

Energy-Efficient Resource Allocation for Simultaneous Wireless Information and Power Transfer in GFDM Cooperative Communications

Yuting Guo, Xin Liu, *Senior Member, IEEE*, Xueying Liu, and Tariq S Durrani, *Life Fellow, IEEE*

Abstract—Simultaneous wireless information and power transfer (SWIPT) for generalized frequency division multiplexing (GFDM) cooperative communications is proposed to save consumed energy of relay and destination. GFDM subsymbols are allocated for information decoding (ID) and energy harvesting (EH), respectively. Energy efficiency of SWIPT based GFDM system is maximized by jointly optimizing subsymbol and power allocations for ID and EH. A joint optimization algorithm is proposed to obtain the optimal solution to the energy-efficiency optimization problem. Simulation results show that energy efficiency of this scheme is 5bps/J/Hz higher than that of power-splitting SWIPT at total transmit power of 5mW.

Index Terms—SWIPT; GFDM; cooperative communications; energy efficiency; joint optimization

I. INTRODUCTION

Generalized frequency division multiplexing (GFDM) is one of the candidate multi-carrier communication schemes for 5G communications [1]. Compared with the Orthogonal Frequency Division Multiplexing (OFDM), it has the advantages of high spectrum utilization[2], low out-of-band radiation[3], low peak-to-average ratio and setting parameters that meet the requirements of different application scenarios[4]. Different from OFDM, GFDM can use its time-frequency focusing to design a shaping filter suitable for channel delay, which can resist both inter-symbol interference and inter-carrier interference and thus obtain higher spectrum efficiency[5]. However, multi-carrier transmission may consume more energy compared with the single-carrier communication.

Simultaneous wireless information and power transfer (SWIPT) has been proposed to save energy by collecting radio frequency energy of the receiving signal when decoding its information. There have been two models for SWIPT: time switching (TS) and power splitting (PS). TS-SWIPT or PS-SWIPT use different time slots or power streams for information decoding (ID) and energy harvesting (EH) [6], [7]. In [8], the optimal allocation ratio for EH and ID was calculated to

evaluate the optimal balance between rate and energy of TS-SWIPT and PS-SWIPT in nonlinear energy harvesting model. PS-SWIPT can be used in point-to-point OFDM communication for the EH and ID of each subcarrier, where the achievable system rate can be maximized by optimizing the subcarrier power [9]. In [10], the influence of TS ratio on the system performance was analyzed, whereby the best allocation factor was obtained to improve the overall system throughput. [11] proposed a relaying PS-SWIPT system, where the PS ratio was optimized to minimize the outage probability. In [12], a SWIPT based multiuser OFDM system was presented, where channel allocation, PS ratio and power allocation are jointly optimized to minimize user interruption probability.

Most of the existing literatures focus on OFDM-SWIPT, but only a few of them study GFDM-SWIPT. In [13], a multiuser GFDM scheme for PS-SWIPT based Internet of Things was proposed, where the power of each GFDM subsymbol is divided into ID stream and EH stream respectively. The sum rate is maximized by jointly optimizing the subsymbol allocation, power allocation and PS ratio under the constraint of EH and power budget. However, the TS-SWIPT and PS-SWIPT schemes both assume each subcarrier has a fixed allocation ratio for ID and EH, which are unable to adapt to the dynamic channel states. In cooperative communication, relay nodes usually consume a lot of energy for forwarding information to the destination nodes. Therefore, the integration of cooperative communication and SWIPT enables continuous power supply to the relay while keeping its normal data transmissions.

This letter proposes a time-frequency resource allocation scheme for SWIPT based GFDM cooperative communications, which can allocate resources for ID and EH adaptively according to the time-varying characteristics of the channels. The contributions of this letter are drawn as follows: (1) a SWIPT based GFDM DF cooperative communication system is modeled, where both relay and destination perform ID and EH simultaneously. Compared with the traditional TS-SWIPT and PS-SWIPT, the proposed scheme allocates different subsymbols for EH and ID according to the time-frequency channel states, thus improving the performance of ID and EH in fading channel; (2) energy-efficiency optimization problem for the GFDM system is formulated by jointly optimizing subsymbol and power allocations for ID and EH, which seeks to maximize the target transmission rate under the constrained EH performance; (3) a subsymbol pairing algorithm for the first and second time phases is put forward to ensure that relay can use the best channel to forward source information,

