



Half-Duplex Two-Way AF Relaying Network with Energy Harvesting

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Abstract. In this paper, we consider a three-node, half-duplex two-way relaying wireless network where an amplify-and-forward relay harvests energy from radio frequency wave transmitted by the two source nodes. Different from time switching (TS) and power splitting (PS), we group subcarriers to realize the information decoding (ID) and energy harvesting (EH) separately. This two-way relaying transmission is consisted of two phases, which is more efficiency and complicated than one-way relaying. System is orthogonal frequency division multiplexing modulated, and subcarrier grouping scheme is the same for the two source nodes. Subcarrier power of source nodes is average allocated, while that of relay is optimized. In this amplify-and-forward relaying network, subcarrier pairing is also under consideration. With the aim of sum rate maximized, we purpose a joint subcarrier grouping, relay subcarrier pairing and power allocation scheme. We use dual decomposition method to solve this problem, after transforming it into an equivalent convex optimization problem. Simulation results also show the impact of the relay location on subcarrier grouping and on sum rate.

Keywords: TWR network · Energy harvesting · Subcarrier grouping

1 Introduction

Nowadays, simultaneous wireless information and power transfer (SWIPT) has attracted significant research interests, which could harvest energy from radio frequency (RF) signals, since RF signals could also be considered as a kind of energy. Compared with other nature resources, RF signals are more stable and reliable, providing a potential method to prolong lifetime of wireless devices and having high potential especially in wireless communication area [1, 2].

In general, there are two practical schemes in SWIPT, one is time switching (TS) and the other is power splitting (PS) [3, 4]. In the TS scheme, the receiver

switches between information decoding (ID) and energy harvesting (EH). As for PS scheme, the receiver splits the received signal into two signal streams by a power splitter, then processes ID and EH respectively. Combine relaying protocols with SWIPT, many works have done on various forms relaying networks, in Amplify-and-Forward (AF) or Decode-and-Forward (DF) relay, in one-way relay (OWR) [5–7] or two-way relay (TWR) [3, 8, 9] protocols. [5] proposed TS based SWIPT in AF and DF relaying one-way cooperative communications, analyzed achievable throughput. In [7] PS and TS transmission protocols are compared in one-way AF relaying networks, the TSR (time switching relaying) protocol outperforms the PSR (power splitting relaying) protocol in terms of throughput at low signal-to-noise-ratios and high transmission rates. [4] introduced optimal PS in two-way DF relay networks. Optimal power allocated is derived to achieve the maximum achievable sum rate, and performance is compared with that of AF relay protocols.

In this paper, we address OFDM based half-duplex two-way AF relaying network with energy harvesting. Instead of PS and TS scheme, we adopt OFDM modulation method, where subcarriers are divided into two groups to achieve information decoding and energy harvesting separately. We assume that source nodes are stable power supplied, while relay node is powered by the energy harvested from the RF signal of the source nodes.

2 System Model

Our model is consisted of two source nodes S1, S2, and one AF relay node R. A completed transmission is composed of two equal length phases. During the first phase, source nodes S1 and S2, transmit its signal $x_{1,k}$, $x_{2,k}$ to relay over subcarrier k . $h_{1,k}$ and $h_{2,k}$ denote the channel coefficient of the S1 → R link and S2 → R link over subcarrier k . Direct link is not taken into consideration here due to the bad channel state. We assumed that noise at each node is complex Gaussian random variables, subject to $CN(0, \sigma_k^2)$. The received signal at relay can be given as

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

According to the subcarrier ordinal, signals are divided into 2 groups, G_1 and G_2 . Where $G_1 + G_2 = K$. Specifically, signals with subcarrier numbers belonging to G_1 are used for information decoding, and with that belonging to G_2 are used for energy harvesting. Therefore, energy harvested at relay can be given as

$$Q = \sum_{k \in G_2} \zeta (p_{s1,k}^E |h_{1,k}|^2 + p_{s2,k}^E |h_{2,k}|^2 + \sigma_k^2) \tag{2}$$

ζ represents the conversion efficiency of energy harvesting.

