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Adaptive wireless transmission strategy for maximizing energy efficiency

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Abstract

In a traditional wireless transmission system, studies about energy efficiency (EE) are usually for a fixed transmission mode. In this paper, we propose an adaptive wireless transmission (AWT) strategy with consideration of circuit power. In this AWT strategy, the transmission mode is switched between the direct transmission (DT) mode and the two-way relay transmission (TWRT) mode. The switch strategy is based on a transmission rate threshold R_{th} which makes the EEs of the DT mode and the TWRT mode equal. Furthermore, we propose a transmission rate threshold determining (TRTD) algorithm with a bisection method to find the threshold R_{th}. The simulation results also show that our AWT strategy has the maximum EE at a reasonable range of transmission rate.

Keywords: Energy efficiency (EE), Direct transmission (DT), Two-way relay transmission (TWRT), Circuit power, Adaptive wireless transmission (AWT) strategy

1 Introduction

Energy consumption in wireless transmission system has been continuously increasing to cater for the explosive growth in demand for high-data-rate wireless applications and a wide variety of diverse quality of service (QoS) requirements during the last decade. Nowadays, the wireless terminals are usually powered by batteries. It is known that high-level energy consumption has a profound influence on the wireless terminals due to the limit of battery capacity. Therefore, it is very important to reduce energy consumption of the wireless terminals and increase energy efficiency (EE) [1–3]. Recently, a lot of advanced wireless communication techniques, such as relay technique [4, 5] and small cells [6], have been adopted to provide a significant capacity improvement and reduce the energy consumption. In order to further reduce the energy consumption, there is also a lot of research work focusing on the optimal power allocation [7, 8].

A relay communication system, in which the relay forwards the signal transmitted from a source node to a destination node, has attracted a lot of attention, due to its ability in expanding the coverage, increasing the capacity, and reducing the power consumption. Two-way relay communication is a promising spectral-efficient transmission protocol for it only needs two time slots to complete a process of signal exchange [9, 10]. In such a communication technique, two source nodes exchange signals with the help of relay(s). As a result, there are two traffic flows in a two-way relay transmission (TWRT) process and they are supported by the same physical channels concurrently, which enhances spectral efficiency (SE) [11].

Most current studies on the two-way relay technique mainly focus on the relay schemes, relay selection, and resource allocation from the perspective of SE [12]. However, there are less research work focusing on EE. In [13], authors studied maximizing aggregated EE utility while provisioning proportional fairness. The power allocation schemes to improve the EE in multiuser multi-carrier two-way relay networks have been designed in [14]. The issue of resource allocation problem in orthogonal frequency division multiple access (OFDMA) two-way relay networks has been considered in [15]. Its objective is to minimize the total transmit power to improve EE. However, in these research works, only transmit power has been considered. Actually, in practical wireless transmission system, energy consumption does not only include

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transmit power but also include circuit power for non-ideal transmitter [16]. In [17], it has been demonstrated that the circuit power is consumed by signal processing and the device working in the active mode. The authors in [18] designed an optimal power allocation scheme to maximize EE for two-way amplify and forward (AF) relay networks with consideration of circuit power. Furthermore, the discussions above mainly focus on a fixed transmission mode, in which EE is not always the maximum at a range of transmission rate.

In this paper, to improve EE, we propose an adaptive wireless transmission (AWT) strategy in which the transmission mode is switched between the direct transmission (DT) mode and the TWRT mode. The switch strategy is based on a transmission rate threshold R_{th}, which makes EEs of the DT mode and the TWRT mode equal. However, the traditional metric for EE is not suitable for the subsequent analysis, and the certain threshold R_{th} cannot be found. In this work, we first investigate the transmission rates of the DT mode and the TWRT mode when the scenario of two source nodes exchanging signals is considered. Then, energy consumption ratio (ECR) which is used to evaluate EE of various kinds of transmission modes is introduced with consideration of the circuit power. The ECR is defined as minimum power consumption of unit transmission rate. Finally, we propose a transmission rate threshold determining (TRTD) algorithm with a bisection method to find the threshold R_{th}.

The main contribution of this paper can be summarized as follows:

- We give a detailed analysis of ECRs with consideration of the circuit power.
- We propose the AWT strategy in which the transmission mode is switched between the DT mode and the TWRT mode based on the threshold R_{th}. With this strategy, it can be seen that EE is always the maximum at a range of transmission rate.
- We also propose the TRTD algorithm with a bisection method to find the threshold R_{th}.

The remainder of this paper is as follows. Section 2 describes the system model. Section 3 introduces the power consumption and the metric of EE. Comparison and analysis of EE are presented in Section 4. Simulation results are presented in Section 5, followed by the conclusions in Section 6.

Notation: $y_{(\cdot)}$ denotes received signal at relay and source nodes. The transmission rate of source nodes S_1 and S_2 are denoted by R_{s_1} and R_{s_2}. R_{s} denotes the sum transmission rate. The ECRs of the DT mode and the TWRT mode are denoted by $\eta_{\mathrm{d}}$and η_{t}. The ECR of the AWT strategy is defined by $\eta_{\mathrm{a}} = \min\{\eta_{\mathrm{d}}, \eta_{\mathrm{t}}\}$. The EEs of the DT mode and the TWRT mode are denoted by $e_{\mathrm{d}}$and e_{t}. The EE of the AWT strategy is defined by $e_{\mathrm{a}} = \max\{e_{\mathrm{d}}, e_{\mathrm{t}}\}$. $w_i \sim (0, \sigma^2)$ denotes a zero-mean complex-valued additive white Gaussian noise (AWGN) with variance σ^2. The transmit power of the source nodes and the relay node are denoted by P_{s_j} $(j = 1, 2)$ and P_{r}. P_{t} denotes the power consumption. P_{c} and P_{sic} denote the circuit power and self-interference cancelation power. $E_{(\cdot)}$ represents the expectation. $f(\cdot)$ denotes the primitive function, and $f^{'}(\cdot)$ denotes the derived function.

