Energy-Efficient Full-Duplex Transmission Strategies Design in Two-Way AF Relay Networks With SWIPT

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RESEARCH

Energy-efficient full-duplex transmission strategies design in two-way AF relay networks with SWIPT

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Abstract

This paper designs two energy-efficient full-duplex transmission strategies to maximize energy efficiency (EE) of two-way amplify-and-forward relay (TWAFR) networks with simultaneous wireless information and power transfer. In the two designed transmission strategies, there are direct links (DLs) between two end nodes and the DLs can be used to convey more information. At the same time, one of the end nodes is considered battery limited and has the capability of energy harvesting from the received signals. With the first designed transmission strategy, the EE can be maximized by optimizing the power allocation, and the analytical expressions of optimal power allocation (OPA) are obtained with transformation of EE maximization problem. With the second transmission strategy, the EE can also be maximized by optimizing the power allocation, and the numerical solutions of OPA are obtained with alternating optimal algorithm. Simulations show that the EEs of the TWAFR networks can be improved with our two designed transmission strategies.

Keywords: Amplify-and-forward; Full-duplex; Simultaneous wireless information and power transfer; Direct Links; Energy efficiency

1 Introduction

Wireless networks are expected to affect all aspects of our daily lives for its ever growing and emerging applications. In the wireless networks, networks' lifetime is usually limited by the operational time of energy-constrained devices [1]. To address the problem of battery limitation in wireless devices, different energy harvesting (E-H) techniques by harvesting energy from surrounding environment are introduced. Simultaneous wireless information and power transfer (SWIPT) has emerged as a sustainable solution to the scenarios where replacing or recharging batteries is very costly and hardly [2, 3]. With SWIPT technique, since radio frequency signals can carry information and energy simultaneously, the received radio frequency signals can be utilized for EH to keep energy-constrained devices operational [4]. Existing studies adopt two different protocols to implement a SWIPT receiver architecture, namely time-switching and power-splitting (PS) protocols [5]. With these protocols, either the power or time of the received signal is split. In this way, one part of segregated resources is used for information processing, and the other is used for EH. In particular, joint transmit power and time-switching control in SWIPT cellular networks was considered in [6] to maximize device-to-device rate, and

resource allocation in a underlaid cellular network was studied in [7] to maximize device-to-device energy efficiency (EE).

Relay technique can improve reliability, enhance spectral efficiency (SE), and improve network connectivity by taking advantage of wireless links' broadcast nature [8]. The integration of SWIPT into relay networks has received significant attention, because it can improve the range of wireless communications and keep energy-constrained nodes active. Wireless-powered relay networks with SWIPT have been extensively studied with time-switching-based relaying and/or PS-based relaying [9, 10]. Specifically, the EE was maximized in [9] for the multi-user energy-constrained multi-relay network. Moreover, PS based one-way relaying and outage probability were studied in [10] to improve outage performance. Furthermore, transmission performance with non-coherent modulation was examined in [11] by considering both time-switching-based and PS-based protocols.

To enable ultra high rate applications, future wireless networks such as beyond 5G or 6G networks are expected to support extremely high data rates [8]. Therefore, SE becomes one of the main performance measures for the design and optimization of future wireless networks. It should be pointed out that only one-way relaying has been considered in [9, 10, 11], which means they suffer from SE loss to some extent with two time slots (TSs) to achieve a one-way communication. Comparing with the one-way relay networks, two-way amplify-and-forward relay (TWAFFR) networks are widely studied. The TWAFFR networks are popular not only for the SE advantage, but also for the easy implementation characteristic. The two-way relaying has SE advantage for the development of advanced digital signal processing. The advanced digital signal processing can minimize the number of TSs required for two mutually hidden nodes to exchange information via a shared half-duplex (HD) relay with physical-layer network coding (PNC) [12]. The easy implementation characteristic is mainly for amplify-and-forward (AF) relay protocol only requires coarse synchronization. Thus, the TWAFFR networks are also considered in this paper. By considering SWIPT in the TWAFFR networks, a PS ratio optimization scheme was proposed in [13] to maximize EE and a dynamic asymmetric PS scheme was proposed in [14] to minimize outage probability. However, only HD transceivers were considered in [13, 14], therefore they also partly suffer from SE loss. Thanks to technological progress in self-interference cancellation (SIC) techniques, full-duplex (FD) transceivers can be incorporated to overcome the inherent SE loss associated with HD transceivers [15, 16].

With both TWAFFR networks and FD transceivers can significant enhance SE, considering FD transceivers in the TWAFFR networks can further improve SE. Thus, a multiuser FD TWAFFR network was investigated in [17] to improve outage probability and average rate, and relay power optimization of FD TWAFFR network was analyzed in [18] to improve SE. But it should be noted that SWIPT architecture has not been considered in [17, 18]. To consider the TWAFFR networks with SWIPT, relay selection problem was discussed in [19, 20] to improve capacity. Although the FD transceivers also have been considered in [19, 20], the [19, 20] are all restricted to simplified system model. In the simplified system model, direct links (DLs) in relay transmission are assumed to be ignored. It means that the links directly source node and destination node have been ignored. Actually, to consider the DLs

Table 1 Existing Literatures Comparison with This Paper.

SWIPT	[3-7],[9-11],[13-15],[19-20],[26],this paper
TWAFR	[12-15],[17-20],[22],[24],[26],this paper
FD	[12],[15-20],this paper
DL	[10],[21-23],this paper
EE	[1],[5],[7],[9],[11-13],[15],[22],[24-26],this paper

exist in relay transmission can achieve further SE performance gain. Because DLs can be used to convey more information, and some works have been done on it. For example, authors in [21] have discussed optimal source and relay design for multiuser AF relay communication system with DLs, and authors in [22] have studied energy-efficient bidirectional transmissions with DLs to maximize EE.

Recently, the rapid development of wireless networks has led to a great concern about their energy consumption, therefore green communication has become an attractive research area no matter in industry or in academia [23]. The main goal of green communication is to consume the least energy and satisfy required quality of service (QoS) simultaneously [24]. To measure green communication, one of the most popular metrics is EE. The EE is defined as the ratio of total transmission bits to total consumed energy [25]. In order to improve EE, EE maximization problem has been investigated in several relay networks. For example, authors in [22, 24] and [12] respectively have studied EE maximization problem in HD and FD relay networks without considering SWIPT architecture, and authors in [13, 26] and [15] respectively have examined EE maximization problem in HD and FD relay networks with considering SWIPT architecture. However, it appears that the EE maximization problem of TWAFR networks with SWIPT by simultaneously considering FD transceivers and DLs has not been studied in open literature.

Motivated by the limitations of the existing related works, whose studied characteristics are summarized in Table 1, this paper designs two energy-efficient transmission strategies to maximize the EE of the TWAFR networks with SWIPT by simultaneously considering FD transceivers and DLs. To the best of our knowledge, this is the first paper to consider all of the five characteristics in the Table 1 and the contributions of this paper can be summarized as follows:

- Two energy-efficient transmission strategies are designed to maximize the EE of the TWAFR networks with SWIPT by simultaneously considering FD transceivers and DLs. For simplicity, the two designed transmission strategies can be respectively expressed as FD-SWIPT-TWAFR-2TS and FD-SWIPT-TWAFR-1TS transmission strategies in the following parts.
- In the FD-SWIPT-TWAFR-2TS transmission strategy, a bidirectional communication is achieved in two TSs. With the FD-SWIPT-TWAFR-2TS transmission strategy, the EE can be maximized by optimizing the power allocation, and the analytical expressions of optimal power allocation (OPA) are obtained with transformation of EE maximization problem.
- In the FD-SWIPT-TWAFR-1TS transmission strategy, a bidirectional communication is achieved in only one TS with the help of PNC. With the FD-SWIPT-TWAFR-1TS transmission strategy, the EE can also be maximized by optimizing the power allocation, and the numerical solutions of OPA are obtained with alternating optimal algorithm.

