ENERGY EFFICIENT HYBRID ONE-WAY AND TWO-WAY RELAY TRANSMISSION STRATEGY

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ABSTRACT

In this paper, we design energy efficient relay transmission strategy in a system where two source nodes transmit to each other assisted by an amplify-and-forward relay node. We first compare the energy efficiencies (EEs) between one-way relay transmission (OWRT) and two-way relay transmission (TWRT), which shows that when the bidirectional data amounts are equal, TWRT performs better, otherwise, OWRT may offer higher EE. To achieve the maximal EE in various settings, we propose hybrid relay transmission (HRT) that transmits partial messages with OWRT and the remaining messages with TWRT, and jointly optimize the data amounts and transmission time allocated to the OWRT and TWRT parts. Simulation results show the superiority of the HRT over both OWRT and TWRT.

Index Terms— energy efficiency, one-way relay, two-way relay, hybrid relay

1. INTRODUCTION

Since the explosive growth of wireless services is sharply increasing their contribution to the carbon footprint and the operating costs, energy efficiency (EE) has drawn more and more attention recently as a new design goal for various systems [1].

Relaying is viewed as an energy saving technique because it can reduce the transmit power by breaking one long range transmission into several short range transmissions. Recently, the EEs of one-way relay transmission (OWRT) and two-way relay transmission (TWRT) [2] have been studied and compared, by taking into account not only the power consumption (PC) for transmitting information bits, but also the power consumed by various signaling [3] and circuits [4,5] in practical systems. Although TWRT offers higher spectral efficiency (SE) than OWRT for half-duplex relay node, it is not always more energy efficient than OWRT. It was shown that when the system operates at the region of high SE, TWRT is more energy efficient, otherwise OWRT may offer higher EE, when both TWRT and OWRT transmit with optimized transmit powers [5].

In this paper we further compare the maximal EEs of TWRT and OWRT in a more general case, where the bidirectional data amounts are different and the transmit power and time for different phases are jointly optimized. We consider a simple amplify-and-forward (AF) relay system where two source nodes intend to exchange messages. We find that TWRT offers higher EE than OWRT with symmetric data amounts, while it may be less energy efficient than OWRT under asymmetric data amounts. To ensure maximal EE for various settings, we design a hybrid relay transmission (HRT) strategy by combining one-way and two-way relaying. By adjusting the data amounts allocated to the OWRT and TWRT parts, the proposed HRT can degenerate into either OWRT or TWRT. By jointly optimizing the data amounts allocation and transmission time, HRT always achieves maximal EE no matter if the data amounts in two directions are identical or not.

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2. SYSTEM MODEL

Consider a system consisting of two source nodes $\mathbb{A}$ and $\mathbb{B}$, and a half-duplex AF relay $\mathbb{R}$, each equipped with a single antenna. The transmission is divided into multiple blocks, each with a time duration of T. In each block, nodes $\mathbb{A}$ and $\mathbb{B}$ respectively intends to transmit messages of B_{ab} and B_{ba} bits to each other with bandwidth W, and the direct link is not considered for transmission. We assume frequency-flat block fading channels, where h_{ar} and h_{br} denote the channels from nodes $\mathbb{A}$ and $\mathbb{B}$ to node $\mathbb{R}$, respectively. Perfect channel knowledge is assumed at each node, and the noise power N_0 is assumed to be identical at each node.

To reduce the energy consumption (EC), the system may not use the entire duration T for transmission in each block. After the B_{ab} and B_{ba} bits have been transmitted, the nodes can operate in an idle status until next block. In other words, each node has three modes: transmission, reception and idle, whose circuit PCs are respectively P^{ct}, P^{cr} and P^{ci}. It is reasonable to assume that $P^{ci} \leq P^{ct}$ and $P^{ci} \leq P^{cr}$. The circuit PCs at each node are assumed identical. We consider the case that all the circuit PCs are dominated by the radio-frequency circuit PCs, which can be modeled as constants independent of data rate [6].

3. ENERGY EFFICIENCIES OF ONE-WAY AND TWO-WAY RELAYING

In this section, we compare the maximal EEs of OWRT and TWRT. The EE is defined as the number of bits transmitted per unit of energy, i.e., $\eta_{EE} = (B_{ab} + B_{ba})/E$, where E is the EC per block.