This work was supported in part by the Natural Science Foundations of Liaoning Province under Grant 2019-ZD-0014 and Grant 2020-HYLH-13, and in part by the Fundamental Research Funds for the Central Universities under Grant DUT21JC20. (*Correspondence author: Xin Liu*)

Y.T. Guo, X. Liu, and X.Y. Liu are with the School of Information and Communication Engineering, Dalian University of Technology, Dalian 116024, China (e-mail: guoyt98@163.com; liuxinstar1984@dlut.edu.cn; 1095934045@qq.com).

T.S. Durrani is with the Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow G1 1XQ, U.K. (e-mail: t.durrani@strath.ac.uk).

then a joint optimization algorithm is performed to achieve the optimal solution to the optimization problem.

II. SYSTEM MODEL

A SWIPT based GFDM DF cooperative communication system is molded in Fig. 1, which consists of a source node S , a DF relay node R and a destination node D . Each GFDM block from S is transmitted through K subcarriers, each of which consists of M subsymbols. $\mathcal{K} = \{1, \dots, K\}$ represents the subcarrier set and $\mathcal{M} = \{1, \dots, M\}$ denotes the subsymbol set. In the first phase, all the KM subsymbols form into a symbol set \mathcal{N} . Subsymbol (k, m) denotes the time-frequency resource block in m th subsymbol on k th subcarrier. Considering a slow fading channel, the channel over each subsymbol is assumed to be flat, and the channel power gain can be seen as a constant during one subsymbol. The subsymbols are allocated for ID and EH in two phases of cooperative communication. In the first phase, R receives the information from S through the subsymbol set \mathcal{G}_I and collects the energy of S through the subsymbol set \mathcal{G}_E , where $\mathcal{G}_I + \mathcal{G}_E = \mathcal{N}$. The harvested energy is used for R to decode and forward the received source information. In the second phase, R relays the information from \mathcal{G}_I to D through the paired subsymbols in \mathcal{G}_S and transfer the energy to D with the remaining subsymbols in \mathcal{G}_P . Thus, we have $\mathcal{G}_S + \mathcal{G}_P = \mathcal{N}'$, where \mathcal{N}' is the symbol set in the second phase.

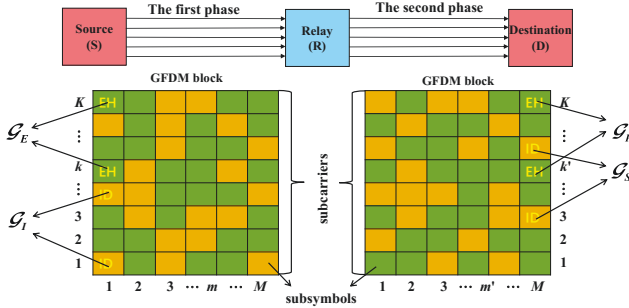


Fig. 1. System model.

III. MODEL OPTIMIZATION

A. Optimization Problem

Assume the transmitter can know the channel state information. In the first phase, the transmit power, channel power gain and noise power of subsymbol (k, m) from S to R are defined by $p_{k,m}$, $h_{k,m}$ and $\sigma_{k,m}^2$, respectively. The information rate in bps/Hz at the relay is given as

$$R_1 = \sum_{(k,m) \in \mathcal{G}_I} \log_2 \left(1 + \frac{p_{k,m} h_{k,m}}{\sigma_{k,m}^2} \right) \quad (1)$$

