# Bidirectional Link Resource Allocation Strategy in GFDM-based Multiuser SWIPT Systems

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## Abstract

In order to enhance system energy efficiency, bidirectional link resource allocation strategy in GFDM-based multiuser SWIPT systems is proposed. In the downlink channel, each SWIPT user applies power splitting (PS) receiver structure in information decoding (ID) and non-linear energy harvesting (EH). In the uplink channel, information transmission power is originated from the harvested energy. An optimization problem is constructed to maximize weighted sum ID achievable rates in the downlink and uplink channels via bidirectional link power allocation as well as subcarriers and subsymbols scheduling. To solve this non-convex optimization problem, Lagrange duality method, sub-gradient-based method and greedy algorithm are adopted respectively. Simulation results show that the proposed strategy is superior to the fixed subcarrier scheme regardless of the weighting coefficients. It is superior to the heuristic algorithm in larger weighting coefficients scenario.

***Keywords:*** Bidirectional link resource allocation strategy; GFDM; Multiuser SWIPT systems; Non-linear energy harvesting; Non-convex optimization problem.

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## 1. Introduction

Simultaneous wireless information and power transfer (SWIPT) can prolong battery life in device-to-device (D2D) communications [1]. How to reasonably allocate system resources to achieve certain targets, such as spectral or energy efficiency, network throughput, *etc*., has become research hotspots in SWIPT networks [2]. Due to the path loss in wireless channels, SWIPT has in general low energy harvesting efficiency [2-3]. To overcome this drawback, multiple input multiple output (MIMO) technology is applied in SWIPT practical use, with the objective of spectral efficiency as well as energy harvesting performance enhancement [4-5].

The authors in [6] investigated multiuser orthogonal frequency division multiplexing (OFDM)-based SWIPT systems with emphasis on optimal design of SWIPT for the downlink channel, in which each SWIPT user implements either time switching (TS) or power splitting (PS) to balance energy harvesting (EH) and information decoding (ID). The authors also indicated that each OFDM subcarrier peak power constraint and SWIPT user numbers play key roles in the system rate-energy performance. In [7], the authors considered joint optimization of bidirectional link resources in multiuser OFDM-based SWIPT systems. Based on the proposed bidirectional link two-way resource allocation strategy, energy harvested in the downlink is utilized for uplink information transmission. More recently in [7], the Lagrange duality method and the ellipsoid method are used for solving the optimization problem of bidirectional link resource allocation in multiuser OFDM-based SWIPT systems.

### A. Related Works

Due to the advantages of low out-of-band (OOB) radiation, high spectral efficiency as well as non-strict time synchronization, generalized frequency division multiplexing (GFDM) is proposed as flexible multicarrier modulation strategy for certain systems [8]. *i.e.*, Internet of Things (IoT), tactile Internet and industrial automation. GFDM adopts a block structure consisting of a number of subcarriers with each subcarrier comprising a number of subsymbols for data transmission. The combination of SWIPT and GFDM not only provides the benefits of multicarrier but also improves energy efficiency for the device, which enhances the overall system performance. The authors in [9] investigated the downlink resource allocation in GFDM-based multiuser SWIPT IoT systems and showed that the characteristics of 2-D sub-block structure of GFDM allocate system resources more flexibly and efficiently.

Most of the above-mentioned studies are based on the target of maximizing SWIPT network throughput via optimal resource allocation schemes. Some references consider security and reliability performance in SWIPT network. Ref. [10] mainly investigates secure transmission in the SWIPT Internet of Things (IoT) system with full-duplex IoT devices. It presents the corresponding strategies and simulation results for both perfect channel state information (CSI) and imperfect CSI scenarios [10]. Ref. [11] studies the outage performance of a joint transmission coordinated multipoint cooperative non-orthogonal multiple access (JT-CoMP-CNOMA) network. It considers the cell-center users that act as relays for the cell-edge user, and the energy-constrained cell-center users implement information decoding and energy harvesting in the network. The closed-form approximate expression of outage probability and the Monte Carlo simulations are presented to verify the theoretical results [11].

### B. Motivation and Contribution

It is noticeable that GFDM can meet the quality of service (QoS) requirements such as high spectral-efficiency and low latency [8]. The combination of SWIPT and GFDM not only enhances system energy efficiency but also realizes flexible and efficient resource allocation [9]. In addition, most of the former studies mainly focus on the resource allocation in downlink channel, and few references investigate bidirectional link resource allocation in multiuser SWIPT system. There are few studies that consider the combination of SWIPT and GFDM to improve bidirectional link spectral-efficiency (achievable rates).

According to the current resource allocation research in multicarrier multiuser SWIPT system, we investigate bidirectional link resource allocation strategy in GFDM-based multiuser SWIPT systems in this paper, with an objective of the weighted sum achievable rates maximization in both downlink and uplink channels. A constrained optimization problem is constructed for the allocation of subcarriers, subsymbols, as well as bidirectional link powers. An iterative strategy along with Lagrange duality method, subgradient-based method and greedy algorithm are implemented to find the solution of the proposed non-convex optimization problem. It is shown that the new strategy outperforms the conventional fixed subcarrier scheme and heuristic algorithm.