For given data amounts B_{ab} and B_{ba}, the maximal η_{EE} can be obtained by minimizing the EC. In the following, we respectively introduce the EC models of OWRT and TWRT.

3.1. One-way Relaying

During each block, the system allocates duration T_{ab} for $\mathbb{A} \rightarrow \mathbb{B}$ transmission, which is completed in two phases. In the first phase, node $\mathbb{A}$ transmits to the relay, while node $\mathbb{B}$ is idle. In the second phase, the relay forwards its received signal to node $\mathbb{B}$, while node $\mathbb{A}$ is idle. With AF relay protocol, the two phases employ identical time duration $T_{ab}/2$. The energy consumed during T_{ab} is given by

$$E_{ab}(B_{ab}, T_{ab}, P_a^t, P_r^t) = T_{ab}[(P_a^t + P_r^t)/(2\epsilon) + P_O^c], \quad (1)$$

where P_a^t and P_r^t are respectively the transmit powers of nodes $\mathbb{A}$ and $\mathbb{R}$, $\epsilon \in (0, 1]$ denotes the power amplifier efficiency, the factor $1/2$ is because each of the nodes $\mathbb{A}$ and $\mathbb{R}$ only transmits with duration of $T_{ab}/2$, and P_O^c is the total circuit PC, which is

$$P_O^c \triangleq P^{ct} + P^{cr} + P^{ci}, \tag{2}$$

because there is always one transmitting node, one receiving node and one idle node during T_{ab}.

By using the capacity formula and the expression of signal-to-noise ratio (SNR) of the OWRT system, the transmit power $P_a^t + P_r^t$ can be derived as a function of transmission time T_{ab} as follows (the derivation can be found in [7]),

$$P_a^t + P_r^t = N_0(2^{\frac{2B_{ab}}{T_{ab}W}} - 1)/|h_{eff}|^2, \tag{3}$$

where $|h_{eff}| \triangleq 1/(\frac{1}{|h_{ar}|} + \frac{1}{|h_{br}|})$.

The transmit power derived via Shannon capacity formula is the minimum transmit power that can support the required transmission of B_{ab} bits with transmission time T_{ab}. As a result, we can analyze the maximal EE for given SE. We will also use Shannon capacity formula to formulate the EE of TWRT systems.

The transmit power should not exceed a maximum value, otherwise, outage occurs. Considering maximum transmit power constraint renders rather involved derivation, but the conclusions are almost the same no matter it is considered or not [7]. Therefore, we do not consider the maximum power constraint here for concise.

By substituting (3) into (1), we obtain

$$E_{ab}(B_{ab}, T_{ab}) = T_{ab}(\frac{N_0(2^{\frac{2B_{ab}}{T_{ab}W}} - 1)}{2\epsilon|h_{eff}|^2} + P_O^c). \tag{4}$$

Consider that the system allocates time duration T_{ba} for $\mathbb{B} \rightarrow \mathbb{A}$ transmission. The energy consumed during T_{ba} can be obtained similarly as

$$E_{ba}(B_{ba}, T_{ba}) = T_{ba}(\frac{N_0(2^{\frac{2B_{ba}}{T_{ba}W}} - 1)}{2\epsilon|h_{eff}|^2} + P_O^c). \tag{5}$$

After the B_{ab} and B_{ba} bits messages have been transmitted, all the three nodes remain idle during the remaining time $T - T_{ab} - T_{ba}$. Finally, the EC of OWRT per block is obtained as

$$E_O = E_{ab}(B_{ab}, T_{ab}) + E_{ba}(B_{ba}, T_{ba}) + (T - T_{ab} - T_{ba})(3P^{ci}). \tag{6}$$

