Energy Efficiency of Distributed Cooperative Relaying

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***Abstract*—Distributed cooperative relaying is an attractive method to combat fading in wireless communications because of its performance advantages, simplicity, scalability, and low overhead. In [1], the spectral efficiency of two previously proposed distributed relaying strategies is investigated: Timer-based Best-Select relaying and M-group Dis-STBC All-Select relaying. From the perspective of spectral efficiency, M-group Dis-STBC All-Select relaying outperforms Best-Select relaying; however, when every node in the decoded set retransmits the source message, much more power will be consumed. In this paper, the energy efficiency of these two relaying strategies is studied to provide a more comprehensive guide for system designers to determine which strategy fits a specific application. Numerical results indicate that, although Best-Select relaying conserves transmit power, in some cases, it is also less energy efficient than M-group Dis-STBC All-Select relaying.**

I. Introduction

Due to the spatial diversity benefits it can provide, cooperative relaying is an effective way to improve the performance of end-to-end wireless communications [2]-[3]. Among the relaying strategies that have been proposed (for example, see [4]-[6]), distributed cooperative relaying is particularly attractive because of its performance advantages, simplicity, scalability, and low overhead.

One popular distributed cooperative strategy is Timer-based Best-Select relaying [7], which selects the "best" potential relay to forward the source signal. For example, if *Decode-and-Forward* relaying is utilized, the "best" potential relay is the one with the highest channel power gain to the destination. The selection can be accomplished in a fully distributed way as follows: every node in the decoded set, which consists of all the potential relays that have successfully decoded the source signal, sets up a timer that is inversely proportional to its channel power gain to the destination. Once the timer expires, this node begins transmitting, and the other nodes back off. Clearly, the best node has the shortest timer, and will be selected.

M-group Dis-STBC All-Select relaying is an alternative distributed cooperative relaying scheme [6]. In this approach, all the nodes in the decoded set forward the source message, and Dis-STBC [5] is utilized to coordinate the transmissions from multiple relays to the destination. Specifically, each node in the decoded set randomly chooses one column of the underlying M-columned STBC matrix to transmit. All the nodes that use the same column comprise a "group," and all M groups transmit simultaneously.

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The spectral efficiency of Timer-based Best-Select relaying and M-group Dis-STBC All-Select relaying is investigated in [1]. The results there show that M-group Dis-STBC All-Select relaying performs better in terms of spectral efficiency. However, it consumes much more power than Timer-based Best-Select, especially when the size of the decoded set is large, since all the nodes in the decoded set will transmit the source message. In this paper, the objective is to evaluate the energy efficiency of these two strategies.

There has been extensive previous work on the energy efficiency, or power efficiency, of cooperative communications (for example, see [8]-[9]), but most of this research has considered only the transmission power consumption with little or no attention paid to the power consumed by the nodes that are not transmitting, which can be significant [10]-[11]. In this paper, power consumption is addressed by taking into account the power consumed in all possible modes: *Transmit, Receive, Idle,* and *Sleep*.

The rest of this paper is organized as follows: The system model is presented in Section II. In Section III, energy efficiency is defined and then derived for the two strategies. Results are presented and discussed in Section IV, and, conclusions are drawn in Section V.

II. System Model

As in [1], we consider a system with one source-destination pair and N potential relays. The direct link between the source and the destination is assumed to be unreliable due to the large source-destination separation and/or the presence of deep fading. As shown in Fig. 1, a two-phase relaying scheme is utilized. In the first phase, the source broadcasts the signal and all potential relays listen; the nodes that can successfully decode the message comprise the decoded set $\mathcal{D}$. In the second phase, in Best-Select relaying, the best node in $\mathcal{D}$ is selected to forward the source message to the destination; on the other hand, all the nodes in $\mathcal{D}$ could transmit together, which we call All-Select relaying.

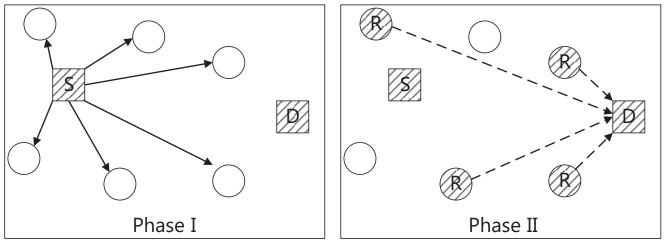

Fig. 1. Two-phase relaying scheme: in the first phase, the source broadcasts its message to all potential relays; in the second phase, the selected relay(s) forward(s) the source information to the destination.