The rest structure of this paper is shown as below. System model is investigated in Section 2. The proposed bidirectional link resource allocation strategy in GFDM-based multiuser SWIPT systems is discussed in Section 3, with the non-convex optimization problem and the specific solution procedure presented in this Section. Simulation results with performance analysis are presented in Section 4. Finally, conclusion and future prospects are given in Section 5.

## 2. System Model

GFDM-based multiuser SWIPT system consisting of one base station (BS) and $N$ SWIPT users is illustrated in **Fig. 1**, where the BS has $N_T$ antennas and each SWIPT user is deployed with one single antenna. In the downlink channel, PS structure is implemented at each SWIPT user that separates the received signal into two portions, namely, one for ID and the other for non-linear EH [12-14]. In the uplink channel, SWIPT users make use of the energy harvested from the downlink channel for information transmission.

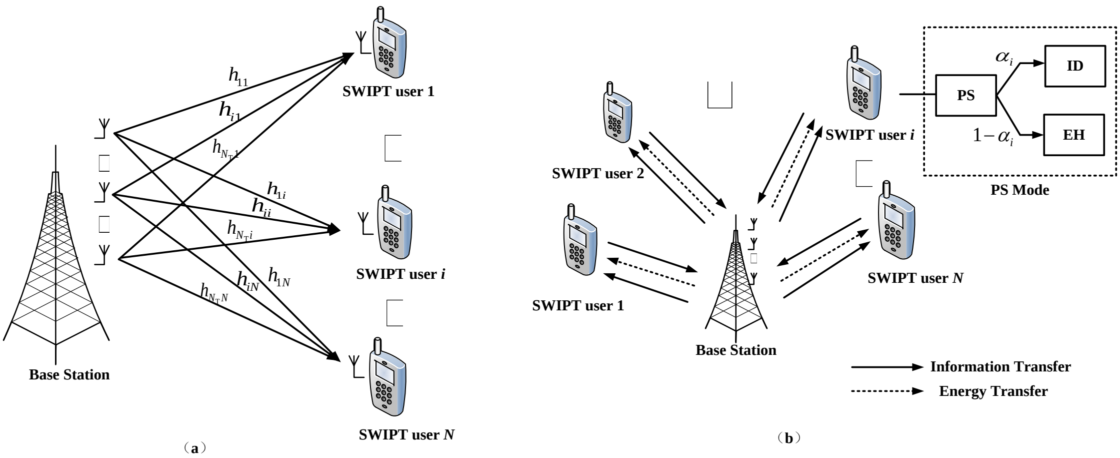


**Fig. 1.** SWIPT communication system with GFDM modulation.
(a) Downlink transmission TAS scheme;
(b) SWIPT users with PS receiver structures, they use the harvested energy for information transmission.

The downlink transmission antenna selection (TAS) [15] scheme is implemented at BS. One optimal antenna is selected for one SWIPT user via the TAS scheme. Each antenna can only be assigned to one SWIPT user, namely, each SWIPT user only receives information from the assigned optimal transmitting antenna.

Assume that $K$ subcarriers are available in the system and each subcarrier comprises $M$ subsymbols. The subcarrier set is denoted by $\boldsymbol{K}=\{1,2,3,\cdots,K\}$ while the subsymbol set is written as $\boldsymbol{M}=\{1,2,3,\cdots,M\}$. Let sub-block unit $(k,m)$ represent resource unit on the $k$th subcarrier and in the $m$th subsymbol [9]. Each sub-block is allocated to one user only. The power allocated in sub-block unit $(k,m)$ are denoted by $P_{D,\max}$ and $P_{U,\max}$ in downlink and uplink respectively, with $0 \le p_{D,k,m} \le P_{D,\max}$ and $0 \le p_{U,k,m} \le P_{U,\max}$, $k \in \boldsymbol{K}, m \in \boldsymbol{M}$ . $P_{D,\max}$ and $P_{U,\max}$ denote the maximum allowable powers in downlink and uplink respectively. Channel gains from the BS to SWIPT users in the downlink and that from SWIPT users to BS are denoted as $\boldsymbol{h}_{D,n} = \left[h_{D,n,1,1}, h_{D,n,1,2}, \cdots, h_{D,n,K,M}\right]^{\mathrm{T}}$ and $\boldsymbol{h}_{U,n} = \left[h_{U,n,1,1}, h_{U,n,1,2}, \cdots, h_{U,n,K,M}\right]^{\mathrm{T}}$, $n = 1,2,\cdots,N$ respectively.

