Short Papers

Simultaneous Wireless Information and Power Transfer Based on Time–Frequency Block Allocation in OFDM Cooperative Communication System

Xin Liu , Xueying Liu, Min Jia , Feng Li , and Tariq S. Durrani

Abstract—In this paper, simultaneous wireless information and power transfer based on time–frequency block allocation (TFBA-SWIPT) is proposed to save the energy of an orthogonal frequency-division multiplex (OFDM) decode-and-forward cooperative communication system, by allocating different resource blocks for information decoding and energy harvesting at the relay and destinations. The joint allocation of time–frequency blocks and power is optimized to maximize the transmission rate of the destination, while ensuring the transmission rate and energy supply of the relay. The time–frequency block pairing algorithm and the block power allocation algorithm are integrated to achieve the optimal solution. Simulation results illustrate the benefits of using TFBA-SWIPT in the OFDM cooperative communication system over time-varying channels.

Index Terms—Cooperative communication system, orthogonal frequency-division multiplexing (OFDM), relay, simultaneous wireless information and power transfer based on time–frequency block allocation (TFBA-SWIPT), transmission rate.

I. INTRODUCTION

A cooperative communication system can improve transmission performance by relaying source information to destination. However, due to the forwarding energy consumption, the transmission performance of relay may be decreased. Recently, simultaneous wireless information and power transfer (SWIPT) has been put forward to collect radio frequency (RF) energy of the transmitting signal when decoding its information [1]. To mitigate energy consumption, SWIPT-enabled relay can collect RF energy of the source signal while forwarding.

SWIPT mainly includes time-switching-based SWIPT (TS-SWIPT), power-splitting-based SWIPT (PS-SWIPT), and subcarrier-allocation-based SWIPT (SA-SWIPT). TS-SWIPT and PS-SWIPT use different

time slots and power streams for energy harvesting (EH) and information decoding (ID) [2], respectively. SA-SWIPT allocates different subcarriers for EH and ID [3]. In [4], Xu and Zhu jointly allocated subcarrier, power, and power-splitting (PS) ratio for PS-SWIPT to minimize the interruption probability. In a multiuser orthogonal frequency-division multiplex (OFDM) system, PS-SWIPT and TS-SWIPT were both considered to minimize the interruption probability while constraining EH and total transmit power [5]. In [6], PS-SWIPT-enabled cooperative relay achieved self-energy recycling by collecting energy from the source and itself. In SWIPT-based amplify-and-forward cooperative communications [7], the system outage probability is minimized under the asymmetric instantaneous channel between relay and destination by adjusting the asymmetric PS ratio between EH and ID adaptively. In [8], Huang and Tu maximized the end-to-end rate of the EH-enabled decode-and-forward (DF) cooperative network by optimizing the time-switching ratio. In [9], Chen *et al.* optimized the SWIPT model to maximize the signal-to-noise ratio by updating the PS ratio and transmit power for each link iteratively. In [10], Lu *et al.* jointly optimized the subcarrier and power allocation for SA-SWIPT-based relay to maximize the achievable rate. Traditional SWIPT models allocate resources over constant channels, resulting in possible performance degradation when the channel is time varying.

To improve the performance of SWIPT-based OFDM cooperative communications over time-varying channels, SWIPT based on time–frequency block allocation (TFBA-SWIPT) is investigated. The major contributions of this paper are summarized as follows.

- 1) Compared with the TS-SWIPT [2], [5], [8] and PS-SWIPT [4], [6], [9], which use part of the time and power to transfer energy, the TFBA-SWIPT can use the whole time–frequency block to transfer energy, thus improving the EH performance. Compared with the SA-SWIPT [3], [10], which allocates fixed subcarriers for energy transfer over the whole transmission time, the TFBA-SWIPT allocates different time–frequency blocks to transfer energy according to the channel changes in each phase, which can improve the EH performance over time-varying channels.
- 2) Time–frequency block pairing for the first and second phases is proposed to allocate the optimal block sets for EH and ID, which can better improve the forwarding and harvesting performance of the relay.
- 3) By optimizing the block power allocation, the transmission rate of destination is maximized while guaranteeing the power supply and transmission rate of the relay.