The harvested power at the relay is expressed as

$$Q_1 = \xi \sum_{(k,m) \in \mathcal{G}_E} (p_{k,m} h_{k,m} + \sigma_{k,m}^2) \quad (2)$$

where ξ is energy conversion efficiency. In the second phase, the transmit power, channel power gain and noise power

of the subsymbol (k', m') is defined by $p_{k',m'}$, $g_{k',m'}$ and $\sigma_{k',m'}^2$, respectively. Then the achievable rate in bps/Hz at the destination node D is given by

$$R_2 = \sum_{(k,m) \in \mathcal{G}_I} \sum_{(k',m') \in \mathcal{N}'} \rho_{k,m}^{k',m'} \log_2 \left(1 + \frac{p_{k',m'} g_{k',m'}}{\sigma_{k',m'}^2} \right) \quad (3)$$

where $\rho_{k,m}^{k',m'}$ denotes the subsymbol pairing indicator. That is, if the information of subsymbol (k, m) in the first phase is relayed through subsymbol (k', m') in the second phase, $\rho_{k,m}^{k',m'} = 1$, otherwise, $\rho_{k,m}^{k',m'} = 0$. Then the harvested power at D is given as

$$Q_2 = \xi \sum_{(k,m) \in \mathcal{G}_I} \sum_{(k',m') \in \mathcal{N}'} (1 - \rho_{k,m}^{k',m'}) (p_{k',m'} g_{k',m'} + \sigma_{k',m'}^2) \quad (4)$$

Finally, the total achievable rate at D within one GFDM block is obtained as

$$R_T = \min(R_1, R_2) \quad (5)$$

We can get the total consumed power of the cooperative communication system over the two phases as

$$U_T = \sum_{k=1}^K \sum_{m=1}^M p_{k,m} + \sum_{k'=1}^K \sum_{m'=1}^M p_{k',m'} + 2E_b - Q_1 - Q_2 \quad (6)$$

where E_b represents the power consumption for ID at the relay and destination. We can get the system energy efficiency (the ratio of total achievable rate to total consumed power) as

$$EE(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) = \frac{R_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho})}{U_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho})} \quad (7)$$

The energy efficiency can be maximized by jointly optimizing power allocation $\mathbf{p} = \{p_{k,m}, p_{k',m'}\}$, subsymbol sets $\mathcal{G} = \{\mathcal{G}_I, \mathcal{G}_E\}$ and subsymbol pairing indicator $\boldsymbol{\rho} = \{\rho_{k,m}^{k',m'}\}$, under the constraints of minimum target transmission rate, R_{min} , maximum power of source node, P_{max} , and minimum harvested power for relay and destination. We formulate the optimization problem as

$$\begin{aligned} & \max_{\{\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}\}} EE(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) \\ & \text{s.t. } C1 : R_T \geq R_{min} \\ & C2 : \sum_{k=1}^K \sum_{m=1}^M p_{k,m} \leq P_{max} \\ & C3 : \sum_{k'=1}^K \sum_{m'=1}^M p_{k',m'} + E_b \leq Q_1 \\ & C4 : E_b \leq Q_2 \end{aligned} \quad (8)$$

where the constraints $C3$ and $C4$ denote that the harvested power should afford the power consumption of R and D , respectively.

As the the numerator and denominator of $EE(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho})$ are nonlinear and linear functions, respectively, equation (8) is a nonlinear non-convex optimization problem that is difficult to solve directly. Dinkelbach method is adopted to solve fractional programming problem [14]. Let q^* equal to the maximum achievable energy efficiency, which can be obtained only when the equation $\max_{\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}} R_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) - q^* U_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) = 0$ is satisfied, where

$q^* = \frac{R_T(\mathcal{G}^*, \mathbf{p}^*, \boldsymbol{\rho}^*)}{U_T(\mathcal{G}^*, \mathbf{p}^*, \boldsymbol{\rho}^*)} = \max_{\{\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}\}} \frac{R_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho})}{U_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho})}$. By utilizing q , the fractional objective function can be transformed into a more solvable function of subtraction form, which is given by

$$\begin{aligned} \max_{\{\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}\}} \quad & R_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) - qU_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) \\ \text{s.t.} \quad & C1, C2, C3, C4 \end{aligned} \quad (9)$$

B. Optimal Solution

Lagrangian dual method is adopted to solve non-convex optimization problem with sufficient subsymbols [15]. The Lagrange dual function of (9) is given as

$$g(\boldsymbol{\beta}) = \max_{\{\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}\}} L(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) \quad (10)$$

where $L(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho})$ is given as

$$\begin{aligned} L(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) = & R_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) - qU_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) \\ & + \beta_1(R_1 - R_{min}) + \beta_2(R_2 - R_{min}) \\ & + \beta_3(P_{max} - \sum_{k=1}^K \sum_{m=1}^M p_{k,m}) + \beta_4(Q_1 - \sum_{k'=1}^K \sum_{m'=1}^M p_{k',m'} - E_b) \\ & + \beta_5(Q_2 - E_b) \end{aligned} \quad (11)$$