The remainder of this paper is organized as follows. Section 2 gives the system model. Section 3 introduces the methods. Section 4 gives the results and discussion, and followed by the conclusion in Section 5.

2 System Model

The system model is given in this section, and the transmission models of FD-SWIPT-TWAFR-2TS and FD-SWIPT-TWAFR-1TS transmission strategies can be respectively seen as Fig.1 and Fig.2. In the transmission models, there are two end nodes A and B , and one relay node R . The node R is FD node, and the node A and B are HD or FD nodes. The HD nodes are configured with a single antenna, and the FD nodes are configured with two antennas. The three-node bidirectional transmission model is the same as [12]. As it has been stated in [12], it also can be seemed as an in-band FD two-way relay point-to-point wireless transmission model. However, in [12], the relay protocol is decode-and-forward and all the signals forwarded by relay are assumed as unit signals to simplify the analysis. That is not appropriate in our work. Because this assumption cannot make full use of the AF relay protocol's characteristics to get the relay gain. What's more, different from [12], the DLs exist between two end nodes and the DLs can be used to transmit signal. The node A is an energy-constrained node and this assumption is the same as [26], i.e., the node B and R are powered by electric, while the node A is powered by battery. For the PS-based SWIPT mechanism requires no change in the receiver circuits and frame structures except for adding the EH circuit to conventional communication nodes [27], the node A in this paper harvest energy with the PS-based SWIPT mechanism. The power splitter at the node A divides the received signal into an information decoder with α portion and an energy harvester with $(1 - \alpha)$ portion [5]. The channels experience quasi-static Rayleigh fading and remain unchanged within the fixed duration of one frame $T_t = 5\text{ms}$ [28, 29]. The channels between the same two nodes are reciprocal. A central processor exists in the network. The central processor has access to all channel state information (CSI) and other required information for processing signal. At the same time, this processor feeds back the calculated data to all the network nodes and help all the nodes to receive and forward signal [26]. The transmit signals of the node A and B are respectively denoted by x_a and x_b with $E\{x_a^2\} = E\{x_b^2\} = 1$. The node A and B combine the received signals with maximum ratio combining (MRC) technique. The noises at three nodes are zero-mean symmetric complex Gaussian vector with variance σ^2 .

2.1 Capacity Analysis Model

With the considered three-node bidirectional transmission model and the fixed duration of one frame T_t , a round of bidirectional communication is accomplished [12]. Then, with Shannon capacity formula, the total capacity is given by

$$C_t = C_a + C_b = T^t W \log_2(1 + \gamma_a) + T^t W \log_2(1 + \gamma_b), \quad (1)$$

where C_a and C_b are the capacities in two directions. The γ_a and γ_b are signal-to-noise-ratios (SNRs) in two directions. The W is bandwidth and the T^t is transmit time, where $T^t \in (0, T_t]$. The transmit times in two directions can be assumed equal for fairness in this paper.

2.2 Energy Consumption Model

The total energy consumption contains transmit powers and circuit powers [26, 29]. Then, the total energy consumption is given by

$$E_t = T^t(P^t + P^c), \quad (2)$$

where P^t is the total transmit power and P^c is the total circuit power.

2.3 Problem Formulation

As it has been stated in introduction, the EE is defined as the ratio of total transmission bits to total consumed energy, and it can be expressed as $\eta = \frac{C_t}{E_t}$ [25, 26]. Thus, to maximize EE, the EE optimization problem is given by

$$\max_{C_t, E_t} \eta(C_t, E_t). \quad (3)$$

3 Methods

The details of the two designed transmission strategies and the methods to maximize the EEs of the two designed transmission strategies are given in this section.

3.1 FD-SWIPT-TWAFR-2TS Transmission Strategy

The transmission model of the FD-SWIPT-TWAFR-2TS transmission strategy is shown in Fig.1. In it, only the node R is FD node and the node A, B are HD nodes. The FD-SWIPT-TWAFR-2TS transmission strategy can complete information exchange between the node A and B in two TSs. The red and purple lines in Fig.1 respectively represent the signals transmitted in the first and second TSs.

3.1.1 Description of FD-SWIPT-TWAFR-2TS Transmission Strategy

In the first TS of the FD-SWIPT-TWAFR-2TS transmission strategy, for node A , it transmits signal $x_a(m)$ to node R and B ; for node R , it transmits signal $x_{ra}(m-1)$ to node B and it receives signal $x_a(m)$ from node A ; and for node B , it receives signal $x_a(m)$ from node A and it receives signal $x_{ra}(m-1)$ from node R . There can be a one-frame delay from node R receiving the signals $x_a(m-1)$ till it forwarding the signals $x_{ra}(m-1)$, but this pipeline delay does not compromise the transmission capacity [12]. With SIC and MRC technique, the received signals at node R and B in the first TS are respectively given by

$$y_{ar}^{2TS}(m) = \sqrt{P_a^t} h_a x_a(m) + \vartheta_r \sqrt{P_{rb}^t} \tilde{h}_{rr} x_{ra}(m-1) + n_r, \quad (4a)$$

$$y_{rb}^{2TS}(m) = \sqrt{P_{rb}^t} h_b x_{ra}(m-1) + \sqrt{P_a^t} h_a x_a(m) + n_b, \quad (4b)$$

where the $m-1$ and m are frame number. The $\tilde{h}_{ii}$ is self-interference channel gain at node i , where $i \in \{a, b, r\}$. The h_j is channel gain between node j and R , where $j \in \{a, b\}$. The h is channel gain between node A and B . The P_j^t is transmit power of node j , and the P_{rj}^t is relay transmit power to node j . The ϑ_i is residual self-interference (RSI) coefficient at node i after the node cancels interference from its own transmitter, where $\vartheta_i \in (0, 1)$ [31]. The $x_{ra}(m-1) = A_a(\sqrt{P_a^t} h_a x_a(m-1) + n_r)$ is

node R forwards signal in the first TS. The $A_j = \frac{1}{\sqrt{P_j^t |h_j|^2 + \sigma^2}}$ is amplification factor. The n_r and n_j are thermal noises at node R and j , respectively.

In the second TS of the FD-SWIPT-TWAFR-2TS transmission strategy, for node B , it transmits signal $x_b(m)$ to node R and A ; for node R , it transmits signal $x_{rb}(m-1)$ to node A and it receives signal $x_b(m)$ from node B ; for node A , it receives signal $x_b(m)$ from node B and it receives signal $x_{rb}(m-1)$ from node R . There also can be a one-frame delay from node R receiving the signals $x_b(m-1)$ till it forwarding the signals $x_{rb}(m-1)$ [12]. With SIC and MRC technique, the received signals at node R and A in the second TS are respectively given by

$$y_{br}^{2TS}(m) = \sqrt{P_b^t} h_b x_b(m) + \vartheta_r \sqrt{P_{ra}^t} \tilde{h}_{rr} x_{rb}(m-1) + n_r, \quad (5a)$$

$$y_{ra}^{2TS}(m) = \sqrt{\alpha} [\sqrt{P_{ra}^t} h_a x_{rb}(m-1) + \sqrt{P_b^t} h x_b(m) + n_a] + n_a^d, \quad (5b)$$

where $x_{rb}(m-1) = A_b(\sqrt{P_b^t} h_b x_b(m-1) + n_r)$ is node R forwards signal in the second TS, and n_a^d is additional decoding noise at node A , where $n_a^d \sim \mathcal{CN}(0, \sigma_d^2)$ [24]. As in [12], the received signals at node A and B have no self-interference. Because only node R is FD node, and the self-interference will only exist at the relay node. At the same time, different from [12], the AF relay protocol is considered in this paper and the capacity does not need to consider the lower one of the capacities in two hops. Thus, the self-interference will not effect the EE and OPA of FD-SWIPT-TWAFR-2TS transmission strategy in the following parts.