II. SYSTEM MODEL

DF cooperative communication is considered in the system model, which consists of a source node S , a relay node R , a destination node

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Fig. 1. System model.

D_1 , and the relay's destination D_2 , as shown in Fig. 1. D_1 and D_2 are the receivers of S and R , respectively. The OFDM resource is divided into $M = KN$ time-frequency blocks, where K and N represent the numbers of subcarriers and OFDM symbols, respectively. In TFBA-SWIPT, the blocks are allocated for ID and EH. Define the total block set as $\mathcal{M}$ and block (k, n) as the n th symbol on the k th subcarrier. In the first phase, the relay receives source information from block set ω_I and harvests energy from block set ω_E simultaneously. In the second phase, with the harvested energy in the first phase, the relay selects the optimal paired block set ω_S to forward source information to D_1 , while using the remaining block set ω_P to send its own information to D_2 . D_1 uses TFBA-SWIPT to decode information from ω_S and harvest energy from ω_P simultaneously, while D_2 does the opposite.

III. MODEL OPTIMIZATION

A. Optimization Problem

As the time-varying channel for each block can be flat, the channel gain can be constant. Assume that the power for (k, n) in the link $S \rightarrow R$ is $p_{k,n}$, with channel gain as $h_{1,(k,n)}$ and Gaussian noise as $n_{1,(k,n)} \sim CN(0, \sigma_{1,(k,n)}^2)$. In the first phase, the received rate of the relay is expressed as

$$C_R = \frac{1}{2} \sum_{(k,n) \in \omega_I} \log \left(1 + \frac{p_{k,n} h_{1,(k,n)}}{\sigma_{1,(k,n)}^2} \right). \quad (1)$$

The harvested energy of the relay is obtained by

$$E_R = \xi \sum_{(k,n) \in \omega_E} (p_{k,n} h_{1,(k,n)} + \sigma_{1,(k,n)}^2) \quad (2)$$

where ξ is the efficiency of EH.

In the second phase, assume that the power for (k', n') in the links $R \rightarrow D_1$ and $R \rightarrow D_2$ are $p_{k',n'}^{[D_1]}$ and $p_{k',n'}^{[D_2]}$, with the channel gains as $h_{2,(k',n')}$ and $h_{3,(k',n')}$, respectively. The rates of the destination nodes D_1 and D_2 can be described as

$$C_{D_1} = \frac{1}{2} \sum_{(k',n') \in \omega_S} \rho_{[k,n]}^{[k',n']} \log \left(1 + \frac{p_{k',n'}^{[D_1]} h_{2,(k',n')}}{\sigma_{2,(k',n')}^2} \right) \quad (3)$$

$$C_{D_2} = \frac{1}{2} \sum_{(k',n') \in \omega_P} (1 - \rho_{[k,n]}^{[k',n']}) \log \left(1 + \frac{p_{k',n'}^{[D_2]} h_{3,(k',n')}}{\sigma_{3,(k',n')}^2} \right) \quad (4)$$

where $\rho_{[k,n]}^{[k',n']}$ represents the block pairing indicator. Here, $\rho_{[k,n]}^{[k',n]} = 1$ indicates that the information from block (k, n) in the first phase is forwarded through the block (k', n') in the second phase. If (k, n) does not pair with (k', n') , $\rho_{[k,n]}^{[k',n]} = 0$. The power harvested by D_1 and D_2

are, respectively, given by

$$E_{D_1} = \sum_{(k',n') \in \omega_P} (p_{k',n'}^{[D_1]} h_{2,(k',n')} + \sigma_{2,(k',n')}^2) \quad (5)$$

$$E_{D_2} = \sum_{(k',n') \in \omega_S} (p_{k',n'}^{[D_2]} h_{3,(k',n')} + \sigma_{3,(k',n')}^2). \quad (6)$$