In the second phase, the relay amplifies and forwards the information using the energy Q after pairing the subcarriers in G_1 . $\rho_{k,k'}$ represents the indicator of subcarrier pairing. $\rho_{k,k'} = 1$ represents that subcarrier ordinal k in the first phase is paired with

subcarrier ordinal k' in the second phase. It should be noted that one subcarrier could only be paired with one subcarrier in the second phase, that is $\sum_{k'=1}^K \rho_{k,k'} = 1, \forall k$. $h_{3,k'}$ and $h_{4,k'}$ denote the channel coefficient of the $R \rightarrow S1$ link and $R \rightarrow S2$ link over subcarrier k' in the second phase. And $\beta_{k,k'}$ is the amplification factor, satisfying:

$$\beta_{k,k'}^2 = \frac{p_{r,k'}}{p_{s1,k}' |h_{1,k}|^2 + p_{s2,k}' |h_{2,k}|^2 + \sigma_k^2} \tag{3}$$

The signal-to-noise ratio at node S_i is expressed as $SNR_{k,k'}^i$, devoted as

$$SNR_{k,k'}^1 = \frac{\beta_{k,k'}^2 |h_{3,k'}|^2 |h_{2,k}|^2 p_{s2,k}'}{\left(\beta_{k,k'}^2 |h_{3,k'}|^2 + 1\right) \sigma_k^2} \tag{4}$$

$$SNR_{k,k'}^2 = \frac{\beta_{k,k'}^2 |h_{4,k'}|^2 |h_{1,k}|^2 p_{s1,k}'}{\left(\beta_{k,k'}^2 |h_{4,k'}|^2 + 1\right) \sigma_k^2} \tag{5}$$

Thus, information rate of the two opposite links can be described as

$$R_{s1} = \sum_{k \in G_1} \sum_{k'=1}^K \rho_{k,k'} \frac{1}{2} \ln(1 + SNR_{k,k'}^1) \tag{6}$$

$$R_{s2} = \sum_{k \in G_1} \sum_{k'=1}^K \rho_{k,k'} \frac{1}{2} \ln(1 + SNR_{k,k'}^2) \tag{7}$$

Total transmission rate R_s can be given as

$$R_s = R_{s1} + R_{s2} \tag{8}$$

3 Problem Formulation and Optimal Solution

Our target is to maximize the total transmission rate by jointly determining the subcarrier grouping $\mathcal{G} = \{G_1, G_2\}$, relay subcarrier power $p = \{p_{r,k'}\}$ and subcarrier pairing $\rho = \{\rho_{k,k'}\}$ with energy constraints. Subcarriers' power of source node here is average allocated. The problem can be formulated as

$$\max_{\{\mathcal{G}, \mathcal{P}, \rho\}} R_s \tag{9}$$

subject to

$$\begin{cases} \sum_{k \in G_1} \sum_{k'=1}^K \rho_{k,k'} P_{r,k'} \leq Q \\ \rho_{k,k'} \in \{0, 1\} \\ \sum_{k'=1}^K \rho_{k,k'} = 1, \forall k \end{cases}$$

The optimization problem in (9) is a mixed integer non-convex problem. If the “time-sharing” condition [10] is satisfied, which will be always satisfied when the number of subcarriers is larger, the duality gap of the nonconvex optimization problem is zero.

By constructing a Lagrangian function

$$g(\alpha) = \max_{\{\mathcal{G}, \mathcal{P}, \rho\}} L(\mathcal{G}, \mathcal{P}, \rho) \tag{10}$$

where

$$L(\mathcal{G}, \mathcal{P}, \rho) = R_s + \alpha(Q - \sum_{k \in G_1} \sum_{k'=1}^K \rho_{k,k'} P_{r,k'}) \tag{11}$$

And α denotes non-negative Lagrange multiplier subject to power constraints. The dual optimization problem can be expressed as

$$\min_{\alpha} g(\alpha) \tag{12}$$

The minimization problem can be solved by using the sub-gradient based methods. The sub-gradient can be given as

$$\alpha = (Q - \sum_{k \in G_1} \sum_{k'=1}^K \rho_{k,k'} P_{r,k'}) \tag{13}$$

α is updated by $\alpha^{t+1} = \alpha^t - \zeta^t \alpha$, ζ^t is the step size. And the optimal variables can be obtained with the following two steps.

Step 1: assume we had already know \mathcal{G} , ρ , deriving the optimal \mathcal{P} .