In the downlink transmission, the $n$th SWIPT user received signal is processed with PS factor $\alpha_n$, namely, $(1-\alpha_n)$ portion power is for ID while the rest power is for non-linear EH. A sub-block allocation function $\Gamma(k,m)$ is defined to represent the optimal sub-block allocation strategy, that is, to determine which user is suitable to assign sub-block unit $(k,m)$ [9]. Specifically, each sub-block either in downlink or uplink is assigned to the SWIPT user which has the highest CSI value, namely,

$$\begin{aligned}\Gamma(k,m) &= \arg\max_{n=1,2,\cdots,N} \left|h_{D,n,k,m}\right|^2 \\ \Gamma(k^{'},m^{'}) &= \arg\max_{n=1,2,\cdots,N} \left|h_{U,n,k^{'},m^{'}}\right|^2\end{aligned} \tag{1}$$

Hence, the achievable downlink ID rate in bps/Hz can be written as

$$\gamma_D = \sum_{k=1}^{K}\sum_{m=1}^{M} R_{D,k,m} = \sum_{k=1}^{K}\sum_{m=1}^{M} \log_2\left(1+\frac{\left(1-\alpha_{\Gamma(k,m)}\right)\left|h_{D,\Gamma(k,m),k,m}\right|^2 p_{D,k,m}}{\sigma_{D,k,m}^2}\right) \tag{2}$$

where $R_{D,k,m}$ is the achievable downlink ID rate of the SWIPT user corresponding to resource sub-block $(k,m)$ [9], and $\sigma_{D,k,m}^2$ represents additive white Gaussian noise (AWGN) random variable variance.

A non-linear EH model proposed in [12-14] is implemented in practical EH process. Namely, the $n$th SWIPT user harvested energy is based on logistic function, which is modeled as

$$E_n(\alpha_n) = \frac{P_{\max}\left[\Psi(\alpha_n)-\Omega\right]}{1-\Omega}, \quad n \in \boldsymbol{N} \tag{3}$$

where $P_{\max}$ is constant that denotes the maximum EH energy [13-14]. $\Psi(\alpha_n) = \dfrac{1}{1+\exp\left[-A\left(\alpha_n \sum_{k=1}^{K}\sum_{m=1}^{M}\left|h_{D,n,k,m}\right|^2 p_{D,k,m} - B\right)\right]}$ is the traditional logistic function. Constant $\Omega = \dfrac{1}{1+\exp(AB)}$ is designed to guarantee EH a zero-input/zero-output response. $A$

and $B$ are constants which are related to circuit specifications [13-14]. Specifically, the EH circuit for SWIPT user is fixed. $A$ and $B$ are set via a standard tool shown in [13-14].

Meanwhile, $E_{\min}$ represents the minimum EH required by each SWIPT user. Otherwise, the user has to use battery for uplink transmission. If each SWIPT user has sufficient harvested energy for information transmission in the uplink, *i.e.*, the harvested energy for each SWIPT user satisfies $E_n(\alpha_n) \geq E_{\min}$ , then the achievable uplink rate in bps/Hz can be written as

$$\gamma_U = \sum_{k'=1}^{K}\sum_{m'=1}^{M} R_{U,k',m'} = \sum_{k'=1}^{K}\sum_{m'=1}^{M} \log_2\left(1+\frac{\left|h_{U,\Gamma(k',m'),k',m'}\right|^2 p_{U,k',m'}}{\sigma^2_{U,k',m'}}\right) \tag{4}$$

where $R_{U,k',m'}$ is the achievable uplink rate of sub-block unit $(k',m')$ for SWIPT user, and $\sigma^2_{U,k',m'}$ is the additive white Gaussian Noise (AWGN) random variable variance in uplink channel.

## 3. The Proposed Bidirectional Link Resource Allocation Strategy

The optimization target of our bidirectional link resource allocation strategy is the weighted sum ID rate maximization in both downlink and uplink channels, which is subject to the constraints of EH and transmit power. The original optimization is given as follows.

$$\begin{aligned}
&\max_{\gamma_D,\gamma_U} \quad w\gamma_D + (1-w)\gamma_U \\
&\text{s.t.} \quad \sum_{k=1}^{K}\sum_{m=1}^{M} p_{D,k,m} \leq P_{\text{tot}} \\
&\qquad E_n(\alpha_n) \geq E_{\min}, \quad n \in \boldsymbol{N} \\
&\qquad 0 \leq p_{D,k,m} \leq P_{D,\max}, \quad k \in \boldsymbol{K}, m \in \boldsymbol{M} \\
&\qquad 0 \leq \alpha_n \leq 1, \quad n \in \boldsymbol{N} \\
&\qquad \sum_{k'=1}^{K}\sum_{m'=1}^{M} p_{U,k',m'} \leq E_n(\alpha_n), \quad n \in \boldsymbol{N} \\
&\qquad 0 \leq p_{U,k',m'} \leq P_{U,\max}, \quad k' \in \boldsymbol{K}, m' \in \boldsymbol{M}
\end{aligned} \tag{5}$$

where $P_{\text{tot}}$ denotes BS transmit power and $w \in (0,1)$ represents the normalized weighting coefficient between the bidirectional link achievable rates. Obviously, $w=0$ and $w=1$ represent two special cases where only the uplink or downlink rate is considered. In particular, the model in [9] is the special case of our optimization problem when $w=1$ .