And $\boldsymbol{\beta} = (\beta_1, \beta_2, \beta_3, \beta_4, \beta_5)$ is the dual variable vector. The dual optimization problem is then described as

$$\begin{aligned} \min_{\boldsymbol{\beta}} \quad & g(\boldsymbol{\beta}) \\ \text{s.t.} \quad & \boldsymbol{\beta} \geq 0 \end{aligned} \quad (12)$$

where $\boldsymbol{\beta}$ can be solved through the sub-gradient method. And the sub-gradient of the dual function is formulated as

$$\begin{cases} \Delta\beta_1 = R_1 - R_{min} \\ \Delta\beta_2 = R_2 - R_{min} \\ \Delta\beta_3 = P_{max} - \sum_{k=1}^K \sum_{m=1}^M p_{k,m} \\ \Delta\beta_4 = Q_1 - \sum_{k'=1}^K \sum_{m'=1}^M p_{k',m'} - E_b \\ \Delta\beta_5 = Q_2 - E_b \end{cases} \quad (13)$$

$\boldsymbol{\beta}$ can be updated through $\boldsymbol{\beta}^{n+1} = \boldsymbol{\beta}^n + v^n \Delta\boldsymbol{\beta}$, where n is the iteration index, v^n is the step size of each iteration, and $\Delta\boldsymbol{\beta} = (\Delta\beta_1, \Delta\beta_2, \Delta\beta_3, \Delta\beta_4, \Delta\beta_5)$. The optimal $\boldsymbol{\beta}^*$ can be obtained when the iteration convergence is finally reached. With a fixed $\boldsymbol{\beta}$, \mathcal{G} , \mathbf{p} and $\boldsymbol{\rho}$ can be optimized as follows.

1) *Optimizing \mathbf{p} with fixed \mathcal{G} and $\boldsymbol{\rho}$* : when $\boldsymbol{\beta}$, \mathcal{G} and $\boldsymbol{\rho}$ are fixed, equation (10) is a standard maximization problem. We calculate the partial derivatives of $p_{k,m}$, $(k, m) \in \mathcal{G}_I$ and $p_{k',m'}$, $(k', m') \in \mathcal{G}_E$ using the Karush-Kuhn-Tucker conditions. The optimal power allocation in the first phase can be obtained by $\frac{\partial L(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho})}{\partial p_{k,m}, (k,m) \in \mathcal{G}_I} = 0$ and $\frac{\partial L(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho})}{\partial p_{k',m'}, (k',m') \in \mathcal{G}_E} = 0$. The optimal power for ID is obtained as

$$p_{k,m}^* = \left(\frac{\beta_1}{\ln 2(q + \beta_3)} - \frac{\sigma_{k,m}^2}{h_{k,m}} \right)^+, \quad (k, m) \in \mathcal{G}_I. \quad (14)$$

And the optimal power for EH is given as

$$p_{k,m}^* = \begin{cases} p_{\max} & \xi h_{k,m}(q + \beta_4) > q + \beta_3 \\ p_{\min} & \xi h_{k,m}(q + \beta_4) \leq q + \beta_3 \end{cases}, \quad (k, m) \in \mathcal{G}_E \quad (15)$$

where p_{\max} and p_{\min} represent the maximum and minimum power for each subsymbol, respectively. Similarly, the power allocation of $p_{k',m'}$, $(k', m') \in \mathcal{G}_S$ and $p_{k',m'}$, $(k', m') \in \mathcal{G}_P$ in the second phase is obtained as

$$p_{k',m'}^* = \left(\frac{\beta_2}{\ln 2(q + \beta_4)} - \frac{\sigma_{k',m'}^2}{g_{k',m'}} \right)^+, \quad (k', m') \in \mathcal{G}_S \quad (16)$$

$$p_{k',m'}^* = \begin{cases} p_{\max} & \xi g_{k',m'}(q + \beta_5) > q + \beta_4 \\ p_{\min} & \xi g_{k',m'}(q + \beta_5) \leq q + \beta_4 \end{cases}, \quad (k', m') \in \mathcal{G}_P \quad (17)$$