For there are two TSs in the FD-SWIPT-TWAFR-2TS transmission strategy and the transmit times in two directions are equal for fairness, the transmit times in the first and second TS of it can be expressed as $T^t = T = \frac{1}{2}T_t$. The efficiency of energy harvester is assumed to be 1 as in [26]. With it and (5b), the harvested energy of the FD-SWIPT-TWAFR-2TS transmission strategy at node A is given by

$$E_h^{2TS} = T(1 - \alpha)[P_{ra}^t |h_a|^2 + P_b^t |h|^2 + \sigma^2]. \quad (6)$$

For node A is considered battery limited, following inequality should always be met with EH constraint requirement in the SWIPT-TWAFR-2TS transmission strategy, namely

$$E_h^{2TS} \geq T(P_a^t + P_a^{ct} + P_a^{cr}), \quad (7)$$

where P_i^{ct} and P_i^{cr} respectively represent transmit and receive circuit powers of node i . The EH constraint requirement means the harvested energy at node A needs to provide the power consumption at node A .

With (1), the total capacity of the FD-SWIPT-TWAFR-2TS transmission strategy is given by

$$C_t^{2TS} = C_a^{2TS} + C_b^{2TS} = TW \log_2(1 + \gamma_a^{2TS}) + TW \log_2(1 + \gamma_b^{2TS}), \quad (8)$$

where γ_a^{2TS} and γ_b^{2TS} are SNRs in two directions of the FD-SWIPT-TWAFR-2TS transmission strategy. With (4b) and (5b), they are respectively given by

$$\gamma_a^{2TS} = \frac{|A_a|^2 P_a^t P_{rb}^t |h_a|^2 |h_b|^2 + P_a^t |h|^2}{|A_a|^2 P_{rb}^t |h_b|^2 \sigma^2 + \sigma^2}, \quad (9a)$$

$$\gamma_b^{2TS} = \frac{\alpha |A_b|^2 P_b^t P_{ra}^t |h_a|^2 |h_b|^2 + \alpha P_b^t |h|^2}{\alpha |A_b|^2 P_{ra}^t |h_a|^2 \sigma^2 + \alpha \sigma^2 + \sigma_d^2}. \quad (9b)$$

With (2), the total energy consumption of the FD-SWIPT-TWAFR-2TS transmission strategy is given by

$$E_t^{2TS} = T(P^{t2TS} + P^{c2TS}), \quad (10)$$

where $P^{t2TS} = P_a^t + P_{rb}^t + P_b^t + P_{ra}^t$, $P^{c2TS} = P_a^c + P_b^c$, and the efficiency of power amplifier is assumed to be 1 as in [26, 30]. The $P_a^c = P_a^{ct} + P_b^{cr} + P_r^{ct} + P_r^{cr} + P_r^{cs}$ and $P_b^c = P_b^{ct} + P_a^{cr} + P_r^{ct} + P_r^{cr} + P_r^{cs}$ are respectively sum circuit powers in two directions, where P_i^{cs} represents the SIC circuit power of node i with FD transceivers. The circuit powers P_i^{ct} , P_i^{cr} , and P_i^{cs} are static powers with a constant value [26, 29]. At the same time, the circuit powers are from 0 to serval hundreds of mw [29], i.e., $\{P_i^{ct}, P_i^{cr}, P_i^{cs}\} \in (0, 800)\text{mw}$. In such case, $P_a^c = P_b^c = \frac{1}{2}P^{c2TS}$ and they are constants can be further obtained.

It should be noted that linear energy harvester and power amplifier models, ideal energy harvester and power amplifier efficiencies, and static circuit power consumption model have been considered in this paper. The more complex energy harvester and power amplifier models, non-ideal energy harvester and power amplifier efficiencies, and non-linear circuit power consumption model have been considered in other papers. For example, to invest the influences of them, the complex power amplifiers and circuit power models have been considered in [12], and non-ideal power amplifier efficiencies has been considered in our recent work [22]. All of these more complex models and non-ideal efficiencies probably also can be considered in our future work, and this paper just focus on the EE maximization problem with our designed transmission strategies.

3.1.2 EE Maximization of FD-SWIPT-TWAFR-2TS Transmission Strategy

With (3) and (8)-(10), EE maximization problem of the FD-SWIPT-TWAFR-2TS transmission strategy is given by

$$\max_{C_t^{2TS}, E_t^{2TS}} \eta^{2TS} = \frac{C_t^{2TS}}{E_t^{2TS}} = \frac{C_a^{2TS} + C_b^{2TS}}{T(P^{t2TS} + P^{c2TS})}. \quad (11)$$

To be more specific, the maximizing η^{2TS} problem under QoS requirements, transmit power requirements, and EH constraint requirement is given by

$$\begin{aligned} \max_{\alpha, P_a^t, P_b^t, P_{ra}^t, P_{rb}^t} \quad & \eta^{2TS}(\alpha, P_a^t, P_b^t, P_{ra}^t, P_{rb}^t) \\ \text{s.t.} \quad & C_a^{2TS} \geq C_1, C_b^{2TS} \geq C_2, \end{aligned} \quad (12a)$$

$$0 \leq \{P_a^t, P_{rb}^t, P_b^t, P_{ra}^t\} \leq P_t^{max}, \quad (12b)$$

$$\text{and } E_h^{2TS} \geq T(P_a^t + P_a^{ct} + P_a^{cr}). \quad (12c)$$

The QoS requirements mean the minimum transmission tasks C_1 and C_2 that two end nodes need to transmit in two directions. The transmit power requirements mean the transmit powers are smaller than the maximum transmit power P_t^{max} .

From [12, 29], it can be known that EE maximization problem can be transformed into energy consumption minimization problem with the given minimum transmission tasks C_1 and C_2 . To this end, the maximizing η^{2TS} problem can be reformulated as follows

$$\min_{\alpha, P_a^t, P_b^t, P_{ra}^t, P_{rb}^t} E_t^{2TS}(\alpha, P_a^t, P_b^t, P_{ra}^t, P_{rb}^t)$$

$$\text{s.t. } C_a^{2TS}(P_a^t, P_{rb}^t) = C_1, C_b^{2TS}(\alpha, P_b^t, P_{ra}^t) = C_2, \quad (13a)$$

$$0 \leq \{P_a^t, P_{rb}^t, P_b^t, P_{ra}^t\} \leq P_t^{max}, \quad (13b)$$

$$\text{and } E_h^{2TS}(\alpha, P_b^t, P_{ra}^t) \geq T(P_a^t + P_a^{ct} + P_a^{cr}), \quad (13c)$$

where $E_t^{2TS}(\alpha, P_a^t, P_b^t, P_{ra}^t, P_{rb}^t) = T(P_a^t + P_{rb}^t + P_b^t + P_{ra}^t) + TP^{c2TS}$. As shown in (9), γ_a^{2TS} is not a function of P_b^t and P_{ra}^t , while γ_b^{2TS} is not a function of P_a^t and P_{rb}^t . Also, T and TP^{c2TS} can be regard as constants. Because T_t , P_i^{ct} , P_i^{cr} , and P_i^{cs} are all constants. In such case, to find the minimum transmit powers to exchange C_1 and C_2 bits in two directions within T_t , Shannon capacity formula in (8) and SNRs expression in (9) can be used to express transmit powers. Therefore, the above optimization problem can be equivalently reformulated into two sub-problems as

$$\min_{P_a^t, P_{rb}^t} E_a^{2TS} = P_a^t + P_{rb}^t$$

$$\text{s.t. } C_a^{2TS} = C_1, \quad (14a)$$

$$0 \leq \{P_a^t, P_{rb}^t\} \leq P_t^{max}, \quad (14b)$$

and

$$\min_{P_b^t, P_{ra}^t} E_b^{2TS} = P_b^t + P_{ra}^t$$

$$\text{s.t. } C_b^{2TS} = C_2, \quad (15a)$$

$$0 \leq \{P_b^t, P_{ra}^t\} \leq P_t^{max}. \quad (15b)$$

In order to get the analytical expression of transmit powers, α will not be optimized temporarily in the sub-problem (15) and it will be given in the following parts.