It is difficult to solve the above problem and obtain the optimal solution directly. An iterative algorithm is proposed to solve this optimization problem. Firstly, we obtain the PS ratio set $\{\alpha_n\}$ via the assigned bidirectional link sub-block powers $\{p_{D,k,m}\},\{p_{U,k',m'}\}$. Then, we implement Karush-Kuhn-Tucker (KKT) condition to obtain the optimal bidirectional link sub-block powers $\{p_{D,k,m}\},\{p_{U,k',m'}\}$ with a given set of PS ratio $\{\alpha_n\}$ derived in the first step [16].

Given $\{p_{D,k,m}\},\{p_{U,k',m'}\}$ , $\{\Gamma(k,m)\}$ and $\{\Gamma(k',m')\}$ , the optimization problem then becomes convex due to the convex objective despite the unknown PS ratio set $\{\alpha_n\}$ . Therefore, we can reformulate the original optimization problem shown as

$$\begin{aligned} &\max_{\gamma_D,\gamma_U} \quad w\gamma_D+(1-w)\gamma_U \\ &\text{s.t.} \quad E_n(\alpha_n)\geq E_{\min},\ n\in \boldsymbol{N} \\ &\qquad \sum_{k^{'}=1}^{K}\sum_{m^{'}=1}^{M} p_{U,k^{'},m^{'}} \leq E_n(\alpha_n),\ n\in \boldsymbol{N} \end{aligned} \tag{6}$$

The specific solution of optimization problem (6) is presented in Appendix A. According to the EH constraint, the optimal PS ratio can be obtained as below

$$\alpha_n^* = \min\left(\frac{E_{\min}}{\xi\sum_{k=1}^{K}\sum_{m=1}^{M}\left|h_{D,n,k,m}\right|^2 p_{D,k,m}}, \frac{\sum_{k^{'}=1}^{K}\sum_{m^{'}=1}^{M} p_{U,k^{'},m^{'}}}{\xi\sum_{k=1}^{K}\sum_{m=1}^{M}\left|h_{D,n,k,m}\right|^2 p_{D,k,m}}\right) \tag{7}$$

Then, given PS ratio set $\{\alpha_n\}$ and $\{\Gamma(k,m)\},\{\Gamma(k^{'},m^{'})\}$, Eq. (5) original optimization problem can be written into Lagrange function and it would be solved via Lagrange duality method [9][17]. The Lagrange function can be written as

$$\begin{aligned} L = {}& w\gamma_D+(1-w)\gamma_U+\mu\left(P_{\text{tot}}-\sum_{k=1}^{K}\sum_{m=1}^{M}p_{D,k,m}\right)+\sum_{n=1}^{N}\lambda_n\left(\xi\alpha_n\sum_{k=1}^{K}\sum_{m=1}^{M}\left|h_{D,n,k,m}\right|^2 p_{D,k,m}-E_{\min}\right) \\ &+\sum_{n=1}^{N}\tau_n\left(\xi\alpha_n\sum_{k=1}^{K}\sum_{m=1}^{M}\left|h_{D,n,k,m}\right|^2 p_{D,k,m}-\sum_{k^{'}=1}^{K}\sum_{m^{'}=1}^{M}p_{U,k^{'},m^{'}}\right) \end{aligned} \tag{8}$$

where $\mu$ is a non-negative Lagrangian multiplier related with total power constraint, $\lambda_n$ is a non-negative Lagrangian multiplier with respect to the downlink energy harvesting constraint, and $\tau_n$ is a non-negative Lagrangian multiplier concerning the uplink energy constraint. The Lagrange dual function can be derived from (8) as

$$g\left(\mu,\{\lambda_n\},\{\tau_n\}\right)=\max_{\{\{p_{k,m}\},\{p_{k^{'},m^{'}}\},\{\Gamma(k,m)\}\}} L \tag{9}$$

Therefore, the problem can be finally written as the following Lagrange dual function

$$\min_{\mu,\{\lambda_n\},\{\tau_n\}} g\left(\mu,\{\lambda_n\},\{\tau_n\}\right), \qquad \mu,\{\lambda_n\},\{\tau_n\}\geq 0 \tag{10}$$

The above optimization problem satisfies KKT condition and the optimal bidirectional link power can be computed by (11) and (12), respectively.