3.2. Two-way Relaying

During each block, the system allocates duration T_{twr} for bidirectional transmission, which is completed in two phases. First, both nodes $\mathbb{A}$ and $\mathbb{B}$ transmit to the relay, then the relay broadcasts its received signal to nodes $\mathbb{A}$ and $\mathbb{B}$. After receiving the superimposed signal, each of the nodes $\mathbb{A}$ and $\mathbb{B}$ removes its own transmitted signal via self-interference cancelation, and obtains its desired signal [2]. The two phases employ identical time duration $T_{twr}/2$ as in OWRT. The EC during T_{twr} can be derived as follows (see [7]),

$$E_{twr}(B_{ab}, B_{ba}, T_{twr}) = T_{twr}\Big[\frac{N_0(2^{\frac{2B_{ab}}{WT_{twr}}} + 2^{\frac{2B_{ba}}{WT_{twr}}} - 2)}{2\epsilon|h_{eff}|^2} + P_T^c\Big], \tag{7}$$

where the first term in the bracket denotes the total transmit PC used to transmit the B_{ab} and B_{ba} bits message, P_T^c is the total circuit PC. During the first phase, there are two nodes in transmission and one node in reception, while during the second phase, there are one node in transmission and two nodes in reception. Therefore, we have

$$P_T^c \triangleq (2P^{ct} + P^{cr} + P^{ct} + 2P^{cr})/2 = 1.5(P^{ct} + P^{cr}). \tag{8}$$

After the bidirectional transmission, all the nodes remain idle during $T - T_{twr}$. Finally, the EC of TWRT per block is given by

$$E_T = E_{twr}(B_{ab}, B_{ba}, T_{twr}) + (T - T_{twr})(3P^{ci}). \tag{9}$$

3.3. Comparison between One-way and Two-way Relaying

For given traffic amounts B_{ab} and B_{ba}, the EC in (6) or (9) only depends on the transmission time. It is easy to prove that (6) is a convex function of transmission time T_{ab} and T_{ba}, while (9) is a convex function of transmission time T_{twr}. Therefore, efficient convex optimization techniques [8] can be used to find the optimal transmission time which minimizes the ECs.

Although it is hard to obtain closed form expressions of the minimal ECs, i.e., E_O^{min} and E_T^{min}, we can still compare OWRT with TWRT. The following formulas will be used in the comparison,

$$E_{twr}(b_1, b_2, t) - tP_T^c = E_{ab}(b_1, t) + E_{ba}(b_2, t) - 2tP_O^c, \tag{10}$$

$$2P_O^c - P_T^c - 3P^{ci} \geq 0,\ P_T^c \geq P_O^c, \tag{11}$$

where (10) comes from the expressions of $E_{twr}(\cdot)$, $E_{ab}(\cdot)$ and $E_{ba}(\cdot)$ in (7), (4) and (5), and (11) can be obtained using the definitions of P_O^c and P_T^c in (2) and (8) and the assumptions that $P^{ct} \geq P^{ci}$ and $P^{cr} \geq P^{ci}$.

3.3.1. *Equal Bidirectional Data Amounts*

When $B_{ab} = B_{ba}$, the optimal transmission time of OWRT $T_{ab}^{opt} = T_{ba}^{opt} \triangleq T_1$ due to the symmetry of the bidirectional transmission. In this case, by choosing $T_{twr} = T_1$, we have

$$\begin{aligned} &E_T - E_O^{min} \\ =&E_{twr}(B_{ab}, B_{ba}, T_1) + (T - T_1)(3P^{ci}) - \\ &E_{ab}(B_{ab}, T_1) - E_{ba}(B_{ba}, T_1) - (T - T_1 - T_1)(3P^{ci}) \\ =&T_1(3P^{ci} + P_T^c - 2P_O^c) \leq 0, \end{aligned} \tag{12}$$

where for the second equality we applied (10), the last inequality comes from (11).

It means that we can always find a proper transmission time for TWRT, which results in lower EC than OWRT. Therefore, the maximal EE of TWRT is always higher than that of OWRT.