We assume that the two phases are completed in a time period T that is much shorter than the coherence time of the wireless channel; so, the channels from the source to each potential relay and those from each potential relay to the destination remain constant during one end-to-end transmission time. Uniform time allocation is considered here, that is, the data transmission time is equally divided into two phases. We indicate the *power* gain of the channel from the source to potential relay $i, i \in \{1, 2, \cdots, N\}$ as h_i, and the channel from potential relay i to the destination as g_i. For the sake of simplicity, we assume all h_i's and g_i's are i.i.d random variables following an exponential distribution; without loss of generality, the mean is set to 1.

III. Energy Efficiency

We define the energy efficiency as

$$\eta = \frac{1}{2}\frac{rT_e}{E}p_s \tag{1}$$

where r is the bit rate, T_e is the effective transmission time, that is, the time consumed by the data transmission, p_s is the probability of successful transmission from the source to the destination, and E is the total energy consumption during one end-to-end transmission. The factor of one-half results from the two-phase transmission process.

Note that, in practice, not only do the transmitting nodes consume energy, but the nodes in *Receive* mode, and even those in *Idle* or *Sleep* modes also consume energy. For example, Table I lists the power consumption of a commercial IEEE 802.11 wireless transceiver in different modes [10]. Note that the power consumption in *Transmit* mode is not the transmission power, but rather the power consumed by the transceiver in transmitting the signal. These values show that the power consumption of the non-transmitting nodes should also play an important role. Therefore, in the computation of the total energy consumption, instead of considering only the transmitting nodes, here, we take into account all possible modes: *Transmit, Receive, Idle,* and *Sleep*.

The power consumptions of the nodes in *Transmit, Receive, Idle,* and *Sleep* mode are indicated as $P_t, P_r, P_i,$ and P_s, respectively, and the four values represent an energy consumption profile. Intuitively, turning the idle nodes completely off (*Sleep* mode) can save a significant amount of energy. However, power is also required to "wake up" the sleeping nodes. Therefore, scheduling algorithms to conserve energy are needed, but these are often difficult to design and implement. To include this consideration in our analysis, the power consumption of the nodes that are neither transmitting nor receiving is indicated as P_{non}, which ranges from the power consumption in *Sleep* mode to that in *Idle* mode and depends on the efficiency of the scheduling algorithms.

TABLE I
Transceiver power consumption (mW) [10]

MODE	802.11b	802.11a	802.11g
Sleep	132	132	132
Idle	544	990	990
Receive	726	1320	1320
Transmit	1089	1815	1980

A. Ideal Best-Select Relaying

First, we assume that the selection of the best potential relay is ideal in the sense that it is always successful and costs negligible time compared to T, that is, $T_e = T$. In this case, the end-to-end transmission is successful as long as (1) there is no outage in the first phase, that is, the decoded set is not empty, and (2) there is no outage in the second phase. An outage occurs if the received SNR is smaller than a given threshold. In this analysis, we assume the same SNR threshold γ_{th} at all nodes, which means all nodes in the network have the same sensitivity.

In the first phase, for the link from the source to potential relay i, since $h_i \sim Exp(1)$, the outage probability is

$$p = Pr(P_T h_i / P_N < \gamma_{th}) = 1 - e^{-\delta_{th}} \tag{2}$$

where P_T is the transmission power (not P_t, which is the power consumption of the node in *Transmit* mode), P_N is the noise power, and $\delta_{th} = \frac{\gamma_{th} P_N}{P_T}$. Since all h_i's are i.i.d., that is, no path loss is considered in the channel model, all potential relays have the same probability to decode the source signal. Then, the probability that the size of the decoded set $\mathcal{D}$ is L can be written as

$$p_L = Pr(|\mathcal{D}| = L) = \binom{N}{L}(1-p)^L p^{N-L} \tag{3}$$

where $|\cdot|$ denotes the cardinality of a set. Since the source transmits and all N potential relay nodes listen, the energy consumed in this phase is $(P_t + NP_r + P_{non})\frac{T}{2}$.

