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Research Article

Energy-Efficient Relaying Strategy with Network Coding in Two-Way Parallel Channels

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We consider a two-way communication assisted by parallel regenerative decode-and-forward relays operating in orthogonal channels. In a system with limited channel state information at each source and relay node, an optimum distributed power allocation strategy is proposed to minimize the total transmit power, providing a target signal-to-noise ratio at each destination with a target outage probability. Moreover, combined with opportunistic relaying and network coding, a distributed decision mechanism is proposed for the relay node to decide whether to help the transmission or not. In this proposal, each source works out the transmit power and the decision threshold then broadcasts them. The selected relay compares the decision threshold with the channel gain of its weaker relay-to-destination link, then determines whether to forward the networkcoded data or not. Simulation results show the advantage of this strategy in terms of energy efficiency for a two-hop two-way communication scenario. The proposed strategy is very flexible as it can trade outage to power consumption and vice versa.

1. Introduction

Wireless relaying offers space diversity to extend the transmission range and to enhance end-to-end transmission performance such as outage probability and data rate. In conventional single link communication, the transmission between the source and the destination suffers from severe fading due to multipath fading effects and path loss, which results in unreliable communication. Fortunately, relays can provide cooperative diversity [1], and save power to improve the reliability without the need of physical antenna arrays. Recently, some works such as [2–4] introduced network coding [5] to the bidirectional cooperation. Especially, [2, 3] focus on the bit-level transmission, and working out the optimum system throughput provided that both the two source-to-relay channels are better than the direct channel between the two sources in the three-node model. As shown in Figure 1, two source nodes (S_1 and S_2) exchange messages with the help of a relay (namely, R), using time-division scheme in two-way communications. The traditional method [2] needs four phases (Figure 1(a)) to complete the exchange of information. However, by using network coding (a bitwise XOR operation at the relay node), only three phases are needed (Figure 1(b)). In such a three-phase relaying scheme, the messages from S_1 and S_2 are first decoded at the relay node, network coded, re-encoded, and then sent as one message to both destinations simultaneously. Here in this paper, we extend the three-node case to the scenario in which there are multiple relay candidates that could assist the source nodes in the two-way communication as shown in Figure 2.

When there are multiple relay node candidates, the multiple relays could simultaneously assist the transmission [6–8], or the most suitable single relay could be selected for transmission according to the channel state information (CSI). This opportunistic idea is based on instantaneously selecting an "on-peak" receiver with the "good" channel condition to improve system performance [9–12]. These works focused on the multirelay transmission in one-way transmissions (i.e., the messages are sent from S_1 to S_2, but no messages come from S_2 to S_1). Meanwhile, they assume that either the destination cannot directly receive the signals from the source [9], or that the complete CSI of all communication channels can be available at the source node [10, 12].

In addition, from the control mechanism's point of view, the cooperative strategies can be categorized into two types: central control strategy and distributed strategy. In most cases of practical systems, the distributed strategy is more practical since it only needs local and partial CSI, which overcomes the obstacles of a centralized architecture such as the substantial feedback requirements, overhead and delay, and so forth. For example, in [13], users select cooperation partners based on a priority list in a distributed manner for multiuser networks with coded cooperation. Reference [14] provides a relay selection algorithm based on instantaneous channel measurements obtained by each relay node locally, which reduces the cooperative costs among relays work in but only the one-way transmission is considered in [8, 13, 14].

Especially in [8], several optimum distributed power allocation strategies minimize the total transmit power while providing a target signal-to-noise ratio at the destination with a target outage probability. Due to the one-way transmission, [8] only needs to consider the relay-to-destination link after the relays successfully decode the messages. When network coding is introduced to decrease the transmission phases in two-way communications, as shown in Figure 1(b), the outage probability should be investigated on both $R \leftrightarrow S_1$ and $R \leftrightarrow S_2$ links in the third transmission phase after the relay has correctly decoded the messages from the two source nodes.

In this paper, our design target is to maximize power efficiency in two-way relay systems. Due to the limited knowledge of CSI at both source nodes, our distributed strategy mainly focuses on the forwarding decision and distributed power allocation. Firstly, a single relay node will be chosen as the opportunistic relay. Then, the opportunistic relay makes a decision whether to forward the source data according to a proper forwarding threshold. Moreover, the distributed power allocation based on the decode-and-forward (DaF) scheme [15] works out the corresponding transmit powers (P_{S_1}, P_{S_2}) and the forwarding threshold (α_t) at the source nodes. The source nodes broadcast the optimum pair ((P_{S_1}, α_t) and (P_{S_2}, α_t)) to be used by the relay nodes.

The remainder of this paper is organized as follows. The next section describes the system model. The analysis of the distributed strategy is performed in Section 3. Simulation results can be found in Section 4. Finally, concluding remarks are given in Section 5.