2) *Optimizing $\boldsymbol{\rho}$ with fixed \mathbf{p} and \mathcal{G}* : substituting (14), (15), (16) and (17) into (11), the Lagrange dual function (11) is rewritten as

$$\begin{aligned} L(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) = & \sum_{(k,m) \in \mathcal{G}_I} \sum_{(k',m') \in \mathcal{N}'} \rho_{k',m'}^{k',m'} E_{k',m'} - q \left(\sum_{k=1}^K \sum_{m=1}^M p_{k,m} \right. \\ & + \sum_{k'=1}^K \sum_{m'=1}^M p_{k',m'} - \xi \sum_{k'=1}^K \sum_{m'=1}^M (p_{k',m'} g_{k',m'} + \sigma_{k',m'}^2) - \xi \sum_{(k,m) \in \mathcal{G}_E} (p_{k,m} h_{k,m} \\ & + \sigma_{k,m}^2) + 2E_b) + R_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) + \beta_1 \left(\sum_{(k,m) \in \mathcal{G}_I} \log_2 \left(1 + \frac{p_{k,m} h_{k,m}}{\sigma_{k,m}^2} \right) \right. \\ & - R_{min}) - \beta_2 R_{min} + \beta_3 (P_{max} - \sum_{k=1}^K \sum_{m=1}^M p_{k,m}) \\ & + \beta_4 \left(\xi \sum_{(k,m) \in \mathcal{G}_E} (p_{k,m} h_{k,m} + \sigma_{k,m}^2) - \sum_{k'=1}^K \sum_{m'=1}^M p_{k',m'} - E_b \right) \\ & + \beta_5 \left(\xi \sum_{k'=1}^K \sum_{m'=1}^M (p_{k',m'} g_{k',m'} + \sigma_{k',m'}^2) - E_b \right) \end{aligned} \quad (18)$$

where $E_{k',m'}$ is written as

$$\begin{aligned} E_{k',m'} = & \beta_2 \log_2 \left(1 + \frac{p_{k',m'} g_{k',m'}}{\sigma_{k',m'}^2} \right) \\ & - q \xi (p_{k',m'} g_{k',m'} + \sigma_{k',m'}^2) \\ & - \beta_5 \xi (p_{k',m'} g_{k',m'} + \sigma_{k',m'}^2) \end{aligned} \quad (19)$$

It is obvious that $\rho_{k',m'}^{k',m'}$ is only relevant to $E_{k',m'}$ in (19). Thus, with a fixed \mathcal{G} , $\rho_{k',m'}^{k',m'}$ can be optimized by searching for paired subsymbols (k', m') in the second phase that maximize the value of $E_{k',m'}$. The subsymbol pairing algorithm can be described in Algorithm 1.

Algorithm 1 Subsymbol pairing algorithm

- 1: reorder (k, m) in descending order of channel gains;
 - 2: reorder (k', m') in descending order of $E_{k',m'}$ in (19);
 - 3: pair (k, m) with (k', m') sequentially;
 - 4: set $\rho_{[k,m]}^{[k',m']} = 1$, otherwise, set $\rho_{[k,m]}^{[k',m']} = 0$.
-

3) *Optimizing \mathcal{G} with fixed \mathbf{p} and $\boldsymbol{\rho}$* : with the optimal $\boldsymbol{\rho}$, equation (11) can be rewritten as

$$\begin{aligned}
L(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) = & \sum_{(k,m) \in \mathcal{G}_I} F_{k',m'} - q(2E_b + \sum_{k=1}^K \sum_{m=1}^M p_{k,m} + \sum_{k'=1}^K \sum_{m'=1}^M p_{k',m'}) \\
& - \xi \sum_{k=1}^K \sum_{m=1}^M (p_{k,m} h_{k,m} + \sigma_{k,m}^2) - \xi \sum_{k'=1}^K \sum_{m'=1}^M (p_{k',m'} g_{k',m'} + \sigma_{k',m'}^2) \\
& + R_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) - \beta_1 R_{min} - \beta_2 R_{min} \\
& + \beta_3 (P_{max} - \sum_{k=1}^K \sum_{m=1}^M p_{k,m}) \\
& + \beta_4 (\xi \sum_{k=1}^K \sum_{m=1}^M (p_{k,m} h_{k,m} + \sigma_{k,m}^2) - \sum_{k'=1}^K \sum_{m'=1}^M p_{k',m'} - E_b) \\
& + \beta_5 (\xi \sum_{k'=1}^K \sum_{m'=1}^M (p_{k',m'} g_{k',m'} + \sigma_{k',m'}^2) - E_b)
\end{aligned} \quad (20)$$