Substituting $C_a^{2TS} = C_1$ into (8), $2^{\frac{C_1}{TW}} - 1 = \gamma_a = \gamma_a^{2TS}$ can be obtained. With γ_a^{2TS} in (9a), P_{rb}^t can be expressed as the function of P_a^t as follows

$$P_{rb}^t(P_a^t) = \frac{(\gamma_a \sigma^2 - P_a^t |h|^2)(P_a^t |h_a|^2 + \sigma^2)}{|h_b|^2 (P_a^t |h_a|^2 - \gamma_a \sigma^2)} = f_1(P_a^t). \quad (16)$$

Then, the optimal P_a^t and P_{rb}^t with minimizing $P_a^t + P_{rb}^t$ can be obtained through letting the derivative of $E_a^{2TS}(P_a^t) = P_a^t + f_1(P_a^t)$ to zero and verified with $E_a^{2TS''}(P_a^t) > 0$. Finally, the optimal P_a^t , P_{rb}^t , and the minimum $P_a^t + P_{rb}^t$ can

be respectively obtained as

$$\begin{cases} P_a^t = \frac{c_2\gamma_a + \sqrt{c_1c_2\gamma_a(1+\gamma_a)}}{|h_a|^2(|h_b|^2 - |h|^2)} \\ P_{rb}^t = \frac{(|h_b|^2 - 2|h|^2)\sqrt{c_1c_2\gamma_a(1+\gamma_a)+c_3}}{|h_a|^2|h_b|^2(|h_b|^2 - |h|^2)} \\ P_a^t + P_{rb}^t = \frac{(\sqrt{c_1} + \sqrt{c_2})^2\gamma_a - |h|^2\sigma^2}{|h_a|^2|h_b|^2} \end{cases}, \quad (17)$$

where $c_1 = (|h_a|^2 - |h|^2)\sigma^2$, $c_2 = (|h_b|^2 - |h|^2)\sigma^2$, and $c_3 = c_2(|h_a|^2 - 2|h|^2)\gamma_a - |h|^2$.

Following the same solving procedure as the sub-problem (14), and substituting $C_b^{2TS} = C_2$ into (8), $2^{\frac{C_2}{T_W}} - 1 = \gamma_b = \gamma_b^{2TS}$ can be obtained. With γ_b^{2TS} in (9b), P_{ra}^t can be expressed as the function of P_b^t , namely $P_{ra}^t(P_b^t) = f_2(P_b^t)$. The optimal P_b^t and P_{ra}^t with minimizing $P_b^t + P_{ra}^t$ can also be obtained through letting the derivative of $E_b^{2TS}(P_b^t) = P_b^t + f_2(P_b^t)$ to zero and verified with $E_b^{2TS''}(P_b^t) > 0$. Finally, the optimal P_b^t , P_{ra}^t , and the minimum $P_b^t + P_{ra}^t$ can be respectively obtained as

$$\begin{cases} P_b^t = \frac{\alpha c_1\gamma_b + \sqrt{\alpha c_1(\alpha c_2 + |h_b|^2\sigma_d^2)\gamma_b(1+\gamma_b)}}{\alpha|h_b|^2(|h_a|^2 - |h|^2)} \\ P_{ra}^t = \frac{(|h_a|^2 - 2|h|^2)\sqrt{\alpha c_1(\alpha c_2 + |h_b|^2\sigma_d^2)\gamma_b(1+\gamma_b)+c_4}}{\alpha|h_a|^2|h_b|^2(|h_a|^2 - |h|^2)} \\ P_b^t + P_{ra}^t = \frac{(\sqrt{\alpha c_1} + \sqrt{\alpha c_2 + |h_b|^2\sigma_d^2})^2\gamma_b - \alpha|h|^2\sigma^2}{\alpha|h_a|^2|h_b|^2} \end{cases}, \quad (18)$$

where $c_4 = [\alpha(c_1 + c_2) + |h_b|^2\sigma_d^2]\gamma_b(|h_a|^2 - |h|^2) - \alpha[c_1|h_a|^2\gamma_b + c_2|h|^2]$.

It should be noted that the (8) is derived from the Shannon capacity formula, and the maximum achievable capacity is obtained under the given transmit powers. Thus, the transmit powers derived via this formula are the minimum which can support the required capacity. As a result, the minimum total energy consumption with a given C_1 and C_2 is obtained and the EE is the maximum. With (17) and (18), the maximum EE can be obtained as

$$\eta_{max}^{2TS} = \frac{C_t^{2TS}}{E_{tmin}^{2TS}} = \frac{2(C_1 + C_2)}{T_t(P_{min}^{2TS} + P_{c2TS})}, \quad (19)$$

where $P_{min}^{2TS} = \frac{(\sqrt{c_1} + \sqrt{c_2})^2\gamma_a - |h|^2\sigma^2}{|h_a|^2|h_b|^2} + \frac{(\sqrt{\alpha c_1} + \sqrt{\alpha c_2 + |h_b|^2\sigma_d^2})^2\gamma_b - \alpha|h|^2\sigma^2}{\alpha|h_a|^2|h_b|^2}$, $P_{c2TS} = P_a^{ct} + P_b^{cr} + P_r^{ct} + P_r^{cs} + P_b^{ct} + P_a^{cr} + P_r^{ct} + P_r^{cs}$, $\gamma_a = 2^{\frac{C_1}{WT_t}} - 1$, and $\gamma_b = 2^{\frac{C_2}{WT_t}} - 1$.

With (6) and (7), the optimal α can be obtained as

$$\alpha \leq 1 - \frac{P_a^t + P_a^{ct} + P_a^{cr}}{\zeta(P_{ra}^t|h_a|^2 + P_b^t|h|^2 + \sigma^2)}, \quad (20)$$

submitting the optimal P_a^t , P_b^t , P_{ra}^t in (17) and (18) into (20), an equation about α can be obtained. For the equation is too complex, the analytic expressions of the optimal α is not given here and the simulations can be used to show the relation between α and EE.

With (17) and (18), it can be seen that the analytic expressions of the OPA P_a^t , P_b^t , P_{ra}^t , and P_{rb}^t are obtained in the FD-SWIPT-TWAFR-2TS transmission strategy. However, it should be pointed out that the two-way relaying in the FD-SWIPT-TWAFR-2TS transmission strategy is different from the traditional two-phase PNC relaying in [26, 29, 32]. Thus, although the relay node is FD node, it

still needs two TSs to complete a bidirectional communication without the help of PNC. Considering the potentially SE gain of PNC and also to further improve EE with FD transceivers, the FD-SWIPT-TWAFR-1TS transmission strategy will be designed in the following parts.

3.2 FD-SWIPT-TWAFR-1TS Transmission Strategy

The transmission model of the FD-SWIPT-TWAFR-1TS transmission strategy is shown in Fig.2. In it, all the nodes are FD nodes. The FD-SWIPT-TWAFR-1TS transmission strategy can complete the information exchange between two end nodes A and B in only one TS. Because it can combine both the advantages of PNC and FD transceivers. The red line in Fig.2 represents the signals transmitted in the first TS.