2. System Model and Background

As shown in Figure 2, we consider a relay network consisting of an $S_1 \leftrightarrow S_2$ two-way pair and M relay nodes employing DaF. For simplicity, we denote relay i by R_i. We assume that the relaying operates in orthogonal time-division channels. Let h_{1i} and h_{2i} denote the fading coefficient of the $S_1 \leftrightarrow R_i$ and $R_i \leftrightarrow S_2$ channels for the ith relay node, respectively, $i = 1, \dots, M$. The fading coefficient of the $S_1 \leftrightarrow S_2$ link is denoted by h_0. Assume that each channel is slowly varying flat fading, and $\{h_{1i}, h_{2i}, h_0\}$ are all independent realizations of zero-mean complex Gaussian random variables with variance σ_{1i}^2, σ_{2i}^2 and σ_0^2, respectively. We define $\beta_{1i} = 1/\sigma_{1i}^2$, $\beta_{2i} = 1/\sigma_{2i}^2$, and $\beta_0 = 1/\sigma_0^2$.

Firstly, the relay selection is prior to the forwarding decision and the distributed power allocation. That is, in the opportunistic relaying, the "good" relay is chosen prior to the transmission among a collection of M possible candidates and source nodes. As shown in Figure 1(b), in the first transmission phase, S_1 broadcasts X_1 with power P_{S_1}, then S_2 broadcasts X_2 with power P_{S_2}. The corresponding destinations (i.e., S_2 node and S_1 node) observe y_2 and y_1 as

$$\begin{aligned} y_2 &= \sqrt{P_{S_1}} h_0 X_1 + Z_2, \\ y_1 &= \sqrt{P_{S_2}} h_0 X_2 + Z_1, \end{aligned} \tag{1}$$

and the opportunistic relay R_r observes y_{1r} from the $S_1 \leftrightarrow R_r$ link and y_{2r} from the $S_2 \leftrightarrow R_r$ as

$$\begin{aligned} y_{1r} &= \sqrt{P_{S_1}} h_{1r} X_1 + Z_{1r}, \\ y_{2r} &= \sqrt{P_{S_2}} h_{2r} X_2 + Z_{2r}, \end{aligned} \tag{2}$$

where Z_2, Z_1, Z_{1r}, and Z_{2r} are additive white Gaussian noise (AWGN) terms at the corresponding destinations and the selected relay, respectively. Without loss of generality, they are of variance N_0.

The opportunistic relay is chosen based on the following criterion:

$$\begin{aligned} h_i &= \min\left\{|h_{1i}|^2, |h_{2i}|^2\right\}, \quad i = 1, \dots, M, \\ r &= \underset{i}{\operatorname{argmax}}\{h_i\}, \end{aligned} \tag{3}$$

which is similar to that in [9, 16].

That is, a single "good" relay is selected based on the end-to-end instantaneous wireless channel conditions from the M relay candidates to act as the cooperative partner. Among the M relay candidates, the relay node that maximizes h_i is defined as the "good" relay R_r. We denote $\min\{|h_{1r}|^2, |h_{2r}|^2\}$ by A_r. We use this relay selection criterion because the quality of the signals received by each destination depends on the quality of the weaker link [16]. Assume this opportunistic relay node can decode X_1 and X_2 correctly when its received signal-to-noise ratio (SNR) from S_1 and S_2 satisfies

$$\begin{aligned} \Gamma_{1r} &= \frac{P_{S_1} |h_{1r}|^2}{N_0} \geq \gamma_{\text{target}}, \\ \Gamma_{2r} &= \frac{P_{S_2} |h_{2r}|^2}{N_0} \geq \gamma_{\text{target}}, \end{aligned} \tag{4}$$

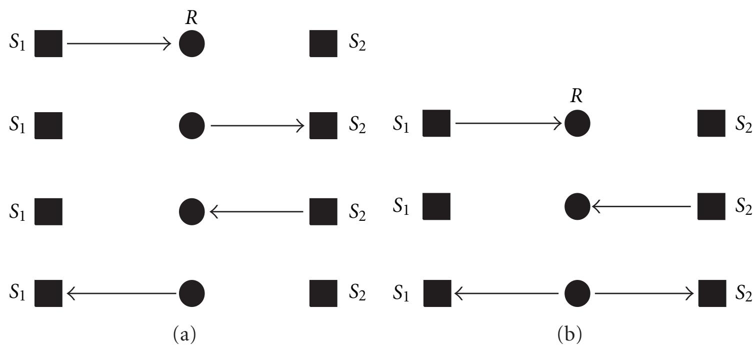

Figure 1: (a) Traditional relaying; (b) three-phase relaying.