We jointly optimize power allocations $\mathbf{p}_1 = \{p_{k,n}\}$, $\mathbf{p}_2 = \{p_{k',n'}^{[D_1]}, p_{k',n'}^{[D_2]}\}$ and block sets $\omega = \{\omega_I, \omega_E, \omega_S, \omega_P\}$ and $\rho = \{\rho_{[k,n]}^{[k',n']}\}$ to maximize the transmission rate of D_1 under the constraint of the total power for the source, the energy supply and transmission rate for the relay, and the energy supply for the destinations. The optimization problem can be reformulated as

$$\begin{aligned} \max_{(\omega, \mathbf{p}_1, \mathbf{p}_2, \rho)} C_1 &= \min(C_R, C_{D_1}) \\ \text{s.t. (a)} &\sum_{(k,n) \in \omega_I} p_{k,n} + \sum_{(k,n) \in \omega_E} p_{k,n} \leq P \\ \text{(b)} &E_R \geq E_b + \sum_{(k',n') \in \omega_S} \rho_{k,n}^{[k',n']} p_{k',n'}^{[D_1]} + \sum_{(k',n') \in \omega_P} (1 - \rho_{k,n}^{[k',n']}) p_{k',n'}^{[D_2]} \\ \text{(c)} &C_{D_2} \geq C_2; \text{(d)} E_{D_1} \geq E_b; \text{(e)} E_{D_2} \geq E_b \end{aligned} \quad (7)$$

where P is the total transmitting power for the source, E_b represents the power consumption for circuit decoding, and C_2 represents the target transmission rate of D_2 ; (a) is the maximum power constraint, (b) is the power supply constraint for relay, (c) is the minimum rate constraint for relay; and (d) and (e) are power supply constraints for circuit decoding.

B. Optimal Solution

The above nonconvex optimization problem can be solved by the Lagrangian dual method under the premise of sufficient blocks. The Lagrange dual function for (7) is given by

$$g(\beta) = \max_{(\omega, \mathbf{p}_1, \mathbf{p}_2, \rho)} L(\omega, \mathbf{p}, \rho, \beta) \quad (8)$$

where $\mathbf{p} = \{\mathbf{p}_1, \mathbf{p}_2\}$ and

$$\begin{aligned} L(\omega, \mathbf{p}, \rho, \beta) &= C_1 + \beta_1 \left(P - \sum_{(k,n) \in \omega_I} p_{k,n} - \sum_{(k,n) \in \omega_E} p_{k,n} \right) \\ &+ \beta_2 (C_R - C_1) + \beta_3 (C_{D_1} - C_1) + \beta_4 (C_{D_2} - C_2) \\ &+ \beta_5 \left(E_R - E_b - \sum_{(k',n') \in \omega_S} \rho_{[k,n]}^{[k',n']} p_{k',n'}^{[D_1]} - \sum_{(k',n') \in \omega_P} (1 - \rho_{[k,n]}^{[k',n']}) p_{k',n'}^{[D_2]} \right) \\ &+ \beta_6 (E_{D_1} - E_b) + \beta_7 (E_{D_2} - E_b) \end{aligned} \quad (9)$$

where $\beta = (\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6) > 0$ are the dual variables, which can be calculated using the subgradient method. The subgradient of β is obtained by

$$\begin{aligned} \Delta \beta_1 &= P - \sum_{(k,n) \in \omega_I} p_{k,n} - \sum_{(k,n) \in \omega_E} p_{k,n} \\ \Delta \beta_2 &= C_R - C_1; \Delta \beta_3 = C_{D_1} - C_1; \Delta \beta_4 = C_{D_2} - C_2 \\ \Delta \beta_5 &= E_R - E_b - \sum_{(k',n') \in \omega_S} \rho_{[k,n]}^{[k',n']} p_{k',n'}^{[D_1]} - \sum_{(k',n') \in \omega_P} (1 - \rho_{[k,n]}^{[k',n']}) p_{k',n'}^{[D_2]} \\ \Delta \beta_6 &= E_{D_1} - E_b; \Delta \beta_7 = E_{D_2} - E_b. \end{aligned} \quad (10)$$