3.3.2. *Unequal Bidirectional Data Amounts*

When $B_{ab} \neq B_{ba}$, the advantage of TWRT diminishes, its EE may be less than that of OWRT. To show this, we consider an extreme case where $B_{ab} \gg B_{ba}$ and $B_{ba} \rightarrow 0$. In this case, the EC of TWRT can be approximated as follows,

$$E_T \approx T_{twr}\Big[\frac{N_0(2^{\frac{2B_{ab}}{WT_{twr}}} - 1)}{2\epsilon|h_{eff}|^2} + P_T^c\Big] + (T - T_{twr})(3P^{ci}). \tag{13}$$

In OWRT, since $B_{ba} \rightarrow 0$, the time allocated to the transmission from node $\mathbb{B}$ to $\mathbb{A}$ $T_{ba} \rightarrow 0$ to save the EC. Then the EC of OWRT can be approximated as

$$E_O \approx T_{ab}\Big[\frac{N_0(2^{\frac{2B_{ab}}{WT_{ab}}} - 1)}{2\epsilon|h_{eff}|^2} + P_O^c\Big] + (T - T_{ab})(3P^{ci}). \tag{14}$$

By choosing $T_{ab} = T_{twr}$ and considering (11), we have $E_O - E_T = T_{ab}(P_O^c - P_T^c) \le 0$. It means that we can always find a proper transmission time for OWRT, which yields lower EC than TWRT, i.e., it is more energy efficient than TWRT.

4. HYBRID RELAY TRANSMISSION STRATEGY

Since TWRT and OWRT are energy efficient in different cases, we propose a HRT strategy in order to exploit the merits of both of them.

In HRT, the system uses one-way relaying to transmit a part of the message of B_{ab} and B_{ba} bits, i.e., B_{ab}^o and B_{ba}^o, and uses two-way relaying to transmit the rest of the message, i.e., $B_{ab} - B_{ab}^o$ and $B_{ba} - B_{ba}^o$. The transmission time for the one-way and two-way relaying are respectively denoted as T_{ab}, T_{ba} and T_{twr}. Using the EC models of OWRT and TWRT, the EC of HRT is given by

$$\begin{aligned} E_H = &E_{ab}(B_{ab}^o, T_{ab}) + E_{ba}(B_{ba}^o, T_{ba}) + E_{twr}(B_{ab} - B_{ab}^o, \\ &B_{ba} - B_{ba}^o, T_{twr}) + (T - T_{twr} - T_{ab} - T_{ba})(3P^{ci}), \end{aligned} \quad (15)$$

where the first two terms are the ECs consumed in one-way relaying, the third term is the EC consumed in two-way relaying, and the last term is that consumed in idle duration.

When $B_{ab}^o = B_{ba}^o = 0$, HRT degenerates into TWRT, while when $B_{ab}^o = B_{ab}$ and $B_{ba}^o = B_{ba}$, it reduces to OWRT. Therefore, by properly adjusting the bit allocations, the EE of HRT will be no less than those of TWRT and OWRT. We can minimize the EC of HRT by jointly optimizing the bit allocation B_{ab}^o and B_{ba}^o, and the transmission time T_{twr}, T_{ab} and T_{ba}.

Given B_{ab}^o and B_{ba}^o, since $E_{ab}(\cdot)$ and $E_{ba}(\cdot)$ are convex functions of T_{ab} and T_{ba}, and $E_{twr}(\cdot)$ is a convex function of T_{twr}, the EC of HRT E_H is a convex function of the transmission time T_{twr}, T_{ab} and T_{ba}. Then the joint optimization of transmission time and bit allocation can be solved via the following procedure.

We find the optimal bit allocations by searching all the possible values of B_{ab}^o and B_{ba}^o. Given each pair of B_{ab}^o and B_{ba}^o, we can find the corresponding optimal transmission time and the minimum EC by solving the following convex optimization problem,

$$\begin{aligned} \min_{T_{twr}, T_{ab}, T_{ba}} \quad & E_H \\ \text{s.t.} \quad & T_{twr} \ge 0, T_{ab} \ge 0, T_{ba} \ge 0, \\ & T_{twr} + T_{ab} + T_{ba} \le T. \end{aligned} \quad (16)$$

Finally, we choose the values of B_{ab}^o and B_{ba}^o which lead to the minimal E_H as the optimal bit allocation results. The corresponding optimal transmission time can also be obtained by solving the problem (16) with the optimal bit allocation.