The partial derivatives of the Lagrangian in (11) with respect to the optimization variables $p_{r,k'}$ is show as

$$\begin{aligned} \frac{\partial L}{\partial p_{r,k'}} = & -\alpha + \frac{1}{2} \frac{p_{s2,k}^I \gamma_{2,k} \gamma_{3,k'} (p_{s1,k}^I \gamma_{1,k} + p_{s2,k}^I \gamma_{2,k} + 1)}{(p_{s1,k}^I \gamma_{1,k} + p_{s2,k}^I \gamma_{2,k} + p_{r,k'} \gamma_{3,k'} + 1)(p_{s1,k}^I \gamma_{1,k} + p_{s2,k}^I \gamma_{2,k} + p_{r,k'} \gamma_{3,k'} + p_{s2,k}^I \gamma_{2,k} p_{r,k'} \gamma_{3,k'} + 1)} \\ & + \frac{1}{2} \frac{p_{s1,k}^I \gamma_{1,k} \gamma_{4,k'} (p_{s1,k}^I \gamma_{1,k} + p_{s2,k}^I \gamma_{2,k} + 1)}{(p_{s1,k}^I \gamma_{1,k} + p_{s2,k}^I \gamma_{2,k} + p_{r,k'} \gamma_{4,k'} + 1)(p_{s1,k}^I \gamma_{1,k} + p_{s2,k}^I \gamma_{2,k} + p_{r,k'} \gamma_{4,k'} + p_{s1,k}^I \gamma_{1,k} p_{r,k'} \gamma_{4,k'} + 1)} \end{aligned} \quad (14)$$

where $\gamma_{1,k} = \frac{|h_{1,k}|^2}{\sigma_k^2}$, $\gamma_{2,k} = \frac{|h_{2,k}|^2}{\sigma_k^2}$, $\gamma_{3,k'} = \frac{|h_{3,k'}|^2}{\sigma_k^2}$, $\gamma_{4,k'} = \frac{|h_{4,k'}|^2}{\sigma_k^2}$. Due to KKT condition, the partial derivative of the Lagrange function is equal to zero at the optimal solution, $\mathcal{P}^* = \{p_{r,k'}^*\}$ is the positive solution of quartic Eq. (15)

$$a_4 p_{r,k'}^4 + a_3 p_{r,k'}^3 + a_2 p_{r,k'}^2 + a_1 p_{r,k'} + a_0 = 0 \quad (15)$$

Where

$$\begin{aligned} a_4 &= \frac{2\alpha}{X(k)} \left(1 + p_{s1,k}^I \gamma_{1,k}\right) \left(1 + p_{s2,k}^I \gamma_{2,k}\right) \gamma_{3,k'}^2 \gamma_{4,k'}^2 \\ a_3 &= 2\alpha \gamma_{3,k'} \gamma_{4,k'} \left(\left(1 + p_{s1,k}^I \gamma_{1,k}\right) \left(2 + p_{s2,k}^I \gamma_{2,k}\right) \gamma_{4,k'} + \left(2 + p_{s1,k}^I \gamma_{1,k}\right) \left(1 + p_{s2,k}^I \gamma_{2,k}\right) \gamma_{3,k'}\right) \\ a_2 &= \left(2\alpha X(k) - p_{s2,k}^I \gamma_{2,k} \gamma_{3,k'}\right) \left(1 + p_{s1,k}^I \gamma_{1,k}\right) \gamma_{4,k'}^2 \\ &\quad + \left(2\alpha X(k) - p_{s1,k}^I \gamma_{1,k} \gamma_{4,k'}\right) \left(1 + p_{s2,k}^I \gamma_{2,k}\right) \gamma_{3,k'}^2 \\ &\quad + 2\alpha \left(4 + p_{s1,k}^I \gamma_{1,k} p_{s2,k}^I \gamma_{2,k} + 2p_{s1,k}^I \gamma_{1,k} + 2p_{s2,k}^I \gamma_{2,k}\right) X(k) \gamma_{3,k'} \gamma_{4,k'} \\ a_1 &= \left(2\alpha X(k) - p_{s2,k}^I \gamma_{2,k} \gamma_{3,k'}\right) \left(2 + p_{s1,k}^I \gamma_{1,k}\right) X(k) \gamma_{4,k'} \\ &\quad + \left(2\alpha X(k) - p_{s1,k}^I \gamma_{1,k} \gamma_{4,k'}\right) \left(2 + p_{s2,k}^I \gamma_{2,k}\right) X(k) \gamma_{3,k'} \\ a_0 &= X(k)^2 \left(2\alpha X(k) - p_{s2,k}^I \gamma_{2,k} \gamma_{3,k'} - p_{s1,k}^I \gamma_{1,k} \gamma_{4,k'}\right) \\ X(k) &= 1 + p_{s1,k}^I \gamma_{1,k} + p_{s2,k}^I \gamma_{2,k} \end{aligned}$$