Letting $\Delta\beta = (\Delta\beta_1, \Delta\beta_2, \Delta\beta_3, \Delta\beta_4, \Delta\beta_5, \Delta\beta_6)$, the subgradient method is described as $\beta^{t+1} = \beta^t + v^t \Delta\beta$, where t is the iteration index and v^t is the step size. By setting v^t reasonably, the solution by the subgradient can converge to the optimal β^* . After obtaining β^* , the optimal block set ω and power $\mathbf{p}_1, \mathbf{p}_2$ can be obtained via the following three steps.

1) *Optimizing $\mathbf{p}_1$ and $\mathbf{p}_2$ With Given ω and ρ* : Using the Karush–Kuhn–Tucker conditions, the optimal solution can be achieved by calculating the partial derivatives of $p_{k,n}, (k,n) \in \omega_I$ and $p_{k,n}, (k,n) \in \omega_E$ as $\frac{\partial L(\omega, \mathbf{p}_1, \mathbf{p}_2)}{\partial p_{k,n}, (k,n) \in \omega_I} = 0$ and $\frac{\partial L(\omega, \mathbf{p}_1, \mathbf{p}_2)}{\partial p_{k,n}, (k,n) \in \omega_E} = 0$. Therefore, the optimal block power for ID in the first phase can be formulated as

$$p_{k,n}^* = \left(\frac{\beta_2}{2\beta_1} - \frac{\sigma_{1,(k,n)}^2}{h_{1,(k,n)}} \right)^+, \quad (k,n) \in \omega_I. \quad (11)$$

Meanwhile, the optimal block power for EH is

$$p_{k,n}^* = \begin{cases} p_{\max}, \beta_5 h_{1,(k,n)} > \beta_1, & (k,n) \in \omega_E \\ p_{\min}, \beta_5 h_{1,(k,n)} \leq \beta_1, & (k,n) \in \omega_E \end{cases} \quad (12)$$

where $p_{\max}$ and $p_{\min}$ denote the minimum and maximum power constraints for each block, respectively. Here, $p_{\min}$ is usually set to 0 and $p_{\max}$ is set to the average power. Similarly, the partial derivatives of $p_{k',n'}^{[D1]}$ and $p_{k',n'}^{[D2]}$ can be given by

$$p_{k',n'}^{[D1]*} = \left(\frac{\beta_3}{2\beta_5} - \frac{\sigma_{2,(k',n')}^2}{h_{2,(k',n')}} \right)^+, \quad p_{k',n'}^{[D2]*} = \left(\frac{\beta_4}{2\beta_5} - \frac{\sigma_{3,(k',n')}^2}{h_{3,(k',n')}} \right)^+. \quad (13)$$

2) *Optimizing $\rho_{[k,n]}^{[k',n']}$ With Given ω and $\mathbf{p}$* : Substituting (11)–(13) into (9), rewrite (9) as

$$\begin{aligned} L(\omega, \mathbf{p}) = & \sum_{(k',n') \in \omega_P} \rho_{[k,n]}^{[k',n']} E_{k',n'} + \beta_1 \left(P - \sum_{(k,n) \in \omega_I} p_{k,n} - \sum_{(k,n) \in \omega_E} p_{k,n} \right) \\ & + \beta_2 (C_R - C_1) + \frac{1}{2} \beta_3 \sum \log \left(1 + \frac{p_{k',n'}^{[D1]} h_{2,(k',n')}}{\sigma_{2,(k',n')}^2} \right) \\ & + \beta_4 \left(\frac{1}{2} \sum_{(k',n') \in \omega_P} \log \left(1 + \frac{p_{k',n'}^{[D2]} h_{3,(k',n')}}{\sigma_{3,(k',n')}^2} \right) - C_2 \right) + (1 - \beta_3) C_1 \\ & + \beta_5 \left(E_R - \sum_{(k',n') \in \omega_P} p_{k',n'}^{[D2]} - \sum_{(k',n') \in \omega_P} p_{k',n'}^{[D1]} \right) + \beta_6 E_{D1} + \beta_7 E_{D2} \\ & - E_b (\beta_5 + \beta_6 + \beta_7) \end{aligned} \quad (14)$$