In the second phase, for a given non-empty $\mathcal{D}$, the outage probability is

$$\begin{aligned} p_{BS,II} &= Pr(\arg\max_{1\le i\le L} g_i < \delta_{th}) \\ &= \prod_{i=1}^{L} Pr(g_i < \delta_{th}) = (1 - e^{-\delta_{th}})^L \end{aligned} \tag{4}$$

The energy consumption in this phase is $(P_t + P_r + NP_{non})\frac{T}{2}$ since the selected node transmits and the destination listens.

Therefore, the energy efficiency of ideal Best-Select is

$$\eta_{BS} = \sum_{1\le L\le N} \frac{p_L}{2}\frac{rT}{E_{BS}}(1-p_{BS,II}) \quad (5)$$

where the total energy consumption is

$$\begin{aligned} E_{BS} &= (P_t+NP_r+P_{non})\frac{T}{2}+(P_t+P_r+NP_{non})\frac{T}{2} \\ &= [2P_t+(N+1)(P_r+P_{non})]\frac{T}{2} \end{aligned} \quad (6)$$

B. Timer-Based Best-Select Relaying

In practice, the implementation of Best-Select relaying is not ideal because of possible collisions and a non-zero selection time. In Timer-based Best-Select relaying, every node in the decoded set sets up its own timer, $t_i = \lambda/g_i$, where λ is a constant system parameter. The node with the best channel to the destination has the smallest timer $t_{(1)}$ and will transmit the source information first.

In order to make sure the timers at the other nodes do not expire before the signal broadcasted by the best node arrives, a guard time t_g is required since it takes some time for the best node to prepare the outgoing packet, and also, for the packet to propagate in the air [1], [7]. If the second smallest timer $t_{(2)}$ is not large enough ($t_{(2)} < t_{(1)}+t_g$), more than one relay will transmit and a collision will occur.

In addition, in the selection process, every node in the decoded set is waiting for the expiration of the timer. During this time, no data is transmitted, which decreases the effective data transmission time. We denote this time consumption as the selection time T_s. In the system discussed here, for a given non-empty $\mathcal{D}$, the expected collision probability p_{coll} and the expected selection time T_s have been derived in [1] as

$$\begin{aligned} p_{coll} &= Pr(t_{(2)} < t_{(1)}+t_g) \\ &= 1-L(L-1)\int_1^{+\infty}(\mu x^{-2}e^{-\frac{\mu}{x}})e^{-\frac{\mu}{x-1}} \\ &\times (1-e^{-\frac{\mu}{x}})^{L-2}\mathrm{d}x \end{aligned} \quad (7)$$

where $\mu = \lambda/t_g$; and

$$T_s = E(t_{(1)}) = L\lambda\int_0^{+\infty}\frac{e^{-\frac{\lambda}{x}}}{x}(1-e^{-\frac{\lambda}{x}})^{L-1}\mathrm{d}x \quad (8)$$

The effective transmission time T_e is then $T-T_s$.

The probability that $|\mathcal{D}| = L$ and the outage probability in the second phase are the same as those in ideal Best-Select relaying, which are given, respectively, in (3) and (4).

In the first phase, the source transmits and all N potential relay nodes listen. So, the energy consumption is $(P_t+NP_r+P_{non})\frac{T_e}{2}$. In the selection process, all the nodes in the decoded set $\mathcal{D}$ are in the *Receive* mode to detect the signal broadcasted by the best relay; the energy consumed in this process is $[LP_r+(N-L+2)P_{non}]T_s$. In the second phase, the best node transmits and the destination listens; the energy consumed is $(P_t+P_r+NP_{non})\frac{T_e}{2}$.

Therefore, the efficiency becomes

$$\eta'_{BS} = \sum_{1\le L\le N}\frac{p_L}{2}\frac{r(T-T_s)}{E'_{BS}}(1-p_{BS,II})(1-p_{coll}) \quad (9)$$

and the total consumed energy is now

$$\begin{aligned} E'_{BS} &= (P_t+NP_r+P_{non})\frac{T_e}{2}+(P_t+P_r+NP_{non})\frac{T_e}{2} \\ &+ [LP_r+(N-L+2)P_{non}]T_s \\ &= E_{BS}+T_s\Delta E_{BS} \end{aligned} \quad (10)$$

where $\Delta E_{BS} = -P_t+(L-\frac{N+1}{2})P_r+(N-L+2-\frac{N+1}{2})P_{non}$.