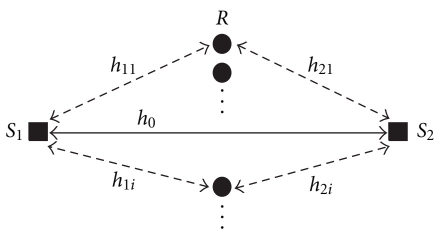

Figure 2: Two-way communication with multiple candidates.

where γ_{target} is the given SNR constraint for correctly decoding. By using network coding, a bitwise XOR operation at the selected relay node encodes the messages from both S_1 and S_2, then the encoded messages are sent to each destination node where S_1 and S_2 could get the desired messages by performing an XOR operation [5]. Thus, it only needs three phases (Figure 1(b)). The destination processes, the messages from the source, and the relay jointly when the decoder operates with log likelihood ratios [2] to achieve the performance gain of maximal ratio combining (MRC). Then, the received SNR at the destination S_2 is

$$\Gamma_2 = \frac{P_{S_1}|h_0|^2 + P_r|h_{2r}|^2}{N_0}. \tag{5}$$

And the resulting SNR at the destination S_1 is

$$\Gamma_1 = \frac{P_{S_2}|h_0|^2 + P_r|h_{1r}|^2}{N_0}. \tag{6}$$

Assume each destination can correctly receive the source data whenever $\Gamma_2 \ge \gamma_{\text{target}}$ and $\Gamma_1 \ge \gamma_{\text{target}}$. Based on the assumption above, the problem of power efficiency for DaF relay networks with parallel channels can be modeled as in Problem (Q_1):

$$\begin{aligned}
&\min_{\{P_{S_1}, P_{S_2}, P_r, \gamma\}} \quad \{P_{S_1} + P_{S_2} + P_r\} \\
&\text{subject to} \quad \frac{P_{S_1}|h_0|^2 + P_r|h_{2r}|^2}{N_0} \ge \gamma_{\text{target}} \\
&\qquad \frac{P_{S_2}|h_0|^2 + P_r|h_{1r}|^2}{N_0} \ge \gamma_{\text{target}} \\
&\qquad \frac{P_{S_1}|h_{1r}|^2}{N_0} \ge \gamma_{\text{target}} \\
&\qquad \frac{P_{S_2}|h_{2r}|^2}{N_0} \ge \gamma_{\text{target}}.
\end{aligned} \tag{Q_1}$$

Since the traditional two-way relaying is decomposed into two one-way transmissions (Figure 1(a)), the optimum power allocation strategy for one-way transmission in DaF relay networks [8] is briefly restated as follows. Assume the one-way transmission is from S_1 to S_2, then [8] works out the optimum power $P_{S_1}^*$ and the forwarding threshold $\alpha_t \cdot P_{S_1}^*$ can only be one of $M + 1$ discrete values $\{\gamma_{\text{target}}N_0/|h_0|^2, \gamma_{\text{target}}N_0/|h_{11}|^2, \gamma_{\text{target}}N_0/|h_{12}|^2, \ldots, \gamma_{\text{target}}N_0/|h_{1M}|^2\}$. The parameters $\{P_{S_1}^*, \gamma\}$ are obtained based on that the channel gain of relay-to-destination, $|h_{2i}|^2$ is exponentially distributed, which does not find out the "bottle-neck" of transmission (i.e., the weaker link of the relays). When relaying is selected (i.e., $P_{S_1}^* < \gamma_{\text{target}}N_0/|h_0|^2$), the source node broadcasts $\{P_{S_1}^*, \alpha_t\}$ to all the candidates. If the channel gain of relay-destination link is greater than the forwarding threshold, namely, $|h_{2i}|^2 \ge \alpha_t$, then the selected relays forward the source data. It implies that multiple relays could participate in the relaying simultaneously.

In the model with network coding and opportunistic relaying, as shown in Figure 1(b), when relaying is selected, $P_{S_1}^* = \gamma_{\text{target}}N_0/|h_{1r}|^2$, the target SNR can be guaranteed at the selected relay during the transmission from S_1 to the selected relay. And it is the same to S_2 when $P_{S_2}^* = \gamma_{\text{target}}N_0/|h_{2r}|^2$. But the outage event may occur in the third transmission phase because the instantaneous channel gain of forwarding links may be less than α_t, which is calculated by the statistics of all the links. Thus, given the target SNR, γ_{target}, at each destination with a target outage probability, ρ_{target}, in two-way communications, we rewrite Problem (Q_1) as Problem (Q_2). $E[P_r]$ is the expected value of the transmit power of opportunistic relay. Problem (Q_2) is the problem of power efficiency in two-way relay networks.