where $F_{k',m'}$ is given as

$$\begin{aligned}
F_{k',m'} = & E_{k',m'} - \xi(q + \beta_4)(p_{k,m} h_{k,m} + \sigma_{k,m}^2) \\
& + \beta_1 \log_2(1 + \frac{p_{k,m} h_{k,m}}{\sigma_{k,m}^2})
\end{aligned} \quad (21)$$

In (21), it can be found that $F_{k',m'}$ is relevant to \mathcal{G}_I . We can achieve the optimal \mathcal{G}_I^* as

$$\mathcal{G}_I^* = \arg \max_{\mathcal{G}_I} \sum_{(k,m) \in \mathcal{G}_I} F_{k',m'}. \quad (22)$$

Obviously, all the subsymbols (k,m) make $F_{k',m'} \geq 0$ form \mathcal{G}_I^* . Then \mathcal{G}_E^* is given by $\mathcal{G}_E^* = \mathcal{N} - \mathcal{G}_I^*$.

The joint optimization of subsymbol and power allocations is shown in Algorithm 2. And the optimal system energy efficiency is finally obtained with the Dinkelbach[14] method in Algorithm 3.

Algorithm 2 Joint optimization of subsymbol and power allocations

- 1: **initialize:** β with nonnegative values, \mathcal{G}_E and \mathcal{G}_I with certain subsymbol sets;
 - 2: **repeat:**
 - 3: obtain $p_{k,m}$ and $p_{k',m'}$ by (14) ~ (17);
 - 4: obtain $\boldsymbol{\rho}$ by Algorithm 1;
 - 5: obtain \mathcal{G}_E^* and \mathcal{G}_I^* by (22);
 - 6: update β by (10);
 - 7: **until:** β is convergent.
-

Algorithm 3 Energy efficiency optimization

- 1: **initialize:** the optimization accuracy ε , $q = 0$;
 - 2: **repeat:**
 - 3: with given q , obtain $\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}$ by Algorithm 1 and Algorithm 2;
 - 4: update $q = \frac{R_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho})}{U_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho})}$;
 - 5: **until:** $R_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) - q U_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}) \leq \varepsilon$.
 - 6: **output:** $q^* = \frac{R_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho})}{U_T(\mathcal{G}, \mathbf{p}, \boldsymbol{\rho})}$, $\{\mathcal{G}^*, \mathbf{p}^*, \boldsymbol{\rho}^*\} = \{\mathcal{G}, \mathbf{p}, \boldsymbol{\rho}\}$.
-

IV. SIMULATION RESULTS AND ANALYSIS

Simulation parameters are set as follows. There are $K = 8$ subcarriers and $M = 8$ subsymbols in each subcarrier. The power consumption for decoding is $E_b = 0.5\text{mW}$, the energy conversion efficiency is $\xi = 0.5$, and the average noise power is $\sigma^2 = -60 \sim -40\text{dBm}$. Consider a Rician fading channel with 6 taps at the center frequency of 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 light-of-sight (LOS) deterministic component, $\hat{\kappa}(t)$ is time-varying Rayleigh fading component and $\theta = 3$ is Rician factor.

Fig. 2 depicts subsymbol pairing between the two phases, where the paired subsymbols are marked with the same number. In the first phase, the subsymbols marked in yellow and green perform ID and EH, respectively. In the second phase, the yellow subsymbols relay source information to the destination, and the energy of the green subsymbols is harvested by the destination. The power allocation for each subsymbol during the two phases is shown in Fig. 3. Since the channel states in the first and second phases are different, through subsymbol pairing, the best subsymbols in the second phase can relay the subsymbol information in the first phase for improving cooperative communication performance over various channels.

