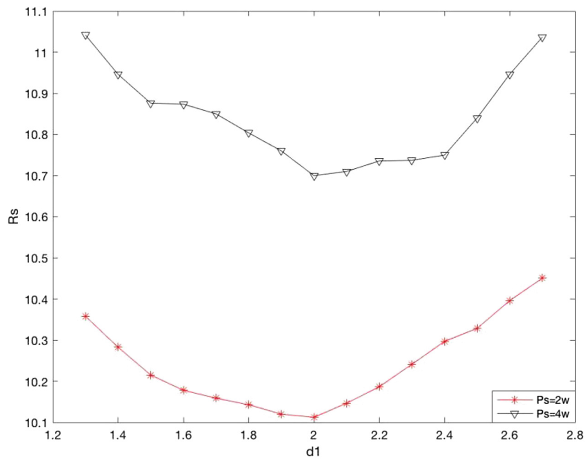

Fig. 4. Total rate versus relay location d1

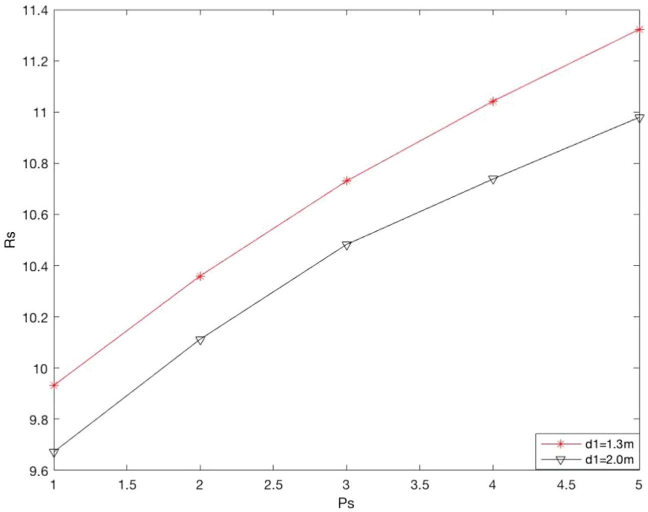

Fig. 5. Total rate versus transmit power.

6 Conclusions

In this paper, we proposed a collaborative energy and information transfer protocol for two-way DF relay network. Explicitly, the received subcarriers at R in the first time slot are divided into a couple of groups, one is for information decoding and another is for energy harvesting. Then relay R uses all the subcarriers to broadcast signal, helping achieving the information transmission of the two sources. Subcarrier grouping is optimized to maximize the total rate.

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