C. M-Group Dis-STBC All-Select Relaying

In M-group Dis-STBC All-Select relaying, all the nodes in the decoded set transmit together to forward the source information. Each of them randomly chooses one column in the underlying M-column STBC matrix to transmit. Hence, there is no time consumed in the relay selection, that is, $T_e = T$. (Note that, if an orthogonal STBC matrix with more than two columns is used, the rate penalty [12] must be taken into account.) To simplify the analysis, 2-group Dis-STBC is considered. Given the decoded set $\mathcal{D}$, the successful transmission probability has been derived in [1]

$$\begin{aligned} p_{AS,II} &= \sum_{k=1}^{L-1}\frac{\binom{L}{k}}{2^L}\int_{x_1+x_2<\delta_{th}}\frac{1}{k}e^{-\frac{x_1}{k}}\frac{1}{L-k}e^{-\frac{x_2}{L-k}}\mathrm{d}x_1\mathrm{d}x_2 \\ &+ \frac{1}{2^{L-1}}(1-e^{-\frac{\delta_{th}}{L}}) \end{aligned} \quad (11)$$

In the first phase, the source transmits and all N potential relay nodes listen. In the second phase, all the nodes in $\mathcal{D}$ transmit, and the destination listens. Therefore, given $\mathcal{D}$, the total energy consumption is $(P_t+NP_r+P_{non})\frac{T}{2}+[LP_t+P_r+(N-L+1)P_{non}]\frac{T}{2}$.

Therefore, the energy efficiency is

$$\eta_{AS} = \sum_{L=1}^{N}\frac{p_L}{2}\frac{rT}{E_{AS}}(1-p_{AS,II}) \quad (12)$$

where

$$E_{AS} = \frac{T}{2}[(L+1)P_t+(N+1)P_r+(N-L+2)P_{non}] \quad (13)$$

IV. Results

We set $t_g = \varepsilon+t_{proc}+t_{prop}$, where ε is the difference among the propagation delays from the source to every potential relay, t_{proc} is the processing time at the best relay to prepare the outgoing packets, and t_{prop} is the propagation time of the signal broadcasted by the best relay to arrive at the other nodes in the decoded set. Since the typical end-to-end physical distance in wireless networks is on the order of $100-1000$ meters, ε and t_{prop} are on the order of 1 μsec. Note that, in realistic networks, all signals are transmitted as data packets. As a lower bound, $t_{proc} = t_{sw}+t_p+t_h$, where the first term is basically the switching time from

Receive mode to *Transmit* mode and the last two account for a packet's preamble and header [13]. Note that imperfect synchronization, payload length, and inter-frame space are not taken into account here. According to [14, Table 17-15], in an Orthogonal Frequency Division Multiplexing (OFDM) system with a bandwidth of 10 MHz, $t_{sw} < 2$ μsec, $t_p = 32$ μsec and $t_h = 8$ μsec. Therefore, the typical guard interval t_g should be on the order of $10 - 100$ μsec, and here, we set $t_g = 50$ μsec. The end-to-end transmission duration is set as $T = 10$ $m$sec, which is roughly 10% of the typical coherence time of a wireless system with low mobility [15]. Since the absolute value of the energy efficiency is not the focus here, we set the data rate as $r = \frac{2}{T}$ bits/s, that is, $\frac{rT}{2} = 1$ bit, to normalize the comparison of these cooperative relaying strategies.

A. Impact of Selection Process

As discussed before, timer-based selection introduces collisions that occur if more than one relay is selected, as well as selection time consumption that reduces the data transmission time. These two factors degrade the performance of Best-Select relaying. In this section, the impact of the timer-based selection process is investigated. The energy consumption profile is set according to IEEE 802.11g in Table I, and P_{non} is set equal to the power consumption in the *Idle* mode; that is, no scheduling is used to make the idle nodes sleep.