3.2.1 Description of FD-SWIPT-TWAFR-1TS Transmission Strategy

In the first TS of the FD-SWIPT-TWAFR-1TS transmission strategy, for node R , it transmits signal $x_r(m-1)$ to node A and B , it receives signal $x_a(m)$ from node A , and it receives signal $x_b(m)$ from node B . There is also a one-frame delay from node R receiving the signals $x_a(m-1)$ and $x_b(m-1)$ till it forwarding the signals $x_r(m-1)$ [12]. With SIC and MRC technique, the received signal at node R is given by

$$y_r^{1TS}(m) = \sqrt{P_a^t} h_a x_a(m) + \sqrt{P_b^t} h_b x_b(m) + \vartheta_r \sqrt{P_r^t} \tilde{h}_{rr} x_r(m-1) + n_r, \quad (21)$$

where $x_r(m-1) = G(\sqrt{P_a^t} h_a x_a(m-1) + \sqrt{P_b^t} h_b x_b(m-1) + n_r)$ is node R forwards signal and $G = \frac{1}{\sqrt{P_a^t |h_a|^2 + P_b^t |h_b|^2 + \sigma^2}}$ is amplification factor with PNC.

At the same time, in the first TS of the FD-SWIPT-TWAFR-1TS transmission strategy, for node A , it transmits signal $x_a(m)$ to node B and R , it receives signal $x_b(m)$ from node B , and it receives signal $x_r(m-1)$ from node R . With SIC and MRC technique, the received signal at node A is given by

$$y_{ra}^{1TS}(m) = \sqrt{\alpha} [\sqrt{P_r^t} h_a x_r(m-1) + \sqrt{P_b^t} h_b x_b(m) + \vartheta_a \sqrt{P_a^t} \tilde{h}_{aa} x_a(m) + n_a] + n_a^d. \quad (22)$$

While for node B , it transmits signal $x_b(m)$ to node A and R , it receives signal $x_a(m)$ from node A , and it receives signal $x_r(m-1)$ from node R . With SIC and MRC technique, the received signal at node B is given by

$$y_{rb}^{1TS}(m) = \sqrt{P_r^t} h_b x_r(m-1) + \sqrt{P_a^t} h_a x_a(m) + \vartheta_b \sqrt{P_b^t} \tilde{h}_{bb} x_b(m) + n_b. \quad (23)$$

In the FD-SWIPT-TWAFR-1TS transmission strategy, two end nodes A and B transmit signals to node R can be seemed as the multiple access phase of PNC, and node R transmits signals to two end nodes A and B can be seemed as the broadcast phase of PNC. In such case, for two end nodes A and B know their own transmitted signals and also perfect CSI for every node is available, then self-interference terms $x_a(m-1)$ and $x_b(m-1)$ can be respectively subtracted from the received signals

$y_{ra}^{1TS}(m)$ and $y_{rb}^{1TS}(m)$ [13, 26, 32]. With the subtracted self-interference terms, the received signals at node A and B are respectively given by

$$y_{ra}^{1TS}(m) = \sqrt{\alpha}[\sqrt{P_r^t}h_a G(\sqrt{P_b^t}h_b x_b(m-1) + n_r) + \sqrt{P_b^t}h_b x_b(m)] \\ + \sqrt{\alpha}[\vartheta_a \sqrt{P_a^t} \tilde{h}_{aa} x_a(m) + n_a] + n_a^d, \quad (24a)$$

$$y_{rb}^{1TS}(m) = \sqrt{P_r^t}h_b G(\sqrt{P_a^t}h_a x_a(m-1) + n_r) + \sqrt{P_a^t}h_a x_a(m) \\ + \vartheta_b \sqrt{P_b^t} \tilde{h}_{bb} x_b(m) + n_b. \quad (24b)$$

The P_j^{cs} represents circuit power for the subtraction of self-interference terms (SIT) in the FD-SWIPT-TWAFR-1TS transmission strategy and $P_j^{cs} \in (0, 800)\text{mw}$ [29].

In this paper, all the FD nodes cancel the interference from its own transmitter by jointly using three-step interference cancelation, i.e., antenna, analog, and digital interference cancelation. Recent experimental results show that the non-linear effect of the transmitter's amplifier is the bottleneck in interference cancelation, and the RSI is mainly composed of non-linear component, which can be modeled as Gaussian noise [31]. Thus, the RSI plus thermal noise at node A can be re-expressed as $N_a = \vartheta_a \sqrt{P_a^t} \tilde{h}_{aa} x_a(m) + n_a$, and the RSI plus thermal noise at node B can be re-expressed as $N_b = \vartheta_b \sqrt{P_b^t} \tilde{h}_{bb} x_b(m) + n_b$, where $N_j \sim \mathcal{CN}(0, \sigma_j^2)$ [31].

For there is only one TS in FD-SWIPT-TWAFR-1TS transmission strategy and the transmit times in two directions are equal for fairness, the transmit time in the first TS of it can be expressed as $T^t = 2T = T_t$. With (22), the harvested energy of the FD-SWIPT-TWAFR-1TS transmission strategy at node A is given by

$$E_h^{1TS} = 2T(1 - \alpha)[P_r^t|h_a|^2 + P_b^t|h|^2 + \vartheta_a^2 P_a^t |\tilde{h}_{aa}|^2 + \sigma^2]. \quad (25)$$

For node A is considered battery limited, the following inequality also should always be met in the FD-SWIPT-TWAFR-1TS transmission strategy

$$E_h^{1TS} \geq 2T(P_a^t + P_a^{ct} + P_a^{cr} + P_a^{cs} + P_a^{c\varsigma}). \quad (26)$$

With (1), the total capacity of the FD-SWIPT-TWAFR-1TS transmission strategy is given by

$$C_t^{1TS} = C_a^{1TS} + C_b^{1TS} = 2TW \log_2(1 + \gamma_a^{1TS}) + 2TW \log_2(1 + \gamma_b^{1TS}), \quad (27)$$

where γ_a^{1TS} and γ_b^{1TS} are SNRs in two directions of the FD-SWIPT-TWAFR-1TS transmission strategy. With (24), they are respectively given by

$$\gamma_a^{1TS} = \frac{G^2 P_a^t P_r^t |h_a|^2 |h_b|^2 + P_a^t |h|^2}{G^2 P_r^t |h_b|^2 \sigma^2 + \vartheta_b^2 P_b^t |\tilde{h}_{bb}|^2 + \sigma^2}, \quad (28a)$$

$$\gamma_b^{1TS} = \frac{\alpha G^2 P_b^t P_r^t |h_a|^2 |h_b|^2 + \alpha P_b^t |h|^2}{\alpha G^2 P_r^t |h_a|^2 \sigma^2 + \alpha \vartheta_a^2 P_a^t |\tilde{h}_{aa}|^2 + \alpha \sigma^2 + \sigma_a^2}. \quad (28b)$$

With (2), the total energy consumption of the FD-SWIPT-TWAFR-1TS transmission strategy is given by

$$E_t^{1TS} = 2T(P_t^{1TS} + P^{c1TS}), \quad (29)$$

where $P^{t1TS} = P_a^t + P_b^t + P_r^t$ and $P^{c1TS} = P_a^{ct} + P_a^{cr} + P_a^{cs} + P_a^{cs} + P_b^{ct} + P_b^{cr} + P_b^{cs} + P_b^{cs} + P_r^{ct} + P_r^{cr} + P_r^{cs}$. The P^{c1TS} is also a constant. Because T_t , P_i^{ct} , P_i^{cr} , P_i^{cs} , and P_i^{cs} are all constants [29].