2 System model

As shown in Fig. 1, the system model consists of two source nodes S_1 and S_2 in the DT mode. There is also a fixed relay node R working in the AF mechanism in the TWRT mode. All the nodes are equipped with a single antenna and operate in the half-duplex mechanism. The total transmission process of signal exchange is two time slots, then there is no direct connection between the nodes S_1 and S_2 in the TWRT mode. The perfect channel state information (CSI) is available at the nodes S_1 and S_2, which can adapt their transmission rates accordingly. In this paper, we assume that the channels are symmetrical.

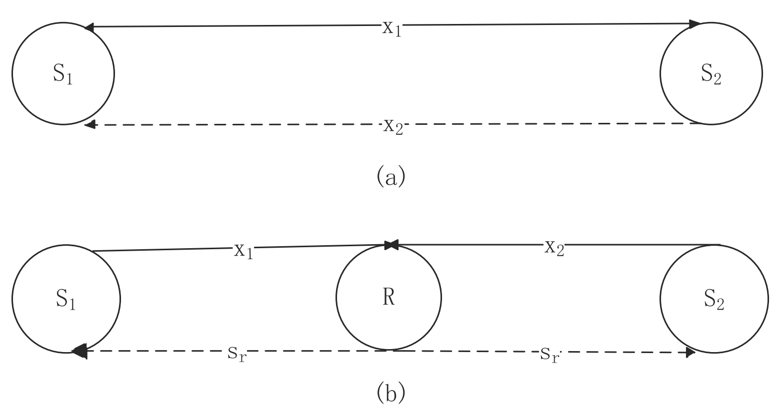

Fig. 1 The system model. **a** Direct transmission mode. **b** Two-way relay transmission mode

The channel coefficient from the node S_1 to node S_2, the nodes S_1 and S_2 to the node R is denoted by h_{ab}, $a,\ b \in \{s_1, s_2, r\}$. The channels between any two nodes are independent. $w_i \sim \left(0, \sigma^2\right), i \in \{s_j, r\}$ $(j = 1, 2)$, denotes a zero-mean complex-valued AWGN with variance σ^2. The nodes S_1 and S_2 intend to exchange their signals x_1 and x_2, respectively, with the transmit power P_{s_1} and P_{s_2}. It is assumed that $E\left\{|x_1|^2\right\} = E\left\{|x_2|^2\right\} = 1$.

2.1 DT mode

In the DT mode, the two source nodes S_1 and S_2 transmit signals to each other without the assistance of the relay node R. Two time slots are required to complete the process of signal exchange. The DT mode is shown in Fig. 1a.

In the first time slot, the source node S_1 transmits signal x_1 to the node S_2. In the second time slot, the source node S_2 transmits signal x_2 to the node S_1. The received signals y_{s_1} and y_{s_2} at the nodes S_1 and S_2 are, respectively, expressed as

$$y_{s_1} = \sqrt{P_{s_2}} h_{s_2 s_1} x_2 + w_{s_1}, \tag{1}$$

and

$$y_{s_2} = \sqrt{P_{s_1}} h_{s_1 s_2} x_1 + w_{s_2}, \tag{2}$$

where w_{s_1} and w_{s_2} denote the noise at the source nodes S_1 and S_2 .

It is stated in [13] that the transmission rates R_{s_1} and R_{s_2} with unit bandwidth are

$$R_{s_1} = \frac{1}{2}\log_2\left(1 + \frac{P_{s_2}}{\sigma^2}|h_{s_2 s_1}|^2\right), \tag{3}$$

and

$$R_{s_2} = \frac{1}{2}\log_2\left(1 + \frac{P_{s_1}}{\sigma^2}|h_{s_1 s_2}|^2\right), \tag{4}$$

where coefficient $\frac{1}{2}$ accounts for the two equal time slots. We assume that $g_{s_1 s_2} = \frac{|h_{s_1 s_2}|^2}{\sigma^2}$, which reflects the instantaneous channel gain to noise ratio (CNR) [18] from the node S_1 to node S_2. Then, the transmission rates at the two source nodes can be expressed as

$$R_{s_1} = \frac{1}{2}\log_2(1 + P_{s_2} g_{s_1 s_2}), \tag{5}$$

and

$$R_{s_2} = \frac{1}{2}\log_2(1 + P_{s_1} g_{s_1 s_2}). \tag{6}$$

2.2 TWRT mode

In a relay communication system, it can be seen that each transmission time interval (TTI) also composes of two time slot periods. In the TWRT mode, the two source nodes S_1 and S_2 transmit signal to each other through the relay node R. The TWRT mode is demonstrated in Fig. 1b.

In the first time slot, the two source nodes S_1 and S_2 respectively transmit signals x_1 and x_2 to the relay node R. The received signal y_r at the relay node R is expressed as

$$y_r = \sqrt{P_{s_1}} h_{s_1 r} x_1 + \sqrt{P_{s_2}} h_{s_2 r} x_2 + w_r, \tag{7}$$

where w_r denotes the noise at the relay node R. We let the power of y_r to be normalized, where $s_r = G y_r$ and

$$G = \frac{1}{\sqrt{P_{s_1}|h_{s_1 r}|^2 + P_{s_2}|h_{s_2 r}|^2 + \sigma^2}}. \tag{8}$$

G is an amplification factor.