$$\begin{aligned}
&\min_{\{P_{S_1},P_{S_2},P_r,\gamma\}} \quad \{P_{S_1}+P_{S_2}+E[P_r]\} \\
&\text{subject to} \quad P_{\text{rob}}\left\{\frac{P_{S_1}|h_0|^2+P_r|h_{2r}|^2}{N_0}\le\gamma_{\text{target}}\right\}\le\rho_{\text{target}} \\
&\qquad P_{\text{rob}}\left\{\frac{P_{S_2}|h_0|^2+P_r|h_{1r}|^2}{N_0}\le\gamma_{\text{target}}\right\}\le\rho_{\text{target}} \\
&\qquad \frac{P_{S_1}|h_{1r}|^2}{N_0}\ge\gamma_{\text{target}} \\
&\qquad \frac{P_{S_2}|h_{2r}|^2}{N_0}\ge\gamma_{\text{target}}.
\end{aligned} \tag{Q_2}$$

Obviously, the transmission through the relaying could be more power efficient than the direct transmission on the condition that each relaying link is better than the direct link (i.e., $|h_{1r}|^2 \ge |h_0|^2$ and $|h_{2r}|^2 \ge |h_0|^2$). In this paper, we will work out this problem.

3. Distributed Relaying Decision and Power Allocation Strategy

In this section, a distributed relaying decision mechanism followed by distributed power allocation strategy is proposed to crack the obstacles of centralized mechanism, using the limited CSI at each node.

When S_1 transmits the training messages, due to the broadcast nature of wireless medium, all relay nodes and S_2 can simultaneously estimate their $S_1 \leftrightarrow R$ and $S_1 \leftrightarrow S_2$ fading coefficients $\{h_{1i}, i = 1,\dots,M\}$,$\{h_0\}$, respectively. Similarly, when the relay and S_2 transmit the training bits, $\{h_0,h_{11},h_{12},\dots,h_{iM}\}$ can be estimated at S_1. However, $\{h_{21},h_{22},\dots,h_{2M}\}$ may not be available at S_1. Thus, the distributed strategy is proposed with the realizations $\{h_0,h_{1i},h_{12},\dots,h_{1M}\}$, the statistics of all the links available at the source S_1, and the realizations $\{h_0,h_{21},h_{22},\dots,h_{2M}\}$, the statistics of all the links available at S_2. The relay nodes are assumed to have their local CSI, that is, h_{1i} and h_{2i} for R_i, $i = 1,2,\dots,M$.

The nature of the distributed strategy requires that each relay should make its decision only on its local CSI. Since the opportunistic relay has been chosen in advance (as mentioned in Section 2), the selected relay only needs to decide whether to forward the source data or not. In this paper, the selected relay broadcasts the network-coded data when its minimal channel gain of relay-to-destination satisfies

$$A_r = \min\left\{|h_{1r}|^2, |h_{2r}|^2\right\} \ge \alpha_t, \tag{7}$$

where α_t is the forwarding threshold value. One reason is because this network coding needs both ends to decode at the same rate, another reason is that the transmission data rate broadcast by the relay is limited by the weaker link. Thus, the opportunistic relay forwards the decoded signals with sufficient power P_r^*

$$P_r^* = \frac{\gamma'_{\text{target}}N_0}{A_r} = \frac{\max\left\{0,\gamma_{\text{target}}N_0 - P_{Sk}^*|h_{kr}|^2\right\}}{\min\left\{|h_{1r}|^2,|h_{2r}|^2\right\}} \tag{8}$$

$$\le \frac{\max\left\{0,\gamma_{\text{target}}N_0 - P_{Sk}^*|h_{kr}|^2\right\}}{\alpha_t}, \tag{9}$$

where γ'_{target} denotes the SNR contribution from the relay.

We note that such a distributed decision mechanism results in a nonzero probability that none of the relay nodes satisfies (7), and hence a nonzero outage probability. A large value of α_t means that the selected relay will transmit with less power and less often, which saves power but at the expense of a high outage probability. On the other hand, a small value for α_t means that the selected relay will transmit possibly higher power and more often, which results in a low outage probability but possibly high power. Hence, the source nodes should work out the pairs $\{P_{S_1}^*,\alpha_t\}$ and $\{P_{S_2}^*,\alpha_t\}$ to meet a system-given specification, that is, an outage probability requirement ρ_{target}.

From the source's point of view, the transmit power of the selected relay node is a random variable with the known statistics, since the realizations of the forwarding link are not available at the source node. Due to (3), we have the cumulative distribution function (CDF) of A_r

$$F_{A_r}(x) = \prod_{i=1}^{M}\left(1-e^{-\beta_i x}\right), \quad x \ge 0, \tag{10}$$

and its probability density function (pdf) is given by

$$f_{A_r}(x) = \sum_{k=1}^{M}\beta_k e^{-\beta_k x}\prod_{i=1,i\ne k}^{M}\left(1-e^{-\beta_i x}\right), \quad x \ge 0, \tag{11}$$

where $\beta_i = \sum_{k=1}^{2}\beta_{ik}$, $i = 1,\dots,M$ (refer to the appendix).