where

$$\begin{aligned} E_{k',n'} = & \beta_5 (p_{k',n'}^{[D2]} + p_{k',n'}^{[D1]}) - \frac{1}{2} \beta_3 \log \left(1 + \frac{p_{k',n'}^{[D1]} h_{2,(k',n')}}{\sigma_{2,(k',n')}^2} \right) \\ & - \frac{1}{2} \beta_4 \log \left(1 + \frac{p_{k',n'}^{[D2]} h_{3,(k',n')}}{\sigma_{3,(k',n')}^2} \right). \end{aligned} \quad (15)$$

From (15), only $E_{k',n'}$ is related to $\rho_{[k,n]}^{[k',n']}$. For a given ω , the block (k',n') with the largest $E_{k',n'}$ may have the best forwarding performance in the second phase. Therefore, we pair (k',n') with the block (k,n) with the best channel gain in the first phase, and let $\rho_{[k,n]}^{[k',n]} = 1$.

Since the channel conditions in different phases are various in the time-varying channel, the source blocks of the first phase must be matched with the relaying blocks of the second phase to maximize the

Algorithm 1: Time–Frequency Block Pairing Algorithm.

- 1: calculate $E_{k',n'}$ according to (15);
 - 2: sort (k',n') in the descending order of $E_{k',n'}$;
 - 3: sort (k,n) in the descending order of their channel gains;
 - 4: pair (k,n) with (k',n') sequentially;
 - 5: set $\rho_{[k,n]}^{[k',n]} = 1$.
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Algorithm 2: Block Power Allocation Algorithm.

- 1: **initialize** $\beta = (\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6)$ with positive values, ω_E and ω_I with any subcarrier sets, and ρ with any values in 1 and 0;
 - 2: **while** β is not convergent **do**
 - 3: calculate $p_{k,n}^*$ by (11) and (12);
 - 4: calculate $p_{k',n'}^{[D1]*}$ and $p_{k',n'}^{[D2]*}$ by (13) and (14);
 - 5: obtain $\rho_{[k,n]}^{[k',n']}$ according to Algorithm 1;
 - 6: calculate ω_E^* and ω_I^* by (17);
 - 7: calculate ω_S^* and ω_P^* by block pairing $\rho_{[k,n]}^{[k',n]} = 1$;
 - 8: update β by (10);
 - 9: **end while**.
-

cooperative throughput. The time–frequency block pairing algorithm is described in Algorithm 1.

3) *Optimizing ω With Given ρ and $\mathbf{p}$* : After obtaining the optimal block pairing, rewrite (9) as

$$\begin{aligned} L(\omega, \mathbf{p}) = & \sum_{(k,n) \in \omega_E} F_{k,n}^* + \beta_1 \left(P - \sum p_{k,n} \right) \\ & + \frac{1}{2} \beta_2 \sum \log \left(1 + \frac{p_{k,n}^* h_{1,(k,n)}}{\sigma_{1,(k,n)}^2} \right) + \beta_3 C_{D1} + \beta_4 (C_{D2} - C_2) \\ & - \beta_5 \left(\sum_{(k',n') \in \omega_S} p_{k',n'}^{[D1]*} + \sum_{(k',n') \in \omega_P} p_{k',n'}^{[D2]*} \right) + (1 - \beta_2 - \beta_3) C_1 + \beta_6 E_{D1} \\ & + \beta_7 E_{D2} - E_b (\beta_5 + \beta_6 + \beta_7) \end{aligned} \quad (16)$$

where

$$F_{k,n}^* = \beta_5 (p_{k,n}^* h_{1,(k,n)} + \sigma_{1,(k,n)}^2) - \frac{1}{2} \beta_2 \log \left(1 + \frac{p_{k,n}^* h_{1,(k,n)}}{\sigma_{1,(k,n)}^2} \right).$$