In the second time slot, the relay node R will broadcast s_r to the nodes S_1 and S_2 with power P_{r}, which is the transmit power of the relay node R. The received signals $y_{s_1}{}'$ and $y_{s_2}{}'$ at the nodes S_1 and S_2 can be respectively expressed as

$$y_{s_1}{}' = \sqrt{P_{\mathrm{r}}} h_{r s_1} s_r + w_{s_1}, \tag{9}$$

and

$$y_{s_2}{}' = \sqrt{P_{\mathrm{r}}} h_{r s_2} s_r + w_{s_2}. \tag{10}$$

Since each of the nodes receives a copy of its own transmitted signal as interference, the signal transmitted from the other source node can be decoded after self-interference cancelation (SIC). The received signals y_{s_1} and y_{s_2} at the nodes S_1 and S_2 are, respectively, expressed as

$$y_{s_1} = G\left(\sqrt{P_{\mathrm{r}} P_{s_2}} h_{r s_1} h_{s_2 r} x_2 + \sqrt{P_{\mathrm{r}}} h_{r s_1} w_r\right) + w_{s_1}, \tag{11}$$

and

$$y_{s_2} = G\left(\sqrt{P_{\mathrm{r}} P_{s_1}} h_{r s_2} h_{s_1 r} x_1 + \sqrt{P_{\mathrm{r}}} h_{r s_2} w_r\right) + w_{s_2}. \tag{12}$$

The transmission rates R_{s_1} and R_{s_2} with unit bandwidth are

$$R_{s_1} = \frac{1}{2}\log_2\left(1 + \frac{P_{\mathrm{r}} P_{s_2}|h_{r s_1}|^2|h_{s_2 r}|^2}{\left(|h_{r s_1}|^2 P_{s_1} + |h_{s_2 r}|^2(P_{s_2} + P_{\mathrm{r}}) + \sigma^2\right)\sigma^2}\right), \tag{13}$$

and

$$R_{s_2} = \frac{1}{2}\log_2\left(1 + \frac{P_{\mathrm{r}} P_{s_1}|h_{r s_2}|^2|h_{s_1 r}|^2}{\left(|h_{r s_1}|^2(P_{s_1} + P_{\mathrm{r}}) + |h_{s_2 r}|^2 P_{s_2} + \sigma^2\right)\sigma^2}\right). \tag{14}$$

We assume that $g_{s_1 r} = \frac{|h_{s_1 r}|^2}{\sigma^2}$ and $g_{s_2 r} = \frac{|h_{s_2 r}|^2}{\sigma^2}$ are the CNRs from the nodes S_1 and S_2 to the node R, respectively. Since the channel is completely symmetrical, and $h_{r s_1} = h_{s_1 r}$, $h_{r s_2} = h_{s_2 r}$. Then, the transmission rates at the two source nodes can be respectively expressed as

$$R_{s_1} = \frac{1}{2}\log_2\left(1 + \frac{P_{\mathrm{r}} P_{s_2} g_{s_1 r} g_{s_2 r}}{P_{s_1} g_{s_1 r} + (P_{s_2} + P_{\mathrm{r}}) g_{s_2 r} + 1}\right), \tag{15}$$

and

$$R_{s_2} = \frac{1}{2}\log_2\left(1 + \frac{P_\mathrm{r}P_{s_1}g_{s_1r}g_{s_2r}}{(P_{s_1}+P_\mathrm{r})g_{s_1r}+P_{s_2}g_{s_2r}+1}\right). \tag{16}$$

3 Power consumption and metric of energy efficiency

In this section, we formulate the power consumptions and the metric of EEs in the DT mode and the TWRT mode. It is shown in [19] that during the entail transmission process, in addition to the transmit power P_{s_1} and P_{s_2}, mobile devices also incur additional circuit power P_c which is relatively independent of the transmission rate. Therefore, the power consumptions in the DT mode and the TWRT mode are mainly composed of the transmit power and the circuit power.

3.1 Power consumption in DT mode

It is stated in [20] that $P_\mathrm{c}$is incurred by signal processing and the device working in active mode, and it can be modeled as a linear function of the transmission rate. Then, $P_\mathrm{c}$is given by $P_\mathrm{c} = P_\mathrm{s} + \alpha R_\mathrm{s}$, where P_s is the static circuit power, α is the dynamic circuit power per unit transmission rate, and $R_\mathrm{s} = R_{s_1} + R_{s_2}$ is the sum transmission rate. In order to simplify the calculation and analysis, $\alpha = 0$ and the constant circuit power consumption model $P_\mathrm{c} = P_\mathrm{s}$ [19] is used in this paper.

Then, in the DT mode, the power consumption is composed of the transmit power and the circuit power as mentioned above. The duration of one time slot is denoted by T. Substituting $P_\mathrm{c} = P_\mathrm{s}$ into the power consumption. Consequently, the power consumption in the DT mode P_t can be calculated as

$$\begin{aligned} P_\mathrm{t} =& \frac{\left(P_{s_1}T + P_{s_2}T\right)}{2T} + P_\mathrm{c} \\ =& \frac{1}{2}(P_{s_1}+P_{s_2}) + P_\mathrm{s}. \end{aligned} \tag{17}$$

3.2 Power consumption in TWRT mode

In the TWRT mode, each of the receivers at the nodes S_1 and S_2 consumes more signal processing power than that in the DT mode owing to the SIC [21]. At the same time, the relay node needs to consume the power P_r to forward signal as it mentioned above. Let P_sic denotes the extra signal processing power for SIC. $P_\mathrm{c} = P_\mathrm{s}$ will also be substituted into the power consumption. Consequently, the power consumption in the TWRT mode P_t can be calculated as

$$\begin{aligned} P_\mathrm{t} =& \frac{\left(P_{s_1}T + (P_{s_2}+P_\mathrm{r}+2P_\mathrm{sic})T\right)}{2T} + P_\mathrm{c} \\ =& \frac{1}{2}(P_{s_1}+P_{s_2}+P_\mathrm{r}) + P_s + P_\mathrm{sic}. \end{aligned} \tag{18}$$

3.3 Metric of energy efficiency

Firstly, we use e to denote EE in this paper. Then, the EEs of the DT mode and the TWRT mode are denoted by $e_\mathrm{d}$and e_t, respectively. In order to simplify the analytical calculation, we use the ECR to evaluate EE. The ECR is the ratio of the power consumption to the sum transmission rate for 1 TTI as follows,

$$\eta = \frac{P_\mathrm{t}}{R_\mathrm{s}} = \frac{P_\mathrm{t}}{R_{s_1}+R_{s_2}}. \tag{19}$$

We assume that $\eta e = 1$. From the relationship of η and e, we can know that the denominator of the ECR can be more simple. It also can be known that the EE in this paper can be determined by the power consumption per unit transmission rate. It means that the transmission mode which consumes less power with the lower ECR will have a higher EE.