Having the pdf of A_r, the expected value of the transmit power of the selected relay R_r is obtained as

$$E[P_r] = \int_{\alpha_t}^{\infty}\frac{\max\left\{0,\gamma_{\text{target}}N_0 - P_{Sk}|h_0|^2\right\}}{x}f_{A_r}(x)dx, \tag{12}$$

where $k = \operatorname{argmax}_{\{j\}}\{|h_{jr}|^2\}$, $j = 1,2$. The factor $\max\{0,\gamma_{\text{target}}N_0 - P_{Sk}|h_0|^2\}$ means that the relay should pay more power according to the channel gain of weaker link to guarantee the correct decoding at both ends in the third transmission phase.

From (3) and (7), the forwarding threshold α_t should be chosen as the value that satisfies the outage probability with equality, that is,

$$\rho_{\text{target}} = \Pr\{A_r < \alpha_t\} = F_{A_r}(\alpha_t) = \prod_{i=1}^{M}\left(1 - e^{-\beta_i \alpha_t^*}\right). \quad (13)$$

Exact expression for the threshold α_t is difficult to obtain but it is possible to derive bounds for it. For instance, by letting $\beta_{\min} = \min\{\beta_1, \beta_2, \ldots, \beta_M\}$ and $\beta_{\max} = \max\{\beta_1, \beta_2, \ldots, \beta_M\}$, we can bound the outage probability as

$$\left(1 - e^{-\beta_{\max}\alpha_t^*}\right)^M \leq \prod_{i=1}^{M}\left(1 - e^{-\beta_i \alpha_t^*}\right) \leq \left(1 - e^{-\beta_{\min}\alpha_t^*}\right)^M. \quad (14)$$

Therefore, α_t^* is bounded as

$$-\frac{1}{\beta_{\max}}\ln\left(1 - \rho_{\text{target}}^{1/M}\right) \leq \alpha_t^* \leq -\frac{1}{\beta_{\min}}\ln\left(1 - \rho_{\text{target}}^{1/M}\right). \quad (15)$$

The value of α_t^* can be obtained by a search in the given range in (15) numerically.

In addition, the transmit power of the source nodes can be calculated by Theorem 1, which provides the following optimal solution.

Theorem 1. *The optimum transmit power of the source nodes, $P_{S_1}^*$ and $P_{S_2}^*$, can only be one of the discrete values in the following sets:*

$$\left\{\frac{\gamma_{target}N_0}{|h_{1r}|^2}, \frac{\gamma_{target}N_0}{|h_0|^2}\right\}, \quad (16)$$

$$\left\{\frac{\gamma_{target}N_0}{|h_{2r}|^2}, \frac{\gamma_{target}N_0}{|h_0|^2}\right\}. \quad (17)$$

respectively.

Each source node's transmit power is equal to $\gamma_{target}N_0/|h_0|^2$ when the direct transmission is preferred. And the source nodes transmit power $\gamma_{target}N_0/|h_{1r}|^2$, $\gamma_{target}N_0/|h_{2r}|^2$, respectively, when the relaying is preferred. Thus, the power consumption of relaying is less than that of direct transmission, that is,

$$P_{S_1}^* + \int_{\alpha_t^*}^{\infty} \frac{\max\left\{0, \gamma_{target}N_0 - P_{S_1}^*|h_0|^2\right\}}{x} f_{A_r}(x)dx \leq \frac{\gamma_{target}N_0}{|h_0|^2}, \quad (18)$$

$$P_{S_2}^* + \int_{\alpha_t^*}^{\infty} \frac{\max\left\{0, \gamma_{target}N_0 - P_{S_2}^*|h_0|^2\right\}}{x} f_{A_r}(x)dx \leq \frac{\gamma_{target}N_0}{|h_0|^2}. \quad (19)$$

Proof. Here, the distributed strategy is based on the opportunistic relaying and network coding. Due to the opportunistic relaying, the "good" relay is chosen prior to the transmission (3). And the source nodes can work out the forwarding threshold α_t with the known statistics of all the links (α_t is the same to both S_1 node and S_2 node) by (15). Then, S_1 node can evaluate (18) to make a decision whether to perform relaying based on the knowledge of h_0 and h_{1r} (for $P_{S_1}^*$). At the same time, S_2 node can also evaluate (19) based on the knowledge of h_0 and h_{2r} (for $P_{S_2}^*$). Consequently, S_1 and S_2 nodes can exchange "1 bit" signaling information (here, this "1 bit" signaling information is little overhead and can be achieved by a one-time handshaking protocol between the two source nodes.) to finally decide whether to transmit the source data by the direct link or relaying link.