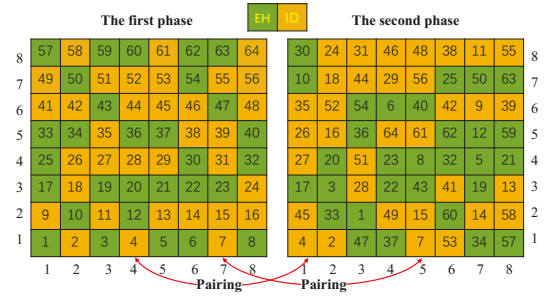


Fig. 2. Subsymbol pairing between the two phases.

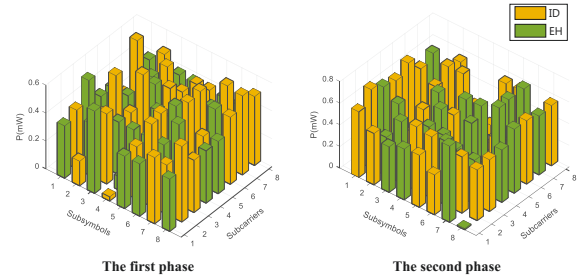


Fig. 3. Power allocation for each subsymbol.

Fig. 4 shows energy efficiency versus total power P under different average noise power σ^2 . It is seen that the energy efficiency improves with the increase of P due to the growing harvested energy Q_1 and Q_2 . In addition, the increase of energy efficiency gradually slows down and tends to converge, because the power for ID will not increase when the target rate is satisfied.

Fig. 5 compares the proposed scheme with PS GFDM-SWIPT scheme [13] and no-pairing GFDM-SWIPT scheme. In

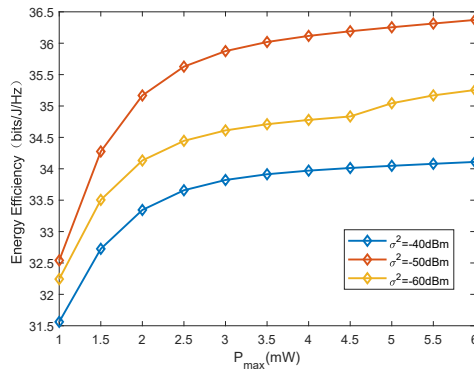


Fig. 4. Energy efficiency verses total power.

the PS GFDM-SWIPT scheme, the power of each subsymbol is split into two streams for ID and EH, respectively. In the no-pairing GFDM-SWIPT scheme, the subsymbol allocation of the two phases is the same without considering the subsymbol pairing. It is seen that energy efficiency of the proposed scheme is higher than that of the other schemes. This is because, the proposed scheme considers the channel state changes in different phases through adopting subsymbol pairing for resource allocation, which can better adapt to various channel states.

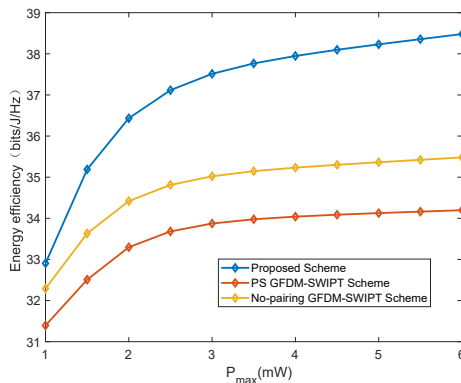


Fig. 5. Energy efficiency comparison of different schemes.

V. CONCLUSIONS

In this letter, a SWIPT based GFDM DF cooperative communication system is modeled, whose communication process is divided into two transmission phases. By allocating GFDM subsymbols for ID and EH in each phase, both the relay and destination can perform ID and EH simultaneously. The subsymbol and power allocations for ID and EH are jointly optimized to maximize the system energy efficiency under the constraint of minimum EH performance. The subsymbol pairing algorithm and joint optimization algorithm are respectively proposed to achieve the optimal solution to the energy-efficiency optimization problem. Simulation results show that the proposed scheme outperforms the PS GFDM-SWIPT scheme and no-pairing GFDM-SWIPT scheme.