In practice, the transmission rates R_{s_1} and R_{s_2} may differ. Moreover, for $0 < R_\mathrm{s} < \infty$, there exist various rate pairs of R_{s_1} and R_{s_2} that satisfy $R_\mathrm{s} = R_{s_1} + R_{s_2}$, but the ECRs of the DT mode and the TWRT mode with different rate pairs are different. In order to compare the ECRs of the modes and transform them into a unified form which is represented by R_s, we define $R_{s_1} = \beta R_\mathrm{s}$ and $R_{s_2} = (1-\beta)R_\mathrm{s}$ to reflect such an asymmetric rate scenario, where $\beta \in (0,1)$ [22] and β is just a ratio of R_{s_1} in R_s.

3.3.1 ECR of DT mode

For an arbitrary R_s, by minimizing P_t to minimize the ECR of the DT mode, that is to maximize the EE of the DT mode, the optimal value can be found by solving the following problem,

$$\begin{aligned} P_{\mathrm{t}\min} =& \underbrace{\min}_{P_{s_1},P_{s_2}} \left\{\frac{1}{2}(P_{s_1}+P_{s_2}) + P_\mathrm{s}\right\} \\ &\text{s.t. } R_{s_1} = \beta R_\mathrm{s} \text{ and } R_{s_2} = (1-\beta)R_\mathrm{s}. \end{aligned} \tag{20}$$

Substituting $R_{s_1} = \beta R_\mathrm{s}$ and $R_{s_2} = (1-\beta)R_\mathrm{s}$ into (5) and (6), P_{s_1} and P_{s_2} in the DT mode can be calculated as

$$\begin{cases} P_{s_1} =& \dfrac{2^{2(1-\beta)R_\mathrm{s}}-1}{g_{s_1s_2}}, \\ P_{s_2} =& \dfrac{2^{2\beta R_\mathrm{s}}-1}{g_{s_1s_2}}. \end{cases} \tag{21}$$

From (17), (19), and (21), the ECR of the DT mode η_d can be expressed as

$$\begin{aligned} \eta_\mathrm{d} =& \frac{P_\mathrm{t}}{R_\mathrm{s}} = \frac{\frac{1}{2}(P_{s_1}+P_{s_2})+P_\mathrm{s}}{R_\mathrm{s}} \\ =& \frac{2^{2\beta R_s}+2^{2(1-\beta)R_\mathrm{s}}-2}{2g_{s_1s_2}R_\mathrm{s}} + \frac{P_\mathrm{s}}{R_\mathrm{s}}. \end{aligned} \tag{22}$$

3.3.2 ECR of TWRT mode

To achieve a rate pair of R_{s_1} and R_{s_2}, it is clear that we need to find P_{s_1}, P_{s_2}, and P_r from (15) and (16). Obviously, the solution is not unique, which leads to multiple choices of P_t. We need to find the minimum P_t to minimize the ECR, namely to maximize the EE as mentioned above. The minimum P_t can be found by solving the following problem,

$$P_{\text{tmin}} = \underbrace{\min}_{P_{s_1},P_{s_2},P_\text{r}} \left\{ \frac{1}{2}(P_{s_1} + P_{s_2} + P_\text{r}) + P_\text{s} + P_\text{sic} \right\}$$
$$\text{s.t. } R_{s_1} = \beta R_\text{s} \text{ and } R_{s_2} = (1-\beta)R_\text{s}. \tag{23}$$

Let us denote c_1 and c_2 as follows,

$$c_1 = 2^{2\beta R_\text{s}} - 1, c_2 = 2^{2(1-\beta)R_\text{s}} - 1. \tag{24}$$

Substituting $R_{s_1} = \beta R_\text{s}$ and $R_{s_2} = (1-\beta)R_\text{s}$ into (15) and (16), then c_1 and c_2 can be expressed as

$$c_1 = \frac{P_\text{r} P_{s_2} g_{s_1r} g_{s_2r}}{P_{s_1} g_{s_1r} + (P_{s_2} + P_\text{r}) g_{s_2r} + 1}, \tag{25}$$

$$c_2 = \frac{P_\text{r} P_{s_1} g_{s_1r} g_{s_2r}}{(P_{s_1} + P_\text{r}) g_{s_1r} + P_{s_2} g_{s_2r} + 1}. \tag{26}$$

Let (25) be divided by (26), and we can get an equation of P_{s_1}, P_{s_2}, and P_r,

$$c_2 {P_{s_2}}^2 g_{s_2r} - c_1 {P_{s_1}}^2 g_{s_1r} + c_2 P_{s_2} P_{s_1} g_{s_1r} - c_1 P_{s_1} P_{s_2} g_{s_2r} + c_2 P_{s_2} - c_1 P_{s_1} = c_1 P_{s_1} P_\text{r} g_{s_2r} - c_2 P_{s_2} P_\text{r} g_{s_1r}. \tag{27}$$

Then, P_r can be calculated as

$$P_\text{r} = \frac{(c_2 P_{s_2} - c_1 P_{s_1})(P_{s_1} g_{s_1r} + P_{s_2} g_{s_2r} + 1)}{(c_1 P_{s_1} g_{s_2r} - c_2 P_{s_2} g_{s_1r})}. \tag{28}$$

Substituting (28) into (25), we will get a equation of P_{s_1} and P_{s_2} as

$$c_2 {P_{s_2}}^2 g_{s_1r} g_{s_2r} + P_{s_2} \left(c_1 c_2 (g_{s_1r} - g_{s_2r}) - c_1 P_{s_1} g_{s_1r} g_{s_2r} \right) = 0. \tag{29}$$