We consider the scenario in which the relaying is preferred. Clearly, the target SNR at the selected relay can be achieved without an outage event in each source-to-relay link with the source transmit power $\gamma_{\text{target}}/|h_{1r}|^2$, $\gamma_{\text{target}}/|h_{2r}|^2$, respectively.

Since each source node only knows the statistics of all the links without the knowledge of the realizations of channel gain in the relay-to-destination link, the outage event may occur in the third phase. Due to (13), the target outage probability can be satisfied when the forwarding threshold α_t^* is calculated from (15). In the following content, it can be shown that the target SNR at destination can be satisfied. Assume the $R_r \leftrightarrow S_2$ link is weaker than the $R_r \leftrightarrow S_1$ link, that is, $|h_{2r}|^2 \leq |h_{1r}|^2$. From (8), we can get $P_r^* = (\max\{0, \gamma_{\text{target}}N_0 - P_{S1}^*|h_0|^2\})/|h_{2r}|^2$, $P_{S_1}^* = \gamma_{\text{target}}N_0/|h_{1r}|^2 \leq \gamma_{\text{target}}N_0/|h_{2r}|^2$ (i.e., the transmit power of S_1 is less than that of souce2, $P_{S_1}^* \leq P_{S_2}^*$).

At S_2, the received SNR is

$$\begin{aligned} P_{S_1}^*|h_0|^2 + P_r^*|h_{2r}|^2 &= P_{S1}^*|h_0|^2 + \frac{\max\left\{0, \gamma_{\text{target}}N_0 - P_{S_1}^*|h_0|^2\right\}}{|h_{2r}|^2}|h_{2r}|^2 \\ &\geq \gamma_{\text{target}}. \end{aligned} \quad (20)$$

At S_1, the received SNR is

$$\begin{aligned} P_{S_2}^*|h_0|^2 + P_r^*|h_{1r}|^2 &= P_{S_2}^*|h_0|^2 + \frac{\max\left\{0, \gamma_{\text{target}}N_0 - P_{S_1}^*|h_0|^2\right\}}{|h_{2r}|^2}|h_{1r}|^2 \\ &\geq P_{S_2}^*|h_0|^2 + \frac{\max\left\{0, \gamma_{\text{target}}N_0 - P_{S_1}^*|h_0|^2\right\}}{|h_{2r}|^2}|h_{2r}|^2 \\ &\geq \gamma_{\text{target}}. \end{aligned} \quad (21)$$

Using the expression in (12), the expected value of total transmit power is as follows:

$$\begin{aligned} E[P_{\text{total}}] &= P_{S_1} + P_{S_2} + E[P_r] \\ &= P_{S_1} + P_{S_2} \\ &\quad + \int_{\alpha_t^*}^{\infty} \frac{\max\left\{0, \gamma_{\text{target}}N_0 - P_{S_1}|h_0|^2\right\}}{x} f_{A_r}(x)dx. \end{aligned} \quad (22)$$

Therefore, the target SNR and the target outage probability can be satisfied. Theorem 1 is proved. □

Table 1: Energy-efficient relaying strategy with network coding in two-way parallel channels.

Prior to the transmission in two-way relaying:
opportunistic relay selection according to (3).
Start the transmission:
at S_1 node, S_2 node:
(1) decide whether to transmit source data by the direct link or by the relaying link according to (18) and (19);
(2) if both (18) and (19) are satisfied, the forwarding threshold is calculated by formula (15), the transmit power of each source node is calculated by (16) and (17);
Otherwise the direct transmission is preferred, the transmit power of each source node is computed by (16) and (17);
(3) the source nodes start the transmission including broadcasting the message of transmit power and α_t.
At the selected relay node (if the relaying is preferred):
(1) decide whether to broadcast the network-coded data by (7);
(2) work out the transmit power of relay node by (8).

The proposed "energy-efficient relaying strategy with network coding" in two-way parallel channels is summarized in Table 1. Here, the opportunistic relaying is applied to decrease the cooperative costs, to save power, and capture the nice link for the practical system. Moreover, the network coding is introduced to save power.

4. Simulation Results

In this section, we will consider the following three different cooperative schemes.

(i) The proposed distributed strategy (for relaying decision and power allocation) combined with opportunistic relaying and network coding (DSON for short).

(ii) The optimum distributed power allocation (ODPA) scheme [8].

(iii) Single relay model (SRM) [8].