Step 2: deriving the optimal ρ , \mathcal{G} with \mathcal{P}^* .

Substituting the optimal \mathcal{P}^* into (11), and taking some mathematical operation, formula can be rewritten as (16)

$$\begin{aligned} L = & \sum_{k \in \mathbf{K}} \alpha \zeta (p_{s1,k}^E |h_{1,k}|^2 + p_{s2,k}^E |h_{2,k}|^2 + \sigma_k^2) \\ & + \sum_{k \in \mathbf{G}_1} \left\{ \sum_{k'=1}^K \rho_{k,k'} E_{k,k'} - \alpha \zeta (p_{s1,k}^E |h_{1,k}|^2 + p_{s2,k}^E |h_{2,k}|^2 + \sigma_k^2) \right\} \end{aligned} \quad (16)$$

where

$$E_{k,k'} = \frac{1}{2} \ln(1 + \text{SNR}_{k,k'}^1) + \frac{1}{2} \ln(1 + \text{SNR}_{k,k'}^2) - \alpha p_{r,k'} \tag{17}$$

We can see only $E_{k,k'}$ is related to ρ , therefore, the optimal subcarrier pairing can be obtained by finding the maximum $E_{k,k'}$ in order. After obtaining ρ^* , we denote

$$F_k = \sum_{k'=1}^K \rho_{k,k'} E_{k,k'} - \alpha \zeta (p_{s1,k}^E |h_{1,k}|^2 + p_{s2,k}^E |h_{2,k}|^2 + \sigma_k^2) \tag{18}$$

Then, we can rewrite (16) as

$$L = \sum_{k \in K} \alpha \zeta (p_{s1,k}^E |h_{1,k}|^2 + p_{s2,k}^E |h_{2,k}|^2 + \sigma_k^2) + \sum_{k \in G_1} F_k \tag{19}$$

Similarly, only F_k is related to G_1 , we only need to find all the k 's that make F_k positive. Then, all these k 's form G_1 .

$$G_1^* = \arg \max_{G_1} \sum_{k \in G_1} F_k \tag{20}$$

Finally, the optimal G_2 can be given as $G_2^* = K - G_1^*$. So far, with given dual variable, we have got all the optimal variables. By updating the dual variable, the joint optimization problem can be finally solved.

4 Simulation Results

In this section, we provide simulation results of our algorithm. We set the distance between S1 and S2 to be 5 m and the relay is located on the line connecting the two source nodes. Channel coefficient $h_{i,k} \sim CN(0, d_i^{-\nu})$, where d_i representing the distance between $S_i, i \in (1, 2)$ and relay, and path-loss index ν is set to be 3. For simplicity, we use d_1 , the distance between S1 and relay to represent the position of relay in the following figures. The number of subcarriers K is set to be 32. Energy harvesting conversion efficiency is set to be 1. No otherwise explanation, sum transmission power of each source node is devoted as P_s , which is set to be 1mW, d_1 is 2 m, and variance of noise is set to be -30 dBm.

Figure 1 shows the subcarrier grouping of source node, which is the same for two source nodes in our algorithm. Figure 2 shows the power allocation of relay after subcarrier pairing. Although there is no information about the one-to-one pairing of subcarriers, it can be seen that the pairing of subcarriers is completed. The number of subcarriers used for information, that is, the number of red stripes in the graph is 16, is the same as the number of subcarriers in the relay node.