It has been shown in [1] that the value of μ, the ratio of λ to t_g, is critical in determining the collision probability p_{coll} and selection time T_s. Therefore, it has an important impact on the energy efficiency of Timer-based Best-Select. As shown in Fig. 2, Timer-based Best-Select relaying schemes with different values of μ have significantly different performances. Although adaptive μ provides the optimal performance, it is not practical to implement in a distributed way. We can see that the Timer-based Best-Select with adaptive μ has very similar performance to 2-group Dis-STBC All-Select; and, when N is small, the former can even be worse than the 2-group Dis-STBC All-Select. If a fixed μ is used (more practical for distributed algorithms), the performance of Timer-based Best-Select can be much worse than 2-group Dis-STBC All-Select.

A larger μ means that the individual timers are separated further from each other; this gives a smaller p_{coll} and a larger T_s. A smaller p_{coll} increases the end-to-end successful transmission probability, and hence, improves the energy efficiency; a larger T_s decreases the effective data transmission time, and thus degrades the energy efficiency. When the network is small, T_s is the main determining factor for the efficiency, and thus a smaller μ is preferred. When p_{coll} is the main factor (N large), a larger μ is required to keep p_{coll} small.

To study the impact of the selection time T_s, we assume p_{coll} is negligible and compare ideal Best-Select, Timer-based Best-Select and 2-group Dis-STBC All-Select; results are shown in Fig. 3, where N is the number of potential relays. Note that the energy efficiencies are normalized by that for ideal Best-Select with $N = 3$. Clearly, if $T_s = 0$, Timer-based Best-Select is ideal; if $T_s = T$, that is, all the transmission time is consumed by the selection process, the efficiency reduces to 0. As expected and already shown in Fig. 2, the energy efficiencies of both Timer-based Best-Select and 2-group Dis-STBC All-Select decrease with the number of potential relays. For the given energy consumption profile, when $N = 3$, the performance of Timer-based Best-Select is worse than 2-group Dis-STBC All-Select relaying if the ratio T_s/T is larger than 0.23, and this value becomes 0.3 and 0.34, respectively, when $N = 6$ and $N = 9$. It means that the probability that 2-group Dis-STBC All-Select is better than Timer-based Best-Select in the sense of energy efficiency is lower, that is, a higher T_s/T is needed when N is larger.

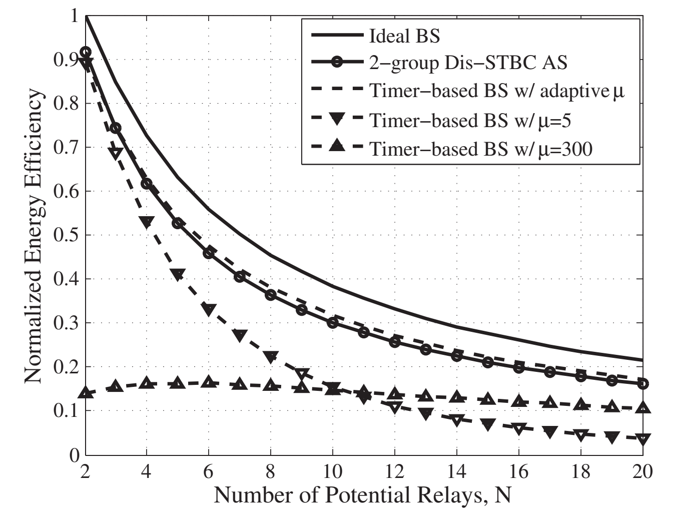

Fig. 2. Energy efficiency of 2-group Dis-STBC All-Select relaying and Best-Select relaying as a function of N, the number of potential relays.

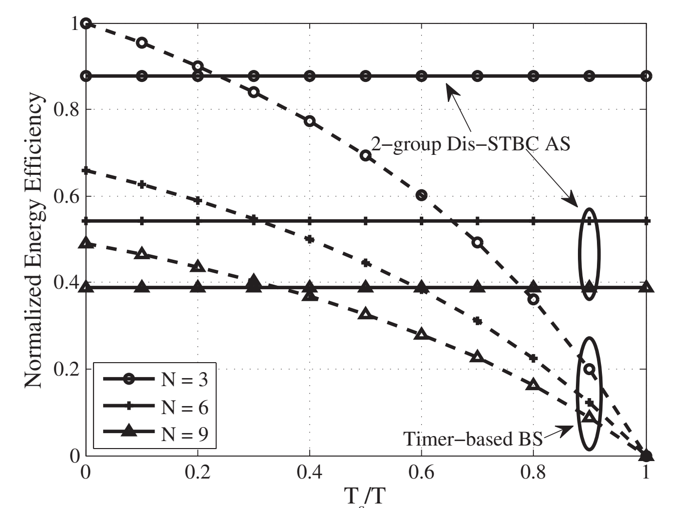

Fig. 3. Energy efficiency of Timer-based Best-Select relaying as a function of T_s/T, the ratio of selection time to total transmission time. (The energy efficiencies are normalized by the efficiency for ideal Best-Select with $N = 3$.)