From (16), we find that only $F_{k,n}^*$ is related to ω_E . Therefore, ω_E is selected to maximize $F_{k,n}^*$ as follows:

$$\omega_E^* = \arg \max_{\omega_E} \sum_{(k,n) \in \omega_E} F_{k,n}^*. \quad (17)$$

All (k,n) enabling $F_{k,n} \geq 0$ are selected to form ω_E^* . Then, the optimal ω_I^* is given by $\omega_I^* = \mathcal{M} - \omega_E^*$. The block power allocation algorithm is shown in Algorithm 2. The algorithm involves an overall computational complexity of $O(7^\alpha \times NK^2)$, where α is related to the number of iterations. We set the number of iterations of the algorithm to 1000 and stop the iteration when the β converges.

IV. SIMULATION RESULTS AND ANALYSIS

Consider a time–frequency-selective fading channel with six taps, where the center frequency is 1.9 GHz. Each subcarrier is modeled as $\kappa(t) = \sqrt{\frac{\theta}{\theta+1}} \tilde{\kappa} + \sqrt{\frac{1}{\theta+1}} \hat{\kappa}(t)$, where $\tilde{\kappa}$ is the line-of-sight deterministic component, $\hat{\kappa}(t)$ is the time-varying Rayleigh fading component,

TABLE I
PARAMETER SETTINGS

variable	value	variable	value
P	5mW	E_b	0.5mW
N	8	ξ	0.4
K	8	C_2	$2 \sim 4\text{bps/Hz}$
σ^2	-50dBm	θ	3

Fig. 2. Time-frequency block allocation and matching.

Fig. 3. Power allocation for each block.

and θ is the Rician factor. The channel power gain is denoted as $h(t) = |\kappa(t)|^2$. The settings of the simulation parameters are shown in Table I. The distance from the source to the relay and the distance from the relay to the destination are both 50 m.

Fig. 2 shows time-frequency block allocation and paring in the two phases, where the same number in the blocks represents the block paring. In the first phase, yellow and blue blocks are used for ID and EH, respectively. In the second phase, yellow blocks are used to forward the source information to the destination, while the blue blocks are used to send the information of the relay. Fig. 3 indicates power allocation for time-frequency blocks in the first phase and the second phase, as shown in Fig. 2, respectively.

Fig. 4 illustrates the performance of TFBA-SWIPT, PS-SWIPT [4], SA-SWIPT [10], and TFBA-SWIPT without block paring. It is seen that the block paring can improve the transmission performance of TFBA-SWIPT via making full use of different channel conditions. TFBA-SWIPT outperforms PS-SWIPT and SA-SWIPT over the time-varying channels, but its performance is closer to than that of SA-SWIPT over the time-invariant channel. Because time-frequency blocks can be allocated according to the instantaneous channel gain, subcarriers can only be allocated according to the average channel gain, which is not suitable for time-varying channels.

Fig. 4. Transmission rate comparison. (a) Time-varying channel. (b) Time-invariant channel.

V. CONCLUSION

A TFBA-SWIPT scheme is proposed for the energy saving of OFDM-based DF cooperative communication. The relay uses the harvested energy from the source signal to forward the information of the source and its own. The time-frequency block paring algorithm and the block power allocation algorithm are proposed to maximize the system transmission rate while guaranteeing the rate and energy for the relay. The simulation results show that the TFBA-SWIPT outperforms the traditional SA-SWIPT and PS-SWIPT over the time-varying channels.

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