The traditional two-way relaying is decomposed into two one-way transmissions (as shown in Figure 1(a)). Moreover, to the best of our knowledge, (ii) and (iii) outperform the existing distributed schemes in one-way relaying, so we focus on comparing the performance of (i) with that of (ii) and (iii). We consider the two-way transmission consisting of S_1 node and S_2 node 100 m apart, and M relay nodes between the source nodes. The fading model is considered as [15], that is, the variance of the channel gain is proportional to the distance between nodes. Here, we have

$$\sigma_{ki}^2 = \frac{0.5C}{d_{S_k R_i}^{\alpha}}, \quad k = 1, 2,$$
$$\sigma_0^2 = \frac{0.5C}{d_{S_1 S_2}^{\alpha}}, \tag{23}$$

where d_{ji} is the distance between node j and node i, the path-loss exponent is denoted by α, the factor 0.5 is due to the above variances defined by two dimension. C is a constant that is expressed as $C = G_t G_r \lambda^2 / L(4\pi)^2$, where G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the wavelength, and L is the system loss factor not related to propagation ($L \geq 1$). The values $\alpha = 3$, $G_t = G_r = 1$, $\lambda = (1/3)m$, $L = 1$, are used in the simulations. Assume the AWGN variances on all links to be $N_0 = 10^{-10}$ and the target SNR (γ_{target}) to be 10 dB.

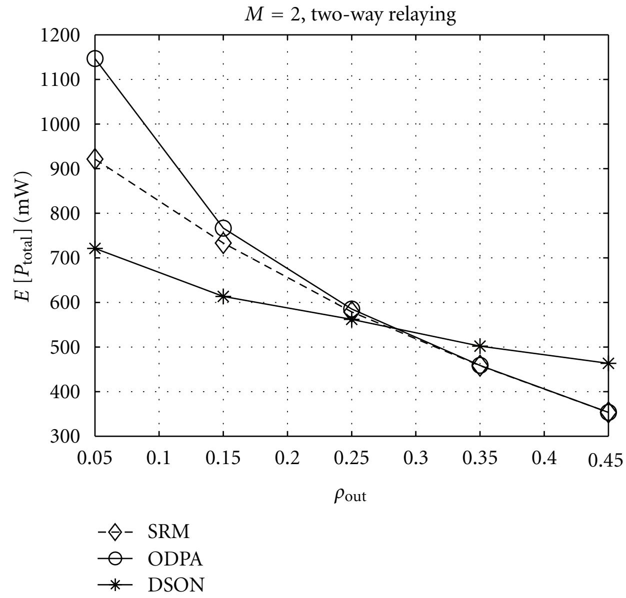

Figure 3: $E[P_{\text{total}}]$ versus the outage probability ρ_{out} for the different distributed strategies with $\{d_{S_1 R_i}\}_{i=1}^{M} = \{0.2, 0.8\}$, $\{d_{R_i S_2}\}_{i=1}^{M} = \{0.8, 0.2\}$, and $M = 2$.

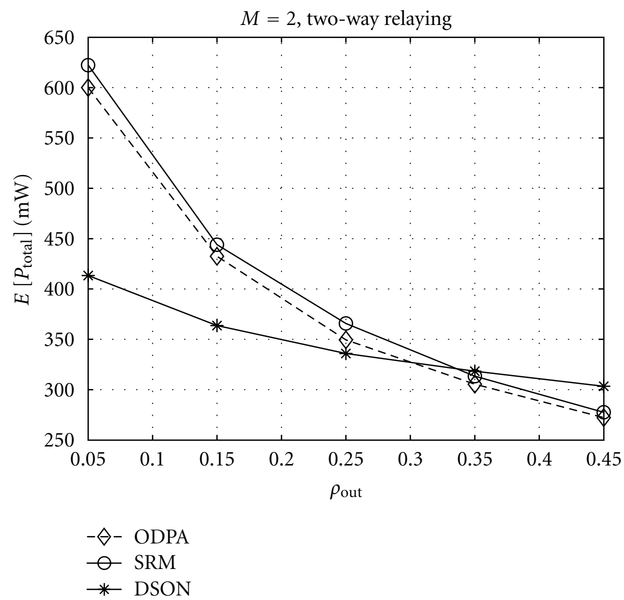

Figure 4: $E[P_{\text{total}}]$ versus the outage probability ρ_{out} for the different distributed strategies with $M = 2$.

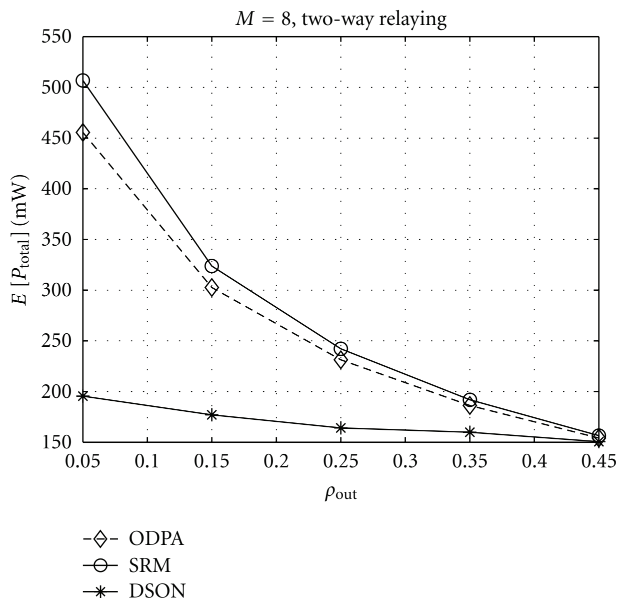

Figure 5: $E[P_{\text{total}}]$ versus the outage probability ρ_{out} for the different distributed strategies with $M = 8$.