As $P_{s_2} > 0$, from (29) we have the function

$$P_{s_1} = f_{s_1}(P_{s_2}) = \frac{c_2 P_{s_2} g_{s_1r} g_{s_2r} + c_1 c_2 (g_{s_1r} - g_{s_2r})}{c_1 g_{s_1r} g_{s_2r}}. \tag{30}$$

Substituting (30) into (28), we have the function

$$P_\text{r} = f_r(P_{s_2}) = \frac{P_{s_2} g_{s_2r} (c_1 g_{s_2r} + c_2 g_{s_1r}) + c_1 c_2 (g_{s_1r} - g_{s_2r}) + c_1 g_{s_2r}}{(c_1 + P_{s_2}) g_{s_1r} {g_{s_2r}}^2}. \tag{31}$$

Then, the problem in (23) can be achieved by solving the following sub-problem

$$\min(P_{s_1} + P_{s_2} + P_\text{r}) = \min \left\{ f_{s_1}(P_{s_2}) + P_{s_2} + f_r(P_{s_2}) \right\}. \tag{32}$$

It is easy to see that (32) includes only one variable P_{s_2}. The optimal P_{s_2} can be found by setting the derivative of $f(P_{s_2})$ to zero. Substituting the optimal P_{s_2} into $f_{s_1}(P_{s_2})$ and $f_r(P_{s_2})$, then, the transmit power P_{s_1}, P_{s_2}, and P_r in the TWRT mode can be calculated as

$$\begin{cases} P_{s_1} = \dfrac{c_1 + c_2}{g_{s_1r}}, \\ P_{s_2} = \dfrac{c_1 + c_2}{g_{s_2r}}, \\ P_\text{r} = \dfrac{\sqrt{(c_1 + c_2)(c_1 + c_2 + 1)}}{\sqrt{g_{s_1r} g_{s_2r}}}. \end{cases} \tag{33}$$

By substituting (24) into (33), the minimum P_t in the TWRT mode can be expressed as

$$\begin{aligned} P_{\text{tmin}} &= \underbrace{\min}_{P_{s_1},P_{s_2},P_r} \left\{ \frac{1}{2}(P_{s_1} + P_{s_2} + P_\text{r}) + P_\text{s} + P_\text{sic} \right\} \\ &= \frac{2^{2\beta R_\text{s}} + 2^{2(1-\beta)R_\text{s}} - 2}{2} \left(\frac{1}{g_{s_1r}} + \frac{1}{g_{s_2r}} \right) \\ &\quad + \frac{\sqrt{\left(2^{2\beta R_\text{s}} + 2^{2(1-\beta)R_\text{s}} - 2\right)\left(2^{2\beta R_\text{s}} + 2^{2(1-\beta)R_\text{s}} - 1\right)}}{\sqrt{g_{s_1r} g_{s_2r}}} \\ &\quad + P_\text{s} + P_\text{sic}. \end{aligned} \tag{34}$$

From (19) and (34), the ECR of the TWRT mode η_t can be expressed as

$$\begin{aligned} \eta_\text{t} = \frac{P_\text{t}}{R_\text{s}} &= \frac{2^{2\beta R_\text{s}} + 2^{2(1-\beta)R_\text{s}} - 2}{2R_\text{s}} \left(\frac{1}{g_{s_1r}} + \frac{1}{g_{s_2r}} \right) \\ &\quad + \frac{\sqrt{\left(2^{2\beta R_\text{s}} + 2^{2(1-\beta)R_\text{s}} - 2\right)\left(2^{2\beta R_\text{s}} + 2^{2(1-\beta)R_\text{s}} - 1\right)}}{\sqrt{g_{s_1r} g_{s_2r}} R_\text{s}} \\ &\quad + \frac{P_\text{s} + P_\text{sic}}{R_\text{s}}. \end{aligned} \tag{35}$$

4 Comparison and analysis of energy efficiency

4.1 Comparison of energy efficiency

In this section, the ECRs of the DT mode and the TWRT mode will be compared to get a comparison between e_d and e_t. An AWT strategy will also be designed to achieve the minimize ECR, that is to achieve the maximum EE.

The difference of ECRs between the DT mode and the TWRT mode $f(R_\text{s})$ can be expressed as follows, i.e.,

$$f(R_\text{s}) = \eta_\text{d} - \eta_\text{t}. \tag{36}$$

From (34), it is easy to see that P_t in the TWRT mode is very complicated. However, when R_s is large enough such that the following approximation can be used

$$2^{2\beta R_\text{s}} + 2^{2(1-\beta)R_\text{s}} - 2 \approx 2^{2\beta R_\text{s}} + 2^{2(1-\beta)R_\text{s}} - 1. \tag{37}$$

Substituting (37) into (36), then $f(R_s)$ can be expressed as

$$f(R_s) = \frac{2^{2\beta R_s} + 2^{2(1-\beta)R_s} - 2}{2R_s}\left[\frac{1}{g_{s_1s_2}} - \left(\frac{1}{\sqrt{g_{s_1r}}} + \frac{1}{\sqrt{g_{s_2r}}}\right)^2\right] - \frac{P_{sic}}{R_s}. \quad (38)$$

We assume that $\theta = \frac{1}{g_{s_1s_2}} - \left(\frac{1}{\sqrt{g_{s_1r}}} + \frac{1}{\sqrt{g_{s_2r}}}\right)^2$, then, when $\theta \le 0, f(R_s) < 0$ as $\frac{P_{sic}}{R_s} > 0$. Otherwise, $\theta > 0$, then, there is a uncertainty about which one of η_d and η_t is the larger. However, it can be seen that when $f(R_s) = 0$, there is a threshold R_{th} which makes the ECRs of the two kinds of transmission modes equal, that is, makes the EEs of the DT mode and the TWRT mode equal. With the threshold R_{th}, we can design an AWT strategy to decrease the ECR, namely as mentioned above to improve the EE of the wireless transmission system. The threshold R_{th} will be considered in the next section.