$$p_{D,k,m}^* = \frac{w}{\left(\mu-\left(\lambda_{\Gamma(k,m)}+\tau_{\Gamma(k,m)}\right)\xi\alpha_{\Gamma(k,m)}\left|h_{D,\Gamma(k,m),k,m}\right|^2\right)\ln 2}-\frac{\sigma_{D,k,m}^2}{\left(1-\alpha_{\Gamma(k,m)}\right)\left|h_{D,\Gamma(k,m),k,m}\right|^2} \tag{11}$$

$$p_{U,k^{'},m^{'}}^* = \frac{1-w}{\tau_{\Gamma(k^{'},m^{'})}}-\frac{\sigma_{U,k^{'},m^{'}}^2\ln 2}{\left|h_{U,\Gamma(k^{'},m^{'}),k^{'},m^{'}}\right|^2} \tag{12}$$

The Lagrange dual function (9) is a linear function of the Lagrange multipliers $\mu,\{\lambda_n\},\{\tau_n\}$, hence the problem (10) transforms into convex problem [17]. The problem would be solved via subgradients-based method [18]. Therefore, Lagrange multipliers increments $\mu,\{\lambda_n\},\{\tau_n\}$ can be written as below

$$\begin{aligned}\Delta\mu &= P_{\text{tot}} - \sum_{k=1}^{K}\sum_{m=1}^{M} p_{D,k,m} \\ \Delta\lambda_n &= \xi\alpha_n \sum_{k=1}^{K}\sum_{m=1}^{M} \left|h_{D,n,k,m}\right|^2 p_{D,k,m} - E_{n,\min} \\ \Delta\tau_n &= \xi\alpha_n \sum_{k=1}^{K}\sum_{m=1}^{M} \left|h_{D,n,k,m}\right|^2 p_{D,k,m} - \sum_{k'=1}^{K}\sum_{m'=1}^{M} p_{U,n,k',m'}\end{aligned} \tag{13}$$

Thus, the updating formula of Lagrange multipliers can be shown in below

$$\begin{aligned}\mu_{\text{new}} &= \mu - v_1\Delta\mu \\ \lambda_{\text{new}} &= \lambda_n - v_2\Delta\lambda_n \\ \tau_{\text{new}} &= \tau_n - v_3\Delta\tau_n\end{aligned} \tag{14}$$

where $v_1, v_2, v_3$ are the subgradients step sizes that are non-negative variables.

To sum up, we summarize the proposed bidirectional link resource allocation strategy in an algorithm table shown in Appendix B.

## 4. Simulation Results and Discussions

Simulation results of the proposed strategy are given with performance analysis and discussions. Rayleigh fading channels are assumed in GFDM-based multiuser SWIPT systems. Consider $N = 3$ SWIPT users in the GFDM-based system and suppose that each user has the same minimum EH requirement *i.e.*, $E_{n,\min} = E_{\min} = 30\,\text{mW}$ [9][13]. Channel bandwidth is set as $10\,\text{MHz}$, subcarrier numbers are supposed to be $K = 16$, GFDM subsymbol numbers are assumed to be $M = 3$ and the maximum harvested energy is $P_{\max} = NP_{\text{tot}} / KM$, the normalized noise power (variance) is $\sigma^2 = 1$, and the step sizes of the subgradients are set as $v_1 = v_2 = v_3 = 0.001$ [9]. Moreover, we set the parameters $A = 6400$ and $B = 0.003$ in non-linear EH which are derived from [19].

**Fig. 2** shows the relationship between sum ID rate and transmit power with different weighting coefficients. As demonstrated in the **Fig. 2**, when the transmit power is fixed, a large weighting coefficients has a large information rate under the same weighting coefficients. According to [20], sum ID rate enhances with the increasing of power. It is worth to note that when weighting coefficient $w = 1$, it equals to the mathematical model in [9] that only considers the downlink resource optimization in GFDM-based multiuser SWIPT system. We notice that the increasing trend of the sum ID rate is gentle with smaller weighting coefficient. This is because more attention should be paid to the uplink information rate in smaller weighting coefficient scenario. However, the energy required for uplink information transmission comes from the SWIPT user harvested energy in the downlink channel, which leads to the energy consumption during energy conversion process and the reduction of overall uplink transmission power.

The proposed strategy is compared with the fixed subcarrier scheme and the heuristic algorithm shown in [20-21]. Without loss of generality, we assume the number of SWIPT users is $N = 2$, GFDM subsymbol numbers is $M = 2$. Then, the specific steps of the fixed subcarrier scheme can be expressed as follows. For the first GFDM subsymbol, the odd-numbered subcarriers are allocated to SWIPT user 1 and the even-numbered subcarriers are assigned to SWIPT user 2, while for the second GFDM subsymbol, the odd-numbered subcarriers are allocated to SWIPT user 2, and the even-numbered subcarriers are assigned to SWIPT user 1. In addition, the specific steps of the heuristic algorithm can be expressed as below. For the first GFDM subsymbol, the algorithm selects the $K/2$ subcarriers with higher channel gain to SWIPT user 1 and allocates the rest subcarriers to SWIPT user 2. For the second GFDM subsymbol, the algorithm selects the $K/2$ subcarriers with higher channel gain to SWIPT user 2 and allocates the rest subcarriers to SWIPT user 1.