3.2.2 EE Maximization of FD-SWIPT-TWAFR-1TS Transmission Strategy

With (3) and (27)–(29), EE maximization problem of the FD-SWIPT-TWAFR-1TS transmission strategy is given by

$$\max_{C_t^{1TS}, E_t^{1TS}} \eta^{1TS} = \frac{C_t^{1TS}}{E_t^{1TS}} = \frac{C_a^{1TS} + C_b^{1TS}}{2T(P^{t1TS} + P^{c1TS})}. \quad (30)$$

To be more specific, the maximizing η^{1TS} problem under QoS requirements, transmit power requirements, and EH constraint requirement is given by

$$\begin{aligned} \max_{\alpha, P_a^t, P_b^t, P_r^t} \quad & \eta^{1TS}(\alpha, P_a^t, P_b^t, P_r^t) \\ \text{s.t.} \quad & C_a^{1TS} \geq C_1, \quad C_b^{1TS} \geq C_2, \end{aligned} \quad (31a)$$

$$0 \leq \{P_a^t, P_b^t, P_r^t\} \leq P_t^{max}, \quad (31b)$$

$$\text{and } E_h^{1TS} \geq 2T(P_a^t + P_a^{ct} + P_a^{cr} + P_a^{cs} + P_a^{cs}). \quad (31c)$$

Observing the SNRs expression in (28), it can be found that γ_a^{1TS} and γ_b^{1TS} are all the functions of P_a^t , P_b^t , and P_r^t . Thus, to find the minimum transmit powers to exchange the C_1 and C_2 bits in two directions within T_t , Shannon capacity formula in (27) and SNRs expression in (28) cannot be used anymore to express the transmit powers. It means that the EE maximization problem of FD-SWIPT-TWAFR-1TS transmission strategy will not be transformed into energy consumption minimization problem. Because the analytic expressions of the OPA P_a^t , P_b^t , and P_r^t cannot be obtained with this transformation. Although the analytic expressions of the OPA cannot be obtained in this way, from [26], it can be known that the numerical solutions of the OPA can be obtained with the alternating optimal algorithm. With the EE definition $\eta = \frac{C_t}{E_t}$, it can be known that the η^{1TS} can be maximized by maximizing C_t^{1TS} and minimizing E_t^{1TS} simultaneously, then the maximizing η^{1TS} problem can be more specific expressed as

$$\max_{\alpha, P_a^t, P_b^t, P_r^t} \frac{W(\log_2(1 + \gamma_a^{1TS}(P_a^t, P_b^t, P_r^t)) + \log_2(1 + \gamma_b^{1TS}(\alpha, P_a^t, P_b^t, P_r^t)))}{P_a^t + P_b^t + P_r^t + P^{c1TS}} \quad (32a)$$

$$\text{s.t. } C_a^{1TS}(P_a^t, P_b^t, P_r^t) \geq C_1, \quad C_b^{1TS}(\alpha, P_a^t, P_b^t, P_r^t) \geq C_2, \quad (32a)$$

$$0 \leq \{P_a^t, P_b^t, P_r^t\} \leq P_t^{max}, \quad (32b)$$

$$\text{and } E_h^{1TS}(\alpha, P_a^t, P_b^t, P_r^t) \geq 2T(P_a^t + P_a^{ct} + P_a^{cr} + P_a^{cs} + P_a^{cs}). \quad (32c)$$

With (25) and (26), the optimal α can be obtained as

$$\alpha \leq 1 - \frac{P_a^t + P_a^{ct} + P_a^{cr} + P_a^{cs} + P_a^{cs}}{\zeta(P_r^t|h_a|^2 + P_b^t|h|^2 + \vartheta_a^2 P_a^t|\tilde{h}_{aa}|^2 + \sigma^2)}. \quad (33)$$

Observing the objective function, it is non-convex in terms of $(\alpha, P_a^t, P_b^t, P_r^t)$ can be known. In addition, its numerator is two logarithmic functions and its denominator is linear. What's more, its numerator and denominator are differentiable.

Thus, the objective function is pseudo-concave. But the objective function is not jointly pseudo-concave in (P_a^t, P_b^t, P_r^t) , then it is quite difficult to solve this problem simultaneously. Since for any optimization problem, some of the variables can be optimized first, and then for the remaining ones [33]. Then, the EE maximization problem can be divided into four sub-optimal problems. Firstly, the EE maximization problem is concave in α for it only exists in the numerator. Thus, the related EE maximization problem has a closed-form solution with respect to it, which can be seen in (33). Secondly, the EE maximization problem is pseudo-concave in P_a^t , P_b^t , and P_r^t , respectively. The concave and pseudo-concave properties of these optimization variables can be proved with the Hessian of them. To prove these properties, we define the numerator of the objective function with respect to P_a^t as $\varphi(P_a^t)$ and calculate the Hessian of it. With $\nabla^2 \varphi(P_a^t) \leq 0$, the numerator of the objective function is concave with respect to P_a^t can be obtained. Hence, the objective function is pseudo-concave in P_a^t . Similarly, the objective function is pseudo-concave in P_b^t , P_r^t and it is concave in α with $\nabla^2 \varphi(P_b^t) \leq 0$, $\nabla^2 \varphi(P_r^t) \leq 0$, and $\nabla^2 \varphi(\alpha) \leq 0$. Finally, each sub-optimal problem can be solved with Dinkelbach's algorithm for its properties in solving non-convex fractional programming problems [34].

3.2.3 Optimal Solutions

From [26] and the above analysis, it can be known that to solve the EE maximization problem, firstly, the optimal value for α can be found while fixing other variables with the objective function. Then with the fixed α , the other optimal variables with Dinkelbach's algorithm will be found. The details of the Dinkelbach's algorithm can be seen in [26].

Since the original EE maximization problem has been divided into four sub-optimal problems, it can be solved in an alternating mode. To this end, the Algorithm 1 leads to the optimal values of each pseudo-concave function. In this regard, firstly, with $\alpha^{(n)}$, $P_a^{t(n)}$, and $P_b^{t(n)}$, the fractional programming of Dinkelbach's algorithm is adopted in order to find $P_r^{t(n+1)}$, where the superscript (n) denotes the iteration number in the Dinkelbach's algorithm. Secondly, with known $\alpha^{(n)}$, $P_b^{t(n)}$, and $P_r^{t(n+1)}$, $P_a^{t(n+1)}$ is computed. Thirdly, with known $\alpha^{(n)}$, $P_r^{t(n+1)}$, and $P_a^{t(n+1)}$, $P_b^{t(n+1)}$ is computed. Lastly, with known $P_r^{t(n+1)}$, $P_a^{t(n+1)}$, and $P_b^{t(n+1)}$, $\alpha^{(n+1)}$ is updated with (33). Consequently, the alternating optimal algorithm is required in order to optimize α , P_a^t , P_b^t , and P_r^t . Algorithm 1 presents the alternating optimal procedure which updates the optimization parameters until convergence.

From [26], it also can be known that the computational complexity of Algorithm 1 can be modeled in polynomial form in terms of variables' number. With this property, the complexity of Algorithm 1 can be given. The complexities from step 3 to step 6 are all $\mathcal{O}(1)$. Thus, the total complexity of one iteration for Algorithm 1 is $\mathcal{O}(\mathcal{I}_{d_1} + \mathcal{I}_{d_2} + \mathcal{I}_{d_3} + \mathcal{I}_{d_4})$, where $\mathcal{I}_{d_1}$, $\mathcal{I}_{d_2}$, $\mathcal{I}_{d_3}$, and $\mathcal{I}_{d_4}$ are respectively the required number of iterations from step 3 to step 6.

It should be noted that the optimal transmit times probably are not $T^t = T = \frac{1}{2}T_t$ and $T^t = 2T = T_t$ in the two designed transmission strategies, respectively. The joint optimization of transmit time and transmit power problem can be seen in our recent works [22]. At the same time, the energy-constrained node can be other nodes, such as, the node R , or not only one node is the energy-constrained node [15].