4.2 Analysis of energy efficiency

The threshold R_{th} can be obtained when $f(R_s) = 0$. From (38) we can get the following equation

$$2^{2\beta R_s} + 2^{2(1-\beta)R_s} - 2 = \frac{2P_{sic}}{\theta}. \quad (39)$$

We assume that $2^{2R_s} = x$, and $\frac{2P_{sic}}{\theta} = Q$. From (39), we can define a function with respect to β as follows

$$\begin{aligned} f(\beta) &= x^{\beta} + x^{(1-\beta)} \\ &= Q + 2. \end{aligned} \quad (40)$$

We take the derivative of $f(\beta)$, then $f'(\beta) = (x^{\beta} - x^{(1-\beta)})\ln x$. Since $R_s > 0$, then $x > 1$ and $\ln x > 0$. We can obtain $f'(\beta) < 0$ when $\beta \in (0, 0.5)$, and $f'(\beta) > 0$ when $\beta \in (0.5, 1)$. The minimum value of the threshold R_{th} can be found by setting the derivative of $f(\beta)$ to zero, i.e., $\beta = 0.5$. After that, the range of $f(\beta)$ is

$$2\sqrt{x} \le f(\beta) \le x + 1, \quad (41)$$

which implies $2\sqrt{x} \le Q + 2 \le x + 1$. Finally, the range of R_{th} can be computed as

$$\frac{1}{2}\log_2(Q+1) \le R_{th} \le \log_2\frac{Q+2}{2}. \quad (42)$$

Next, the range of Q will also be considered to investigate the effect with the location of the relay node R. According to [23], the channel transmission model can be expressed as

$$\bar{H}_{ab} = k(d_{ab})^{-c}, \quad (43)$$

where $\bar{H}_{ab}$ is the mean of channel gain H_{ab}, k is a constant determined by the communication environment, d_{ab} is the distance between the node a and b, and c is the path loss exponent and usually $c > 2$ [24]. Compared with the large-scale fading of the relay location, we are going to ignore the Rayleigh fading in the analysis which simplifies the mathematical analysis [23], thus Q can be expressed in terms of the inter-node distance and the channel gain is proportional to $(d_{ab})^{-c}$. In order to simplify the calculation, we assume that $k = 1$. As it is shown in Fig. 1b, $d_{s_1s_2} = d_{s_1r} + d_{s_2r}$. We also assume that $d_{s_1s_2} = 1$ and $d_{s_1r} = d$, then $d_{s_2r} = 1 - d$. The denominator of Q is θ, from the assumptions of $g_{s_1s_2}$, g_{s_1r}, and g_{s_2r}, then θ can be expressed as

$$\theta = \sigma^2\left(1 - \left((1-d)^{\frac{c}{2}} + d^{\frac{c}{2}}\right)^2\right). \quad (44)$$

From (42), we can know that the threshold R_{th} is a monotone increasing function of Q and P_{sic} is a constant. Then, the range of Q mainly depends on the value of θ. Since $N = (1-d)^{\frac{c}{2}} + d^{\frac{c}{2}} \ge 2\sqrt{(1-d)^{\frac{c}{2}}d^{\frac{c}{2}}}$, the lower bound can be obtained as $N \ge 2^{1-\frac{c}{2}}$ when $d = 0.5$. The upper bound can be obtained as $N < 1$ when d is infinitely approximate to 0 or 1. The range of θ can be found as follows

$$0 < \theta \le \sigma^2\left(1 - 2^{2-c}\right). \quad (45)$$

Consequently, the range of Q can be calculated as

$$\frac{2P_{sic}}{\sigma^2(1 - 2^{2-c})} \le Q < \infty. \quad (46)$$

Substituting (46) into (42), the range of the threshold R_{th} which makes the ECRs of the DT mode and the TWRT mode equal can be determined.

Based on the analysis above, it is clear that the threshold R_{th} is just a range of transmission rate. The threshold R_{th} varies with β which is also a variable rather than a certain value. Therefore, the certain threshold R_{th} cannot be found. From the perspective of a certain threshold R_{th}, the TRTD algorithm with the bisection method which is offline will be used to find the threshold R_{th}. This TRTD algorithm is presented in Algorithm 1.

With the TRTD algorithm, the threshold R_{th} will be found. Then, we can design the AWT strategy to achieve an energy-efficient adaptive transmission. The ECR of the AWT strategy is defined by η_a and $\eta_a = \min\{\eta_d, \eta_t\}$. In the AWT strategy, at first the wireless transmission system is working in the DT mode. When $\theta \le 0$, then $\eta_a = \eta_d$, and the system keeps working in the DT mode. Otherwise, when $\theta > 0$, then, we compare R_s and R_{th} according to Algorithm 1. If $R_s \le R_{th}$, and $\eta_a = \eta_d$, the system still keeps working in the DT mode. The system will change its working mode to the TWRT mode unless $\theta > 0, R_s > R_{th}$, and $\eta_a = \eta_t$.

Algorithm 1 TRTD algorithm

```
Initialize: R_sl = 0, R_su = 0, R_sm = 0 and n = 0, where R_sl, R_su are the lower and upper bound of R_th, R_sm is the average of R_sl and R_su, and n is the number of iterations.
Initialize: P_sic, c, k, σ^2, d, β.
Compute R_sl and R_su according to (42) and (46).
while abs(R_su − R_sl) > ε do, where ε is a small positive constant to control convergence accuracy.
    Set R_th = R_sm.
    Set n = n + 1.
    if f(R_sl)f(R_sm) < 0 then
        R_su = R_th.
    else if f(R_sm)f(R_su) < 0 then
        R_sl = R_th.
    else f(R_sm) = 0
        R_sm = R_th, break.
    end if
end while
```

From the AWT strategy, we can know that when $f(R_s) \leq 0$, the transmission mode of the wireless transmission system will be the DT mode and the relay node is in a state of sleep. When $f(R_s) > 0$, the transmission mode of the wireless transmission system will be the TWRT mode and the source node sends a request (REQ) to the relay node. The relay node changes it state into active and meanwhile the relay node sends an acknowledgement (ACK) to the source node. Then, the TWRT mode will be set up. With the AWT strategy, the ECR is the minimum, then the EE of the wireless transmission system is always the maximum at a range of transmission rate.