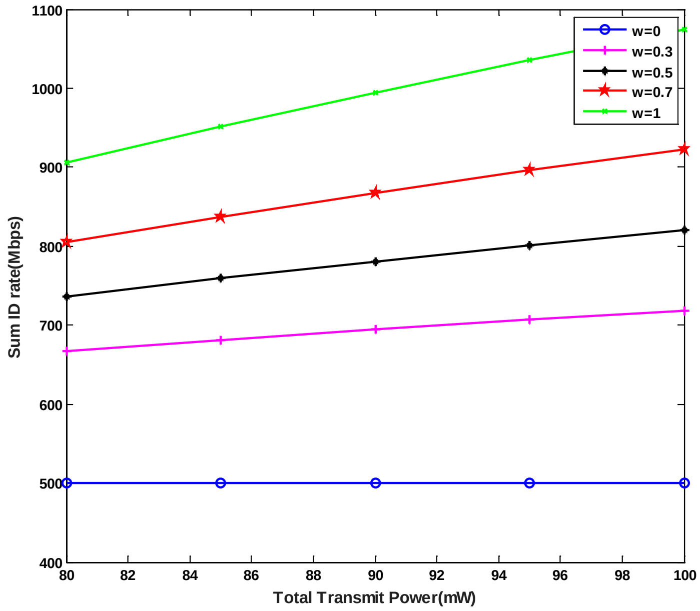


**Fig. 2.** The relationship between sum ID rate and transmit power with different weighting coefficients.

**Fig. 3** illustrates the relationship between the sum ID rate and transmit power with different schemes [7, 20-21]. It is seen that the proposed strategy obviously outperforms the compared two schemes in larger weighting coefficient case [20-21]. However, when the weighting coefficient is small, the proposed strategy is superior to "fixed subcarrier scheme" while it is slightly inferior to "heuristic algorithm". The main reason is attributed to the asymmetric CSI. Due to the fact that the uplink information rate determines more weight in the sum ID rate in this case, the proposed strategy indicates that the number of sub-blocks for one SWIPT user is significantly greater than that for other SWIPT users. Hence, when the uplink transmit power is low, the SWIPT users with more sub-blocks will be assigned less power, which results in the reduction of uplink information rate.

**Fig. 4** shows the relationship between the downlink ID rate and transmit power with different weighting coefficients. For the fixed $\alpha$ scheme, the power splitting factor is fixed as $\alpha = 0.5$. Due to the fact that the proposed strategy can update power splitting factor, it is obvious that the proposed strategy outperforms the fixed $\alpha$ scheme in the same weighting coefficient scenario.