Algorithm 1 Alternating Optimal Algorithm

- 1: **Set** initial points $\alpha^{(0)}$, $P_a^{t(0)}$, $P_b^{t(0)}$, $P_r^{t(0)}$ and $n = 0$.
 - 2: **Repeat**
 - 3: Given $\alpha^{(n)}$, $P_a^{t(n)}$, and $P_b^{t(n)}$, apply the Dinkelbach's algorithm to calculate $P_r^{t(n+1)}$.
 - 4: Given $\alpha^{(n)}$, $P_b^{t(n)}$, and $P_r^{t(n+1)}$, apply the Dinkelbach's algorithm to calculate $P_a^{t(n+1)}$.
 - 5: Given $\alpha^{(n)}$, $P_r^{t(n+1)}$, and $P_a^{t(n+1)}$, apply the Dinkelbach's algorithm to calculate $P_b^{t(n+1)}$.
 - 6: Compute $\alpha^{(n+1)}$ in (33).
 - 7: $n \leftarrow n + 1$.
 - 8: **Until** Convergence.
-

All of these situations also can be discussed in the future work, and this paper just try to give a study about the EE maximization problem in the TWAFR networks with SWIPT by simultaneously considering FD transceivers and DLs.

4 Results and Discussion

In this section, simulations are carried out to evaluate the maximum EE of the two designed transmission strategies, and the simulation parameters are specified in Table 2. All the simulation results in this paper are given with 500 Monte Carlo trails within T_t based on MATLAB platform, the Win10 system, the processor: Inter (R) Core (TM) i5-8250 U CPU @ 1.60 GHz, the RAM:8.00 GB, and the system type: 64-bit operating systems. In the simulations, the EEs of two designed transmission strategies (namely FD-2TS-EH and FD-1TS-EH in the figures) are given. As a basement of comparison, the EE of traditional two-phase PNC relaying with HD transceiver in [32] is given (namely HD-2TS in the figures). To make a better comparison, the EEs of two designed transmission strategies without EH requirements (namely FD-2TS and FD-1TS in the figures) are also given.

Fig.3 shows the EEs of FD-SWIPT-TWAFR-2TS transmission strategy with zero circuit powers (ZCP) and non-zero circuit powers (NCP) situations. In ZCP situation, it means $P_i^{ct} = P_i^{cr} = P_i^{cs} = P_j^{cs} = 0$, and in NCP situation, it means $\{P_i^{ct}, P_i^{cr}, P_i^{cs}, P_j^{cs}\} \in (0, 800)$ mW. From Fig.3, three results can be found: (i) In ZCP situation, the EE of FD-2TS is the highest and the EE of HD-2TS is the lowest; (ii) In NCP situation, when the transmission rate is smaller than 1(bps/Hz), the EE of HD-2TS is the highest and the EE of FD-2TS-EH is the lowest. But when the transmission rate is high, the EE's order of three transmission schemes is almost the same as ZCP situation; (iii) When the transmission rate is low, the EEs of ZCP situation are higher than that of NCP situation in three transmission schemes.

In Fig.3, no matter in ZCP or NCP situation, the FD-2TS has FD and DLs advantages, and it also has no energy-constrained node, which finally results to the highest EE of FD-2TS. However, when the transmission rate is smaller than 1(bps/Hz) in the NCP situation, the circuit power of HD-2TS is the smallest, which finally result to the highest EE of HD-2TS. Because when the transmission rate is low, the EEs are mainly effected by the circuit powers. Thus, when the transmission rate is low, the EEs of ZCP situation are also higher than that of NCP situation. This property suggests that to reflect the EE precisely, the circuit powers should not be ignored especially when the transmission rate is low.

Table 2 Simulation Parameters.

Symbol	Definition	Values
ϑ_i	RSI ratio	0 – 1
σ^2	Noise power	−94 dBm
T_t	Frame duration	5 ms
W	System bandwidth	10 MHz
C_j	QoS requirements	(0, 0.25] Mbits
ν	Path-loss exponent	[2 – 4]
P_i^{cs}	SIT circuit power	(0, 800) mW
P_i^{cs}	SIC circuit power	(0, 800) mW
P_i^{ct}	Transmit circuit power	(0, 800) mW
P_i^{cr}	Receive circuit power	(0, 800) mW
α	Information decoding factor	0 – 1
P_t^{max}	Maximum transmit power	70 dBm

Fig.4 shows the EEs of FD-SWIPT-TWAFR-1TS transmission strategy with ZCP and NCP situations. From Fig.4, two results can be found: (i) No matter in ZCP or NCP situation, the EE of FD-1TS is the highest and the EE of HD-2TS is the lowest; (ii) When the transmission rate is low, the EEs of ZCP situation are higher than that of NCP situation in three transmission schemes. Both of these two phenomena have the similar reasons as Fig.3. However, different from Fig.3, the EE of FD-1TS is always the highest in Fig.4. Because FD-1TS only needs one TS to complete a bidirectional transmission process. This suggests that FD-1TS has the best SE, which offset the effects of circuit power when the transmission rate is low.

Fig.5 shows the EEs of FD-SWIPT-TWAFR-2TS transmission strategy with equal power allocation (EPA) and OPA. With EPA, the SNR is between 0dB to 20dB and all the nodes have the same transmit powers. From Fig.5, when transmission rate is bigger than 1(bps/Hz), it can be found that the EE of FD-2TS with OPA is the highest and the EE of HD-2TS with EPA is the lowest. Because FD-2TS has FD advantage, DLs advantage, and no energy-constrained node. At the same time, it can be found that the EEs of OPA are higher than that of EPA in three transmission schemes. This phenomenon shows the significance of OPA. It should be noted that the EEs of three transmission schemes in Fig.5 have no zero point with EPA. Because when the SNR is 0dB, the transmission rates of three transmission schemes are bigger than zero.

Fig.6 shows the EEs of FD-SWIPT-TWAFR-1TS transmission strategy with EPA and OPA. From Fig.6, it also can be found that the EE of FD-1TS with OPA is the highest and the EE of HD-2TS with EPA is the lowest. At the same time, it can be found that the EEs of OPA are also higher than that of EPA in three transmission schemes. What's more, the EEs of three transmission schemes in Fig.6 also have no zero point with EPA. These three phenomena have the similar reasons as Fig.5.

Fig.7 shows the EEs of different transmission schemes with different α . From Fig.7, two results can be found: (i) The EE of FD-1TS is higher than that of FD-2TS; (ii) The EE of FD-1TS-EH is higher than that of FD-2TS-EH. Because FD-1TS and FD-1TS-EH have better SE with one TS to complete a bidirectional transmission process. At the same time, it can be found that when the transmission rate is low, the bigger the α , the higher the EEs. However, when the transmission rate is high, the EE's difference of FD-2TS-EH with $\alpha = 0.8$ and $\alpha = 0.5$ is small and the EE's difference of FD-1TS-EH with $\alpha = 0.8$ and $\alpha = 0.5$ is also small. This shows that there exists an optimal α in FD-2TS-EH and FD-1TS-EH, and it will be verified in the Fig.8.

Fig.8 shows the EEs of FD-SWIPT-TWAFR-2TS and FD-SWIPT-TWAFR-1TS transmission strategies with different α . From Fig.8, firstly, it can be found that when $\alpha = 0.8$ and the transmission rates are respectively 2(bps/Hz), 4(bps/Hz), and 6(bps/Hz), the EEs of the two designed transmission strategies are the same as the EEs in the other Figs with the same situation. For example, when $\alpha = 0.8$ and the transmission rate is 2(bps/Hz), the EE of FD-1TS-EH is 32.13(bits/ μ J). At the same time, it can be found that when the transmission rate is low, the EE's difference between the FD-1TS-EH and FD-2TS-EH is bigger. This also can be seen in the other Figs. Both of these two phenomena show the continuity of our paper. What's more, it can be found that the EEs of FD-1TS-EH and FD-2TS-EH will no more increase when α achieves a certain value. For example, when the transmission rate is 2(bps/Hz) and $\alpha = 0.92$, the EE of FD-1TS-EH will no more increase. This shows that there exists an optimal α with the two designed transmission strategies and the optimal α corresponding to (20) and (33). However, it also should be noted that when the α is smaller than the optimal α , the bigger the α , the higher the EEs. From the SNRs, it can be found that without the EH constraint requirement, the bigger the α , the bigger the C_t^{2TS} and C_t^{1TS} , which finally results in the higher the η^{2TS} and η^{1TS} . From Fig.9, the maximum optimal α is $\alpha = 0.92$ can also be found, so $\alpha = 0.92$ will be considered in the other Figs.