5 Simulation results

In this section, in order to confirm the validity of the analytical expressions, the simulation results are conducted. The EE of the AWT strategy is denoted by e_a, where $e_a = \max\{e_d, e_t\}$. To evaluate and compare the EEs with various transmission modes, without loss of generality, the Rayleigh fading channel and the AWGN model is considered in the Monte Carlo simulation. It is assumed that $c = 4$, and the noise variance is 1.

5.1 EE comparison with ideal and practical power systems

As a baseline for comparison, we first compare the EEs of the DT mode and the TWRT mode with consideration of the ideal and the practical power system. In the ideal power system, $P_s = 0$. In the practical power system, $P_s = 1$ W and $P_{sic} = 0.1$ W. The other simulation parameters are given as $\beta = 0.5$ and $d = 0.5$.

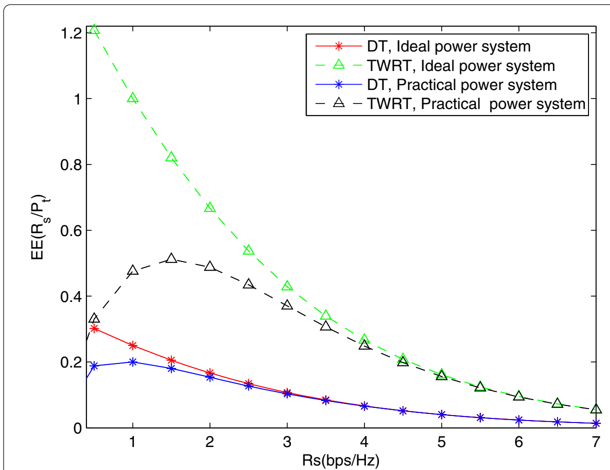

Fig. 2 EE comparison between ideal and practical power system

In Fig. 2, the following observations are obtained. (i) The EEs of the TWRT mode are always better than that of the DT mode. This shows the effectiveness of the relay technique in increasing the capacity and reducing the power consumption. (ii) When R_s is low, the EEs of the ideal power system are always better than that of the practical power system, both in the DT mode and the TWRT mode. This implies the importance to consider the practical power consumption since it influences EE greatly and cannot be ignored.

5.2 EE comparison with effects of different parameters

In this subsection, the EE comparison with the effects of different parameters will be presented based on the theories mentioned above.

In Fig. 3, the EE comparison with the effect of P_s are depicted. The simulation parameters are $\beta = 0.5$, $d = 0.5$, and $P_{sic} = 0.1$ W. The P_s are 0.1, 1, and 10 W, respectively. It can be seen from Fig. 3 that the EEs firstly increase with the increasing of R_s and then decrease. This is because for $R_s \in (0, 7)$, there is a point which makes $\frac{R_s}{P_t}$ the maximum and this is determined by the ECR. The EEs also gradually become worse with the increasing of P_s both in the DT mode and the TWRT mode. It demonstrates the necessity to consider P_s in the wireless transmission system.

In Fig. 4, the EE comparison with the effect of P_{sic} are depicted. The simulation parameters are $\beta = 0.5$, $d = 0.5$, and $P_s = 0.1$ W. The P_{sic} are 0.1, 1, and 10 W, respectively. It can be seen from Fig. 4 that the EEs of the TWRT mode gradually become worse with the increasing of P_{sic} and the EEs of the TWRT mode are not always better than that of the DT mode. We can know that when P_{sic} is big enough, the effectiveness of the relay technique will also be offset, and it demonstrates the significance of P_{sic}.

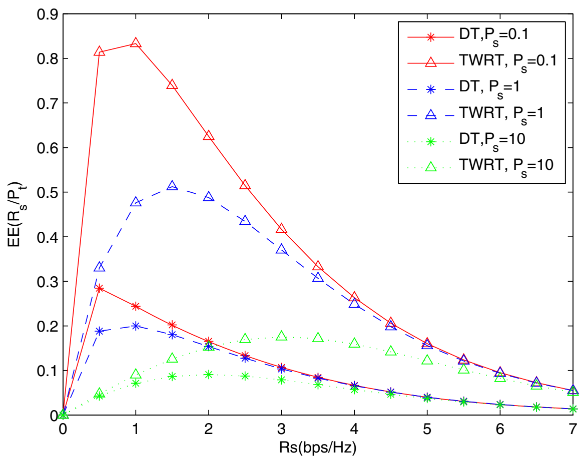

Fig. 3 EE comparison with the effect of P_s

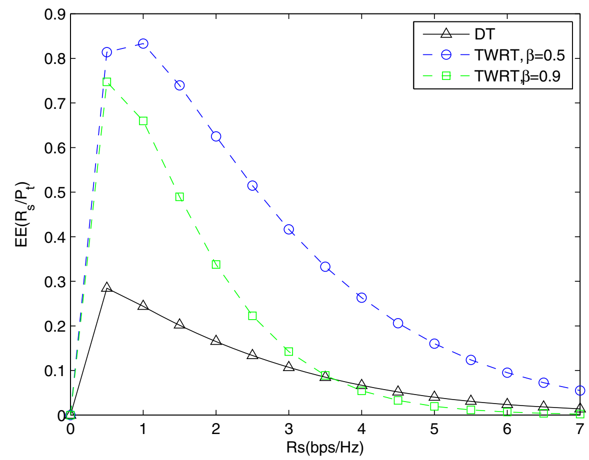

Fig. 5 EE comparison with the effect of β

In Fig. 5, the EE comparison with the effect of β are depicted. The simulation parameters are given as $d = 0.5$, $P_s = 0.1$ W, and $P_{sic} = 0.1$ W. In the DT mode, β is 0.5, and in the TWRT mode, β are 0.5 and 0.9, respectively. It is shown in Fig. 5 that the EE of the DT mode is even better than that of the TWRT mode when R_s is high and $\beta = 0.9$. The EE of the TWRT mode when $\beta = 0.5$ reaches the best status. It shows the significance of the value with β. It means that when the rate pair of R_{s_1} and R_{s_2} are equal, namely the rate task of the source nodes S_1 and S_2 are equal, we will get the maximum EE of the system. This is because in such situation, the channel conditions between any two nodes will not be bad and the relay can forward the signal effectively.