In this procedure, the optimal B_{ab}^o and B_{ba}^o need to be found with a two-dimensional exhaustive searching, whose complexity is prohibitive. In the following, we decrease its complexity by reducing the searching space.

Without loss of generality, we assume that $B_{ab} \ge B_{ba}$, then we can show that the optimal B_{ba}^o equals to zero. To show this, we need the following two lemmas.

Lemma 1. *Suppose that* $b_1 \ge 0$, $b_2 \ge 0$, $t_1 > 0$ *and* $t_2 > 0$*, then*

$$E_{ab}(b_1, t_1) + E_{ab}(b_2, t_2) \ge E_{ab}(b_1 + b_2, t_1 + t_2), \quad (17)$$
$$E_{ba}(b_1, t_1) + E_{ba}(b_2, t_2) \ge E_{ba}(b_1 + b_2, t_1 + t_2), \quad (18)$$

where the equalities hold only when $b_1/t_1 = b_2/t_2$.

Proof. The exponential function $f(x) = \frac{N_0}{2\epsilon|h_{eff}|^2}(2^{\frac{2x}{W}} - 1) + P_O^c$ is convex with respect to x, therefore, we have

$$\theta f(x_1) + (1-\theta) f(x_2) \ge f(\theta x_1 + (1-\theta) x_2), \quad (19)$$

where the equality holds when $x_1 = x_2$.

Define $\theta = t_1/(t_1 + t_2)$, $x_1 = b_1/t_1$ and $x_2 = b_2/t_2$, and substitute them into (19), we obtain lemma 1. □

Lemma 2. *Suppose that* $t_1 \ge t_2 > 0$ *and* $b_1 \ge b_2 > 0$*, then*

$$E_{ab}(b_1, t_2) + E_{ba}(b_2, t_1) \ge E_{ab}(b_1, t_1) + E_{ba}(b_2, t_2). \quad (20)$$

Proof. Upon substituting the definitions of $E_{ab}(\cdot)$ and $E_{ba}(\cdot)$ in (4) and (5), we have

$$\begin{aligned} &[E_{ab}(b_1, t_2) + E_{ba}(b_2, t_1)] - [E_{ab}(b_1, t_1) + E_{ba}(b_2, t_2)] \\ =&\frac{N_0}{2\epsilon|h_{eff}|^2}[f(t_1) - f(t_2)], \end{aligned} \quad (21)$$

where $f(t) \triangleq t(2^{\frac{2b_1}{tW}} - 2^{\frac{2b_2}{tW}})$.

By taking the derivative of $f(t)$, we have $f'(t) = g(b_1) - g(b_2)$, where $g(b) \triangleq 2^{\frac{2b}{tW}}(1 - \ln 2 \frac{2b}{tW})$. By taking the derivative of $g(b)$, it is easy to show that $g'(b) \le 0$ for $b > 0$, i.e., $g(b)$ is a decreasing function of b for $b > 0$. Considering that $b_1 \ge b_2$, we have $f'(t) = g(b_1) - g(b_2) \le 0$, i.e., $f(t)$ is a decreasing function of t. Considering that $t_1 \ge t_2$, the expression in (21) is less than zero, i.e., lemma 2 is true. □

Now we can prove the following proposition.

Proposition 1. *When* $B_{ab} \ge B_{ba}$*, the optimal bit allocation at node* $\mathbb{B}$ *which minimizes the EC of HRT is* $B_{ba}^o = 0$.

Proof. First, we consider an arbitrary group of bit allocation results B_{ab}^{o1} and B_{ba}^{o1}, and the transmission time T_{ab}^1, T_{ba}^1 and T_{twr}^1 for HRT, the corresponding EC is

$$\begin{aligned} E_H^1 = &E_{ab}(B_{ab}^{o1}, T_{ab}^1) + E_{ba}(B_{ba}^{o1}, T_{ba}^1) + E_{twr}(B_{ab} - B_{ab}^{o1}, \\ &B_{ba} - B_{ba}^{o1}, T_{twr}^1) + (T - T_{twr}^1 - T_{ab}^1 - T_{ba}^1)(3P^{ci}). \end{aligned} \quad (22)$$