B. Impact of Energy Consumption Profiles

Clearly, the amount of power consumed in different modes is critical for the energy efficiency. This impact is quantified next. As discussed before, the value of P_{non} depends on the efficiency of the scheduling algorithms. At first, we assume "perfect" scheduling is utilized, that is, $P_{non} = 0$, and study the impact of the ratio of P_r to P_t (Fig. 4). Then, we assume no scheduling algorithm is used and the nodes that are not transmitting or receiving (*Idle* mode) consume a significant amount of energy, i.e., $P_{non} = 0.5P_t$ (Fig. 5). Finally, the impact of the ratio of P_{non} to P_t is presented for a fixed value of P_r/P_t (Fig. 6, $P_r/P_t = 0.5$). In all the figures, where N is the number of potential relays, the energy efficiencies are normalized by that for ideal Best-Select.

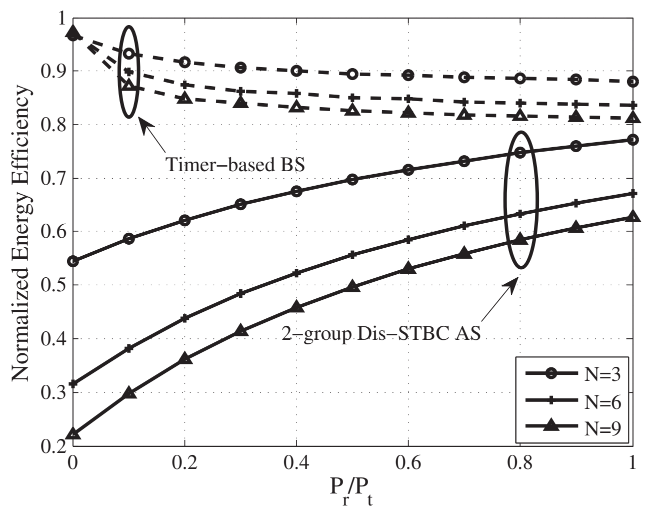

Fig. 4. Energy efficiency of 2-group Dis-STBC All-Select relaying and Best-Select relaying as a function of the ratio of P_r to P_t ($P_{non} = 0$).

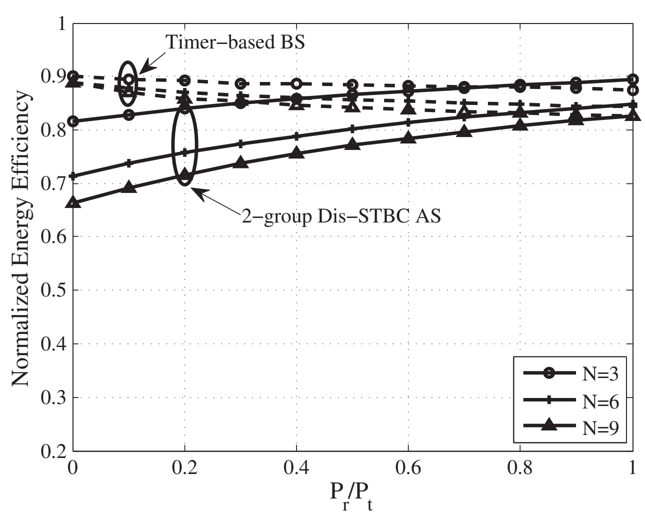

Fig. 5. Energy efficiency of 2-group Dis-STBC All-Select relaying and Best-Select relaying as a function of the ratio of P_r to P_t ($P_{non} = 0.5P_t$).