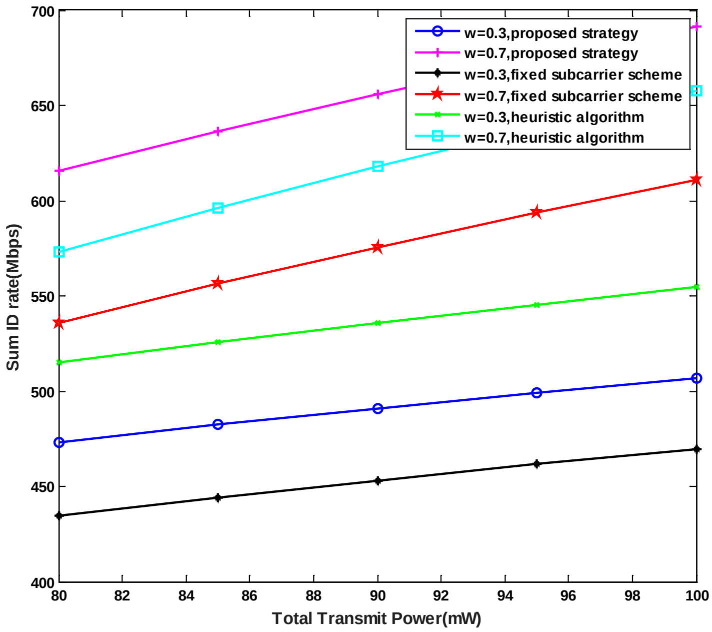


**Fig. 3.** The relationship between the sum ID rate and transmit power.

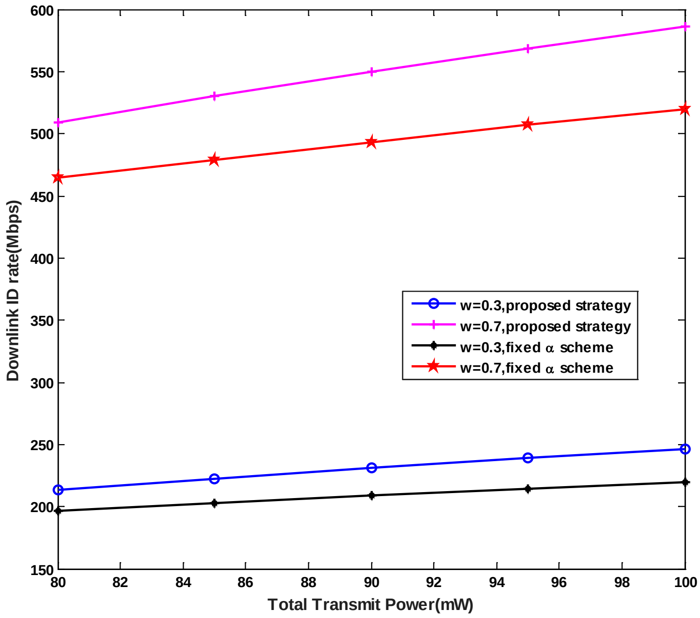


**Fig. 4.** The relationship between downlink ID rate and transmit power.

**Fig. 5** illustrates the relationship between sum ID rate and minimum EH in the case of $P_{tot}$ =100mW . As show in this figure, when the weighting coefficient $w = 0.3$, the sum ID rate increases with the increasing of the minimum EH. When the weighting coefficient $w = 0.7$, the sum ID rate decreases with the increasing of minimum EH. From optimization objective shown in (5), as the minimum EH increases, uplink ID rate improves while downlink ID rate reduces.

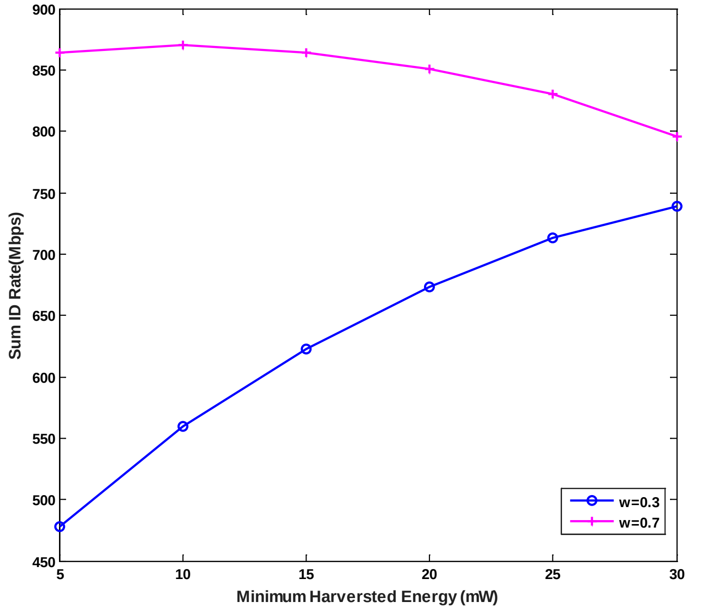


**Fig. 5.** The relationship between sum ID rate and minimum EH.

**Fig. 6** illustrates the relationship between sum ID rate and PS ratio where all SWIPT users employ the same PS ratio. It is shown that when the weighting coefficient $w = 0.3$, sum ID rate enhances with the increasing of the PS ratio. When the weighting coefficient $w = 0.7$, the sum ID rate is inversely proportional to the PS ratio. In this case, the larger PS ratio results in the greater energy harvested in the downlink channel, which is in favor of the uplink ID rate instead of the downlink ID rate.

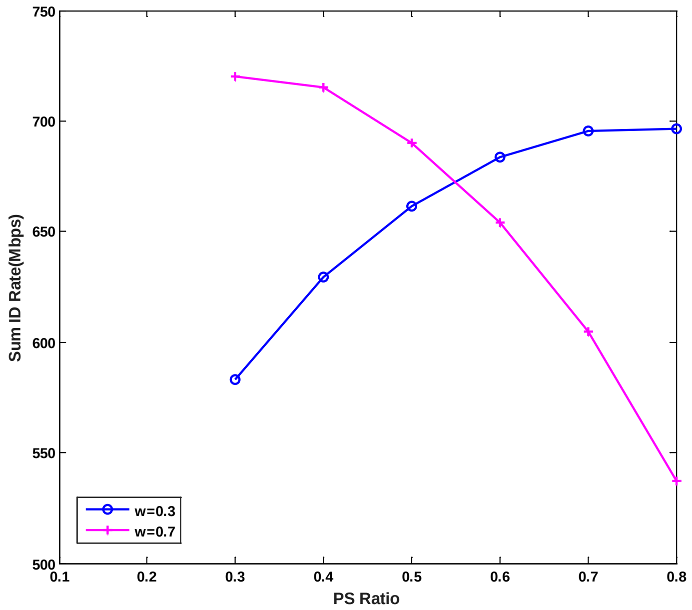


**Fig. 6.** The relationship between sum ID rate and PS ratio.

## 5. Conclusion

In this paper, we have proposed bidirectional link resource allocation strategy in GFDM-based multiuser SWIPT systems. We have investigated the weighted sum rate in bidirectional link achievable rates by allocating subcarriers and subsymbols, based on channel conditions and optimizing power allocation in bidirectional link with energy constraints. The optimal bidirectional link power is derived with analytical expression presented. Compared with the fixed subcarrier scheme and heuristic algorithm, the proposed strategy shows significant advantages. It also outperforms the fixed $\alpha$ scheme in the same weighting coefficient scenario. Simulation results confirm our theoretical derivations and analysis. Meanwhile, the appropriate beamforming design before the implementation of the proposed strategy and the computational complexity of the proposed strategy should be explored and solved. They are the further research points in the realization of the proposed bidirectional link resource allocation strategy.