REFERENCES

- [1] X. Zhang, Z. Wang, X. Ning, and H. Xie, "On the Performance of GFDM Assisted NOMA Schemes," *IEEE Access*, vol. 8, pp. 88 961–88 968, 2020.
- [2] M. Danneberg, R. Datta, A. Festag, and G. Fettweis, "Experimental Testbed for 5G Cognitive Radio Access in 4G LTE Cellular Systems," in *2014 IEEE 8th Sensor Array and Multichannel Signal Processing Workshop (SAM)*, 2014, pp. 321–324.
- [3] R. Datta and G. Fettweis, "Improved ACLR by Cancellation Carrier Insertion in GFDM Based Cognitive Radios," in *2014 IEEE 79th Vehicular Technology Conference (VTC Spring)*, 2014, pp. 1–5.
- [4] N. Michailow, L. Mendes, M. Matth, I. Gaspar, A. Festag, and G. Fettweis, "Robust WHT-GFDM for the Next Generation of Wireless Networks," *IEEE Communications Letters*, vol. 19, no. 1, pp. 106–109, 2015.
- [5] N. Michailow, M. Matth, I. S. Gaspar, A. N. Caldeilla, L. L. Mendes, A. Festag, and G. Fettweis, "Generalized Frequency Division Multiplexing for 5th Generation Cellular Networks," *IEEE Transactions on Communications*, vol. 62, no. 9, pp. 3045–3061, 2014.
- [6] R. Zhang and C. K. Ho, "MIMO Broadcasting for Simultaneous Wireless Information and Power Transfer," *IEEE Transactions on Wireless Communications*, vol. 12, no. 5, pp. 1989–2001, 2013.
- [7] X. Liu, X. Zhang, and X. Liu, "Simultaneous Wireless Information and Power Transfer for OFDM-based Cooperative Communication," *Mobile Networks and Applications*, to appear, 2020.
- [8] R. Jiang, K. Xiong, P. Fan, Y. Zhang, and Z. Zhong, "Power Minimization in SWIPT Networks With Coexisting Power-Splitting and Time-Switching Users Under Nonlinear EH Model," *IEEE Internet of Things Journal*, vol. 6, no. 5, pp. 8853–8869, 2019.
- [9] M. Abedi, H. Masoumi, and M. J. Emadi, "Power Splitting-Based SWIPT Systems With Decoding Cost," *IEEE Wireless Communications Letters*, vol. 8, no. 2, pp. 432–435, 2019.
- [10] J. Tang, J. Luo, M. Liu, D. K. C. So, E. Alsusa, G. Chen, K. Wong, and J. A. Chambers, "Energy Efficiency Optimization for NOMA With SWIPT," *IEEE Journal of Selected Topics in Signal Processing*, vol. 13, no. 3, pp. 452–466, 2019.
- [11] Y. Ye, Y. Li, F. Zhou, N. Al-Dhahir, and H. Zhang, "Power Splitting-Based SWIPT With Dual-Hop DF Relaying in the Presence of a Direct Link," *IEEE Systems Journal*, vol. 13, no. 2, pp. 1316–1319, 2019.
- [12] B. Xu, Y. Zhu, and R. Zhang, "Optimized Power Allocation for Interference Channel With SWIPT," *IEEE Wireless Communications Letters*, vol. 5, no. 2, pp. 220–223, 2016.
- [13] Z. Na, J. Lv, F. Jiang, M. Xiong, and N. Zhao, "Joint Subcarrier and Subsymbol Allocation-Based Simultaneous Wireless Information and Power Transfer for Multiuser GFDM in IoT," *IEEE Internet of Things Journal*, vol. 6, no. 4, pp. 5999–6006, 2019.
- [14] J. Tang, J. Luo, M. Liu, D. K. C. So, E. Alsusa, G. Chen, K.-K. Wong, and J. A. Chambers, "Energy Efficiency Optimization for NOMA With SWIPT," *IEEE Journal of Selected Topics in Signal Processing*, vol. 13, no. 3, pp. 452–466, 2019.
- [15] W. Yu and R. Lui, "Dual methods for nonconvex spectrum optimization of multicarrier systems," *IEEE Transactions on Communications*, vol. 54, no. 7, pp. 1310–1322, 2006.