Fig.9 shows the EEs of FD-SWIPT-TWAFR-1TS transmission strategy with different ϑ_i . It has been suggested in the section 3.1.1 that the self-interference with FD technique will not effect the EE of FD-SWIPT-TWAFR-2TS transmission strategy. Thus, only the EEs of FD-SWIPT-TWAFR-1TS transmission strategy with different ϑ_i will be given in Fig.9. To invest the influence of self-interference, the EEs of FD-1TS-EH with $\vartheta_i = 0.2, 0.5$, and 0.8 are given. From Fig.9, it can be found that the bigger the ϑ_i , the lower the EE of FD-1TS-EH. At the same time, when $\vartheta_i = 0.8$, the EE of FD-1TS-EH is even worse than that of HD-2TS. Both of this two phenomena show the importance of SIC with FD technique. The similar phenomenon of HD transmission strategy's EE is even higher than that of FD transmission strategy can also be seen in [12] for the effect of RSI. As it has been suggested in the section 3.2.1, perfect jointly three-step interference cancelation is used in this paper, so $\vartheta_i = 0.2$ will be considered in the other Figs.

Fig.10 shows the EEs of different transmission schemes. In Fig.10, the EEs of two proposed FD transmission strategies in [12] (namely [12]-FD-2TS and [12]-FD-1TS in the figure) are given. At the same time, to give a comparison with the simulation results, the analytical results of FD-SWIPT-TWAFR-2TS transmission strategy and the numerical results of FD-SWIPT-TWAFR-1TS transmission strategy are also given (namely FD-2TS-EH-A and FD-1TS-EH-N in the figure). In Fig.10, firstly, the EE of FD-2TS-EH-A is close to the EE's simulation result of FD-2TS-EH. At the same time, the EE of FD-1TS-EH-N is close to the EE's simulation result of FD-1TS-EH. Both of these two phenomena show the effectiveness of theoretical analysis. Secondly, the EEs of FD-2TS and FD-1TS are the highest when comparing with other 2TS and 1TS transmission schemes. Because, they have FD advantage, DLs advantage, and no energy-constrained node. Thirdly, the EE of [12]-FD-2TS and [12]-FD-1TS are respectively lower than that of FD-2TS-EH and FD-1TS-EH. Although [12]-FD-2TS and [12]-FD-1TS have no energy-constrained

nodes, they also have no DLs. At the same time, there are two DLs and only part of node A's energy will be used for EH in the FD-2TS-EH and FD-1TS-EH, which finally results in the higher EE of them.

5 Conclusion

In this paper, two energy-efficient transmission strategies have been designed to maximize the EE of the TWAFR networks with SWIPT by simultaneously considering FD transceivers and DLs. In the designed FD-SWIPT-TWAFR-2TS transmission strategy, the EE can be maximized by optimizing the power allocation, and the analytical expressions of OPA have been obtained with the transformation of EE maximization problem. In the designed FD-SWIPT-TWAFR-1TS transmission strategy, the EE can also be maximized by optimizing the power allocation, and the numerical solutions of OPA can be obtained with the alternating optimal algorithm. The simulations have shown the EE advantage of our two designed transmission strategies, which indicates the effectiveness of our two designed transmission strategies. At last, for in many communication situations the relay node is usually powered by battery and multiple-antenna technique can be more effectively to improve system's EE. Thus, the EE maximization problem of energy-constrained relay node system with multiple-antenna transmission can be discussed in the future work.

Abbreviations

EH: energy harvesting; SWIPT: simultaneous wireless information and power transfer; PS: power-splitting; EE: energy-efficiency; SE: spectral-efficiency; TS: time slot; TWAFR: two-way amplify-and-forward relay; AF: amplify-and-forward; HD: half-duplex; PNC: physical-layer network coding; SIC: self-interference cancellation; FD: full-duplex; DL: direct link; QoS: quality of service; OPA: optimal power allocation; CSI: channel state information; MRC: maximum ratio combining; SNR: signal-to-noise-ratio; RSI: residual self-interference; SIT: self-interference terms; ZCP: zero circuit powers; NCP: non-zero circuit powers; EPA: equal power allocation

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Authors' contributions

The main contributions of Caixia Cai, Han Hai, and Fengde Jia were to create the main ideas, perform theoretical analysis, and execute performance evaluation by extensive simulation while Xiaoyan Xu, Xue-Qin Jiang, and Runhe Qiu worked as the advisors to discuss, create, and advise the main ideas and performance evaluations together.

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Availability of data and materials

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Competing interests

The authors declare that they have no competing interests.

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Figures

Figure 1 FD-SWIPT-TWAFR-2TS transmission strategy. This figure depicts the transmission model of FD-SWIPT-TWAFR-2TS transmission strategy.

Figure 2 FD-SWIPT-TWAFR-1TS transmission strategy. This figure depicts the transmission model of FD-SWIPT-TWAFR-1TS transmission strategy.

Figure 3 EEs of FD-SWIPT-TWAFR-2TS with ZCP and NCP. The EEs of FD-SWIPT-TWAFR-2TS with zero circuit power and non-zero circuit power situations.

Figure 4 EEs of FD-SWIPT-TWAFR-1TS with ZCP and NCP. The EEs of FD-SWIPT-TWAFR-1TS with zero circuit power and non-zero circuit power situations.

Figure 5 EEs of FD-SWIPT-TWAFR-2TS with EPA and OPA. The EEs of FD-SWIPT-TWAFR-2TS with equal power allocation and optimal power allocation situations.

Figure 6 EEs of FD-SWIPT-TWAFR-1TS with EPA and OPA. The EEs of FD-SWIPT-TWAFR-1TS with equal power allocation and optimal power allocation situations.

Figure 7 EEs of different transmission schemes with different α . The EEs of different transmission schemes with different information decoding factor α .

Figure 8 EEs of FD-SWIPT-TWAFR-2TS and FD-SWIPT-TWAFR-1TS with different α . The EEs of FD-SWIPT-TWAFR-2TS and FD-SWIPT-TWAFR-1TS with different information decoding factor α .

Figure 9 EEs of FD-SWIPT-TWAFR-1TS with different ϑ_i . The EEs of FD-SWIPT-TWAFR-1TS with different residual self-interference ratio ϑ_i .

Figure 10 EEs of different transmission schemes. The EEs of different transmission schemes.

Figures

Figure 1

FD-SWIPT-TWAFR-2TS transmission strategy. This figure depicts the transmission model of FD-SWIPT-TWAFR-2TS transmission strategy.

Figure 2

FD-SWIPT-TWAFR-1TS transmission strategy. This figure depicts the transmission model of FD-SWIPT-TWAFR-1TS transmission strategy.

Figure 3

EEs of FD-SWIPT-TWAFR-2TS with ZCP and NCP. The EEs of FD-SWIPT-TWAFR-2TS with zero circuit power and non-zero circuit power situations.

Figure 4

EEs of FD-SWIPT-TWAFR-1TS with ZCP and NCP. The EEs of FD-SWIPT-TWAFR-1TS with zero circuit power and non-zero circuit power situations.

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Figure 8

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