For both Timer-based Best-Select relaying and 2-group Dis-STBC All-Select relaying, the degradations in energy efficiency compared to ideal Best-Select relaying increase with the number of potential relays. The reason is that the additional consumed power compared to the ideal Best-Select relaying goes up with N. Another observation is that 2-group Dis-STBC All-Select is worse than Timer-based Best-Select when both P_{non} and P_r are small, especially, when N is large. In this case, the extra consumed transmission energy in the second phase of All-Select is the majority of the total energy consumption. On the other hand, if P_{non} and P_r are large, as shown in Fig. 5, 2-group Dis-STBC All-Select can achieve better efficiencies than Timer-based Best-Select, especially when N is small. The reason is that with high power consumption in *Receive* and *Idle* modes, the selection process in Timer-based Best-Select consumes a significant amount of energy, which degrades the energy efficiency.

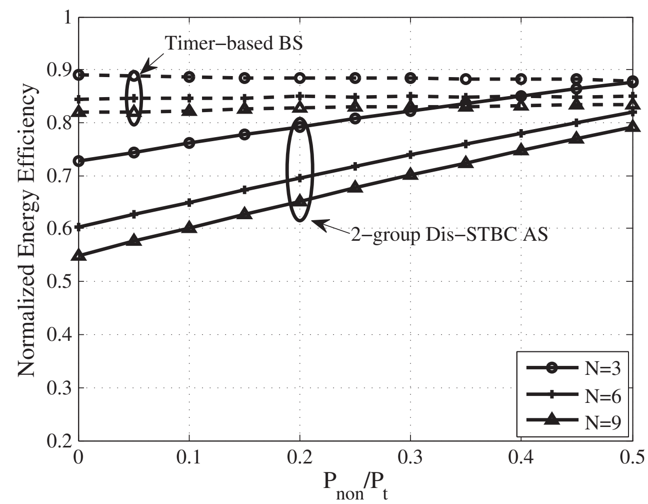

Fig. 6. Energy efficiency of 2-group Dis-STBC All-Select relaying and Best-Select relaying as a function of the ratio of P_{non} to P_t ($P_r = 0.5P_t$).

The same observations apply for the results in Fig 6: the degradations compared to ideal Best-Select relaying increase with N; and 2-group Dis-STBC All-Select is more worse than Timer-based Best-Select when P_r and P_{non} are smaller and N is larger. A specific example is shown in Fig. 2, where the power consumption profile is set according to IEEE 802.11g in Table I, and $P_{non} = P_i$. When N is small, 2-group Dis-STBC AS has slightly higher energy efficiencies than Timer-based Best-Select, even with adaptive μ. Recall that the optimal value of μ depends strongly on the size of the network, the coherence time of the wireless channel, and the required guard time. Therefore, in general, Timer-based Best-Select is not as robust as 2-group Dis-STBC All-Select.

V. Conclusion

The energy efficiency of two distributed relaying strategies is investigated in this paper. The impact of the relay selection process on the performance of Timer-based Best-Select relaying is clearly addressed, and the impact of the energy consumption profiles is also presented. Through analysis and simulation, we showed that, although Best-Select relaying conserves much more transmitting power than All-Select relaying, it is not always better in the sense of energy efficiency because (1) the implementation of the selection process degrades the performance, and, (2) in some cases, the energy consumed by the nodes, not in *Transmit* mode, is comparable to or even higher than that consumed by those nodes that are transmitting.

The power model used here needs refinement. For example, in Best-Select relaying and All-Select relaying, the destination uses different processing to decode the received signal for the two strategies, and hence, the consumed power will be different. A precise power consumption model is essential to obtain accurate results; this is one obvious direction of the future work. In addition, power allocation algorithms would improve the energy efficiency, however, distributed allocation algorithms are difficult to design and implement. Scheduling algorithms that can minimize P_{non} by decreasing the duration that nodes are in *Idle* mode would also save a significant amount of energy.

In practice, the protocols applied in the upper-layers, e.g., MAC layer, could also affect the efficiencies of the relaying schemes. For example, the probability of collisions that occur when more than one relay is selected as the "best" would reduce dramatically if IEEE 802.11 RTS/CTS is utilized to reserve the channel in the selection process of Best-Select relaying. However, the implementation of these protocols consumes energy. Therefore, a holistic analysis at the system level is necessary to reveal the "realistic" efficiencies of distributed cooperative relaying.

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