## Appendixes

### A. The specific solution of optimization problem (6)

The optimization problem (6) is regarded as a function of PS ratio. Hence, the optimization problem (6) can be solved via solving the maximum value of this function. Therefore, we use the derivative method to get the optimization solution. Firstly, define a new function shown as below

$$\begin{aligned} f\left(\alpha_n\right) &= w\gamma_D + (1-w)\gamma_U \\ &= w\sum_{k=1}^{K}\sum_{m=1}^{M}\log_2\left(1+\frac{(1-\alpha_n)\left|h_{D,n,k,m}\right|^2\cdot p_{D,k,m}}{\sigma_{D,k,m}^2}\right) \\ &\quad +(1-w)\sum_{k'=1}^{K}\sum_{m'=1}^{M}\log_2\left(1+\frac{\left|h_{U,n}\right|^2 p_{U,k',m'}}{\sigma_{U,k',m'}^2}\right) \end{aligned} \tag{A1}$$

It is easily to find that the function $f\left(\alpha_n\right)$ increases with the decreasing of the PS ratio $\alpha_n$. Then, we consider the constraint conditions of the optimization problem (6). If $E_n(\alpha_n) \geq E_{\min}$, the PS ratio $\alpha_n$ can be solved as

$$\alpha_n \geq \frac{E_{\min}}{\xi\sum_{k=1}^{K}\sum_{m=1}^{M}\left|h_{D,n,k,m}\right|^2 p_{D,k,m}} \tag{A2}$$

Consider the second constraint condition $\sum_{k'=1}^{K}\sum_{m'=1}^{M} p_{U,k',m'} \leq E_n(\alpha_n)$, PS ratio can be calculated as below

$$\alpha_n \geq \frac{\sum_{k'=1}^{K}\sum_{m'=1}^{M} p_{U,k',m'}}{\xi\sum_{k=1}^{K}\sum_{m=1}^{M}\left|h_{D,n,k,m}\right|^2 p_{D,k,m}} \tag{A3}$$

Therefore, combine equations (A2) and (A3), we obtain the optimal PS ratio shown as

$$\alpha_n^* = \min\left(\frac{E_{\min}}{\xi\sum_{k=1}^{K}\sum_{m=1}^{M}\left|h_{D,n,k,m}\right|^2 p_{D,k,m}}, \frac{\sum_{k'=1}^{K}\sum_{m'=1}^{M} p_{U,k',m'}}{\xi\sum_{k=1}^{K}\sum_{m=1}^{M}\left|h_{D,n,k,m}\right|^2 p_{D,k,m}}\right) \tag{A4}$$

## B. An algorithm table of the proposed strategy

**Table 1.** Specific steps of the proposed bidirectional link resource allocation strategy

| | |
|---|---|
| Joint optimization variables: PS ratio $\alpha_n$; bidirectional link power $\{p_{D,k,m}\},\{p_{U,n,k',m'}\}$; sub-block allocation function $\Gamma(k,m);\Gamma(k',m')$. | |
| Given the normalized weighting coefficient $w$. | |
| 1: | Initialize $\{\alpha_n\}$, and calculate $\Gamma(k,m);\Gamma(k',m')$. |
| 2: | **while** $\{\alpha_n\}$ is not converge to the predefined accuracy, **do** |
| 3: | A) Initialize non-negative variables $\mu,\{\lambda_n\},\{\tau_n\}$. |
| 4: | B) **while** $\mu,\{\lambda_n\},\{\tau_n\}$ is not converge to the predefined accuracy, **do** |
| 5: | a) Calculate $\{p_{D,k,m}\},\{p_{U,n,k',m'}\}$ in accordance with (11) and (12). |
| 6: | b) Calculate the dual function $g\left(\mu,\{\lambda_n\},\{\tau_n\}\right)$ in accordance with (8). |
| 7: | c) Update $\mu,\{\lambda_n\},\{\tau_n\}$ in accordance with (14). |

8: d) **end while**
9: C) Calculate $\{\alpha_n\}$ in accordance with (7).
10: **end while**
11: **return** $\{p_{k,m}^*\},\{p_{k',m'}^*\},\{\alpha_n^*\},\{\Gamma(k,m)\};\{\Gamma(k',m')\}$.


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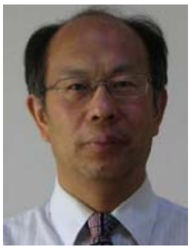

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