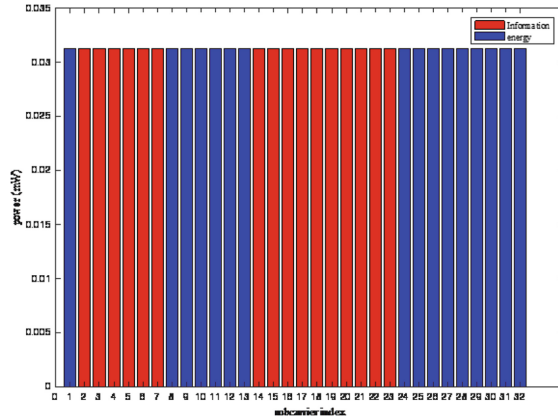


Fig. 1. Power allocation of source nodes (Color figure online)

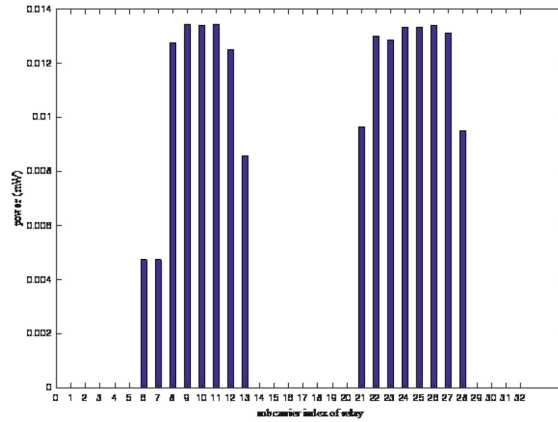


Fig. 2. Power allocation of relay

Figure 3 shows the sum rate versus relay location, when P_s is set to be 1 mW, 1.5 mW and 2 mW, respectively. All the curves descend first and then rise, reach the lowest value when relay is exactly at the middle of S_1 and S_2 . curves are symmetric about $d_1 = 2.5$ m.

Figure 4 shows the harvested energy and the ratio of subcarriers number in G_2 change with d_1 . When relay approaches the central position, more subcarriers can be seen for energy transmission (the orange circle), but the energy collected is still declining, because overall channel condition is not good. It is also consistent with the conclusion in Fig. 3, sum rate reaches the lowest value when d_1 is 2.5 m.

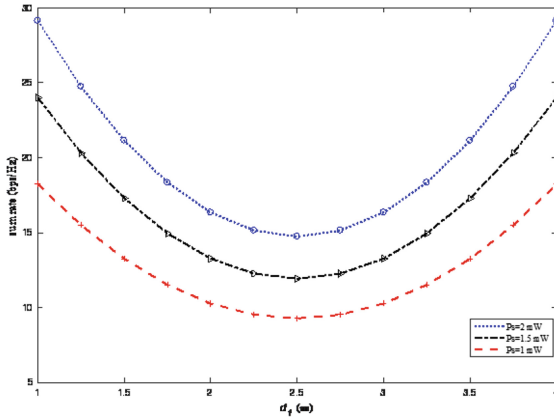


Fig. 3. Sum rate versus d_1

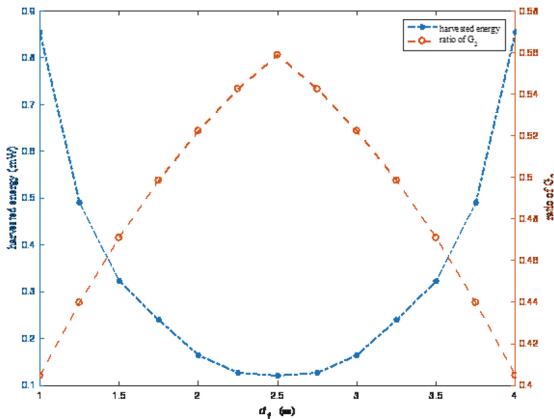


Fig. 4. Harvested energy and the number of subcarriers in G_2 versus d_1 (Color figure online)

5 Conclusion

In this paper, we investigated SWIPT in a two-way AF relaying network, which adopts OFDM technology. Different from TS and PS, the received OFDM subcarriers are partitioned into two groups for information decoding and energy harvesting separately. With the aim of sum rate maximized, we propose a joint subcarrier grouping, subcarrier pairing and power allocation scheme. Our results also demonstrate the impact of relay location on subcarrier grouping and on sum rate.

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