In Fig. 6, the EE comparison with the effect of d are depicted. The simulation parameters are given as $\beta = 0.5$, $P_s = 1$ W, and $P_{sic} = 0.1$ W. d are 0.5 and 0.8, respectively. It is shown in Fig. 6 that the EE of the TWRT mode when $d = 0.8$ (the relay node is closer to the node S_2) is better than that of the DT mode. The effectiveness of the relay technique can still be shown. The EE of the TWRT mode when $d = 0.5$ (the relay node is just in the middle of the node S_1 and the node S_2) is the best. This is because when the relay node is in the middle of the two nodes, the relay node can maximize its advantages of increasing the capacity and reducing the power consumption. It confirms the significance of optimizing the location of the relay node.

5.3 EEs comparison with various transmission schemes

In this subsection, the EEs comparison with various transmission schemes are provided. The simulation parameters are $\beta = 0.9$, $d = 0.5$, $P_s = 1$ W, and $P_{sic} = 1$ W.

It is shown in Fig. 7 that the EE of the TWRT mode is not always better than that of the DT mode when R_s

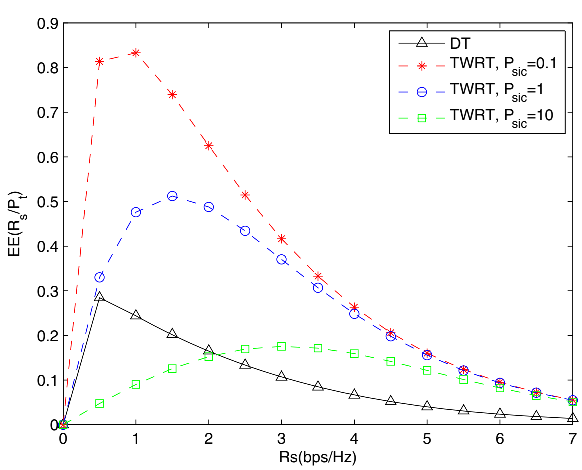

Fig. 4 EE comparison with the effect of P_{sic}

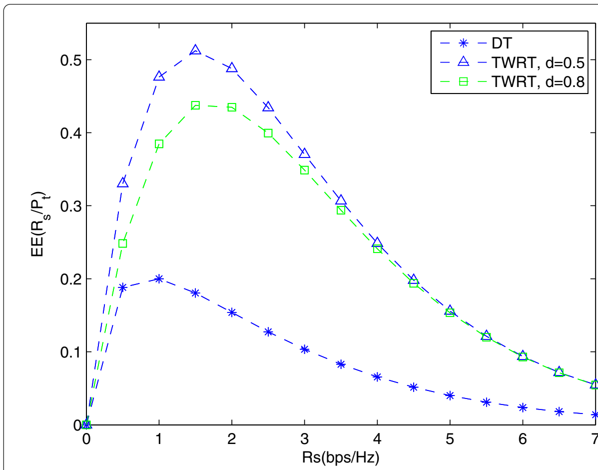

Fig. 6 EE comparison with the location of relay

is low. This is because the relay node R consumes the power to forward the noise for the unreasonable rate pairs with $\beta = 0.9$. It also can be seen that when R_s is about 3.5 (bps/Hz), the EEs of the DT mode and the TWRT mode are equal. Obviously, the threshold $R_{th} = 3.5$ (bps/Hz). With the AWT strategy when R_s is smaller than or is equal to 3.5 (bps/Hz), the EE is equal to that of the DT mode. But when R_s is higher than 3.5 (bps/Hz), the EE is equal to the one of the TWRT mode. This is because the EE of our AWT strategy is the maximum of e_d and e_t and all these results are in accordance with our analysis.

It can be seen from the simulation results that the theoretical analysis is correct. The EE is closely related with the relevant parameters, such as P_c, P_{sic}, β, and d. The EE in our AWT strategy is always the maximum at a range of transmission rate. Evidently, it demonstrates the effectiveness of our proposed AWT strategy.

6 Conclusions

In this paper, to improve EE, we have proposed an AWT strategy with consideration of the circuit power in which the transmission mode was switched between the DT mode and the TWRT mode. The switch strategy was based on a transmission rate threshold, which made the EEs of the DT mode and the TWRT mode equal. The TRTD algorithm with a bisection method has been used to find the threshold. The analytical and simulation results have also shown that our AWT strategy was more efficient at a reasonable range of transmission rate. Future work can consider the position of the relay node more specifically and practically. The two-way full-duplex model to improve EE and SE at the same time can also be considered.

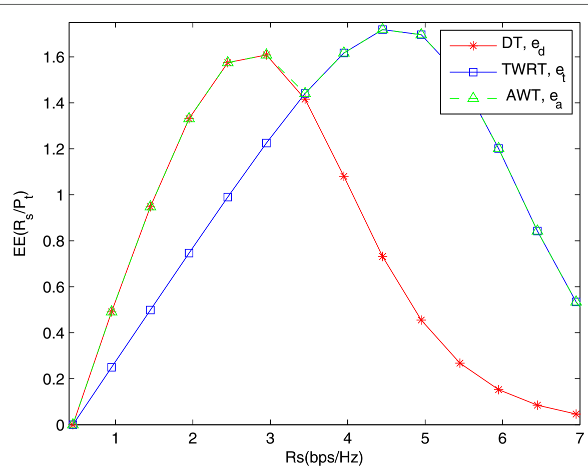

Fig. 7 EE comparison with various transmission modes

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Competing interests
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