Then we show that there always exists a bit allocation strategy B_{ab}^{o2} and B_{ba}^{o2}, which satisfies that $B_{ba}^{o2} = 0$ and yields a lower EC, i.e., $E_H^2 \le E_H^1$. To this end, we rewrite the E_H^1 in (22) as follows,

$$\begin{aligned} E_H^1 =&E_{ab}(B_{ab}^{o1}, T_{ab}^1) + E_{ba}(B_{ba}^{o1}, T_{ba}^1) + E_{ab}(B_{ab} - B_{ab}^{o1}, T_{twr}^1) \\ &+ E_{ba}(B_{ba} - B_{ba}^{o1}, T_{twr}^1) + T_{twr}^1(P_T^c - 2P_O^c) + \\ &(T - T_{twr}^1 - T_{ab}^1 - T_{ba}^1)(3P^{ci}) \\ \ge&E_{ab}(B_{ab}, T_{ab}^1 + T_{twr}^1) + E_{ba}(B_{ba}, T_{ba}^1 + T_{twr}^1) + \\ &T_{twr}^1(P_T^c - 2P_O^c) + (T - T_{twr}^1 - T_{ab}^1 - T_{ba}^1)(3P^{ci}), \end{aligned} \quad (23)$$

where for the equality we applied (10), for the inequality we applied (17) and (18).

Define $T^{\star 1} \triangleq \max\{T_{twr}^1 + T_{ab}^1, T_{twr}^1 + T_{ba}^1\}$ and $T^{\star 2} \triangleq \min\{T_{twr}^1 + T_{ab}^1, T_{twr}^1 + T_{ba}^1\}$, and $\rho = T^{\star 2}/T^{\star 1}$, we have

$$\begin{aligned} &E_{ab}(B_{ab}, T_{ab}^1 + T_{twr}^1) + E_{ba}(B_{ba}, T_{ba}^1 + T_{twr}^1) \\ \ge&E_{ab}(B_{ab}, T^{\star 1}) + E_{ba}(B_{ba}, T^{\star 2}) \\ =&E_{ab}(B_{ab}\rho, T^{\star 2}) + E_{ba}(B_{ba}, T^{\star 2}) + E_{ab}(B_{ab}(1-\rho), T^{\star 1} - T^{\star 2}) \\ =&E_{twr}(B_{ab}\rho, B_{ba}, T^{\star 2}) + E_{ab}(B_{ab}(1-\rho), T^{\star 1} - T^{\star 2}) + \\ &T^{\star 2}(2P_O^c - P_T^c), \end{aligned} \quad (24)$$

where the inequality comes from lemma 2, the first equality comes from the equality condition of (17), for the second equality we applied (10).

Then we define the following bit allocations and transmission time for HRT that $B_{ab}^{o2} = B_{ab}(1-\rho)$ and $B_{ba}^{o2} = 0$, $T_{twr}^2 = T^{\star 2}$, $T_{ab}^2 = T^{\star 1} - T^{\star 2}$ and $T_{ba}^2 = 0$, the corresponding EC can be obtained by substituting these expressions into (15),

$$E_H^2 = E_{twr}(B_{ab}\rho, B_{ba}, T^{\star 2}) + E_{ab}(B_{ab}(1-\rho), T^{\star 1} - T^{\star 2}) + (T - T^{\star 1})(3P^{ci}). \quad (25)$$

By substituting (24) and (25) into (23), we obtain

$$\begin{aligned} E_H^1 \geq & E_H^2 + T^{\star 2}(2P_O^c - P_T^c) - (T - T^{\star 1})(3P^{ci}) + \\ & T_{twr}^1(P_T^c - 2P_O^c) + (T - T_{twr}^1 - T_{ab}^1 - T_{ba}^1)(3P^{ci}) \\ \geq & E_H^2 + (3P^{ci})(T^{\star 1} + T^{\star 2} - 2T_{twr}^1 - T_{ab}^1 - T_{ba}^1) = E_H^2, \end{aligned} \quad (26)$$

where the second inequality comes from (11), and the last equality comes from the definitions of $T^{\star 1}$ and $T^{\star 2}$. □

From proposition 1, we see that if $B_{ab} \geq B_{ba}$, the optimal B_{ba}^o equals to zero. In other words, the EE-maximization strategy is using TWRT to transmit all of the B_{ba} bits of message as well as a part of the B_{ab} message, i.e., $B_{ab} - B_{ab}^o$, and using OWRT to transmit the B_{ab}^o bits of message. This means that we only need a scalar searching to find the optimal B_{ab}^o. For any given value of B_{ab}^o, we solve the convex problem (16) to find the minimum E_H. Finally, we obtain the optimal B_{ab}^o and the corresponding optimal transmission time, which minimizes the EC of HRT. Similar results and optimization procedure can be obtained if $B_{ab} \leq B_{ba}$.

5. SIMULATION RESULTS

In this section, we compare the EEs of OWRT, TWRT and HRT via simulations. Consider that three nodes are located on a straight line. The distance between nodes $\mathbb{A}$ and $\mathbb{B}$ is denoted as D, and the relay is at the midpoint of nodes $\mathbb{A}$ and $\mathbb{B}$. The path loss attenuation is $PL = 30 + 10\log_{10}(\text{distance}^\alpha)$, where α is the attenuation factor. Assume that all the small scale fading channels are i.i.d. Rayleigh fadings, which do not change during one block, but are independent from one block to another. All the results are averaged over 500 Monte-carlo trails of fading channels.

The EEs are compared in Fig. 1, where the x-axis is the data amount normalized by the block duration and bandwidth, i.e., $(B_{ab} + B_{ba})/(TW)$, which can be regarded as the averaged bidirectional SE per block[1].

In the figure, the solid and dash curves respectively correspond to the cases with equal and unequal bidirectional data amounts. The EE curves of OWRT under the two cases overlap.

With equal bidirectional data amounts, the TWRT always outperforms the OWRT. In fact, in this case the proposed HRT degenerates into TWRT, thereby its EE is exactly the same as that of TWRT, i.e., their curves overlap.

When the bidirectional data amounts are unequal, the advantage of TWRT diminishes, and OWRT offers higher EE than TWRT in low traffic region. In this case, by optimizing the data amounts allocated to the OWRT and TWRT parts, HRT provides higher EE than both of OWRT and TWRT. Due to the lack of space, we do not show results with other settings, but the same conclusion can be drawn.

[1]The averaged bidirectional SE per block takes into account the entire block duration, including both the transmission time and the idle duration.

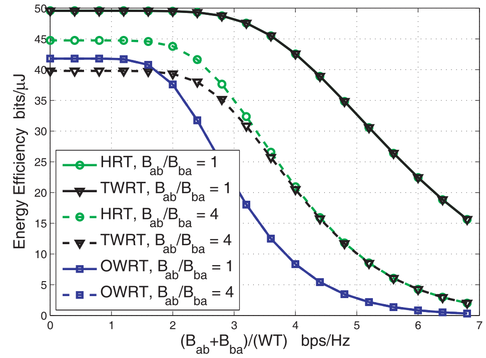

Fig. 1. EE comparison among different strategies, where $D = 100$ m, $\alpha = 4$, the bandwidth $W = 10$ MHz, the block duration $T = 5$ ms, the noise power $N_0 = -95$ dBm, the power amplifier efficiency $\epsilon = 0.35$, and the circuit PC $P^{ct} = P^{cr} = 100$ mW, $P^{ci} = 0$ mW.

6. CONCLUSIONS

We have compared the energy efficiencies of one-way and two-way relaying, which showed that they are energy efficient in different scenarios. To exploit the advantages of both, we proposed a hybrid relay transmission strategy, where a part of the message is transmitted via one-way relaying and the rest part of the message is by two-way relaying. To maximize the energy efficiency of the system, we jointly optimized the data amounts and transmission time allocated to these two parts. We showed that the optimal transmission strategy is using two-way relaying to transmit the whole message in one direction and part of the message in another direction, then using one-way relaying to transmit the rest message, where the optimal bit allocation can be found by a scalar searching. Simulations showed that the proposed hybrid relay transmission provides higher energy efficiency than both of one-way and two-way relaying.

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