We first consider the case in which $\{d_{S_1R_i}\}_{i=1}^{M} = \{0.2, 0.8\}$, $\{d_{R_iS_2}\}_{i=1}^{M} = \{0.8, 0.2\}$, and $M = 2$. Figure 3 illustrates the numerical results of the expected value of the total power $E[P_{\text{total}}]$ as a function of the target outage probability ρ_{out}. It is observed that the proposed strategy (DSON) outperforms the existing schemes at practical values of outage probability. For instance, for an outage $\rho_{\text{out}} = 0.05$, approximately 22%, 37% is saved by the DSON scheme as compared to the ODPA and the SRM schemes, respectively. The performance of the DSON scheme is not better than that of the ODPA and the SRM at the higher outage probability regimes but we know, as fact, that the high outage probability is prohibited in practical systems.

Generally, the relays are located in the midst of two source nodes. The following simulation results are based on the scenario in which all the relay nodes are in the midst of two source nodes. Namely, $\{d_{S_1R_i}\}_{i=1}^{M} = \{d_{R_iS_2}\}_{i=1}^{M} = \{0.5, \ldots, 0.5\}$.

Figure 4 illustrates the numerical results of the expected value of the total power $E[P_{\text{total}}]$ as a function of the target outage probability ρ_{out} for the case $M = 2$. Similarly to the results of Figure 3, Figure 4 shows that the proposed scheme (DSON) outperforms both (ii) and (iii) at the lower ρ_{out} regime. It is also observed that the relative gain of the proposed scheme is larger in comparison to the case of Figure 3. For instance, at outage of $\rho_{\text{out}} = 0.05$, approximately 30%, 31% is saved by the DSON with respect to the ODPA and the SRM, respectively. It is clear that, when the relays are in the middle between the two source nodes, they provide good help to both source nodes. With only two relays ($M = 2$), the opportunistic relaying has less spatial channels to choose from (less spacial diversity) and suffers from broadcasting the network-coded data according to the weaker link in the third transmission phase; this is the implication on the performance of the DSON scheme at higher outage probability regime.

Figure 5 illustrates the numerical results for the case when the number of relay nodes is $M = 8$. Here, it is observed that the DSON strategy has improved considerably in comparison to the case of one- and two-relay nodes. The DSON strategy now enjoys more spatial diversity in the presence of more relay nodes as the candidates. Though the ODPA and the SRM also have more spatial diversities, both the ODPA and the SRM select relays mainly based on source-to-relay links, so their spatial dimension is half of that of the DSON strategy. Moreover, the DSON with network coding only has three transmission phases, this results in more saving in power consumption.

5. Conclusions

In this paper, an energy-efficient relaying strategy with network coding in two-way parallel channels is proposed. In the first stage of this proposal, based on the opportunistic relaying strategy, only one relay is selected to assist the transmission. It decreases the cooperative costs among relays, which is preferred in practical systems. Meanwhile, it guarantees that the DSON chooses the relay from both source-to-relay and relay-to-destination links. Moreover, network coding decreases the transmission phases from four to three. Combined with the opportunistic relaying and network coding, distributed relaying decision and power allocation strategy is applied to obtain the optimal power efficiency. Since only limited CSIs needed in this scheme, it is practical for real applications in two-way relaying networks.

Of course, the DSON suffers from broadcasting the network-coded data according to the weaker link in the third transmission phase for satisfying the requirements of target SNR and target outage probability. From a power saving point of view, the DSON outperforms the ODPA and the SRM in a two-way relaying communication link.

Appendix

For purposes of completeness, we briefly summarize a result from [16], Lemma A.

Lemma A (see [16]). *Random variables $A_i, A_{i1}, \ldots, A_{iK}$, $(i = 1, \ldots, M)$, $A_{i1}, \ldots, A_{iK}$ are independently exponential distributed with parameter $\beta_{i1}, \ldots, \beta_{iK}$, respectively, $A_i = \min\{A_{i1}, \ldots, A_{iK}\}$. Let $r = \operatorname{argmax}_i A_i$, for $F_{A_r}(x)$, the CDF of A_r, there is*

$$F_{A_r}(x) = \prod_{i=1}^{M} \left(1 - e^{-\beta_i x}\right), \tag{A.1}$$

where $\beta_i = \sum_{k=1}^{K} \beta_{ik}$, $i = 1, \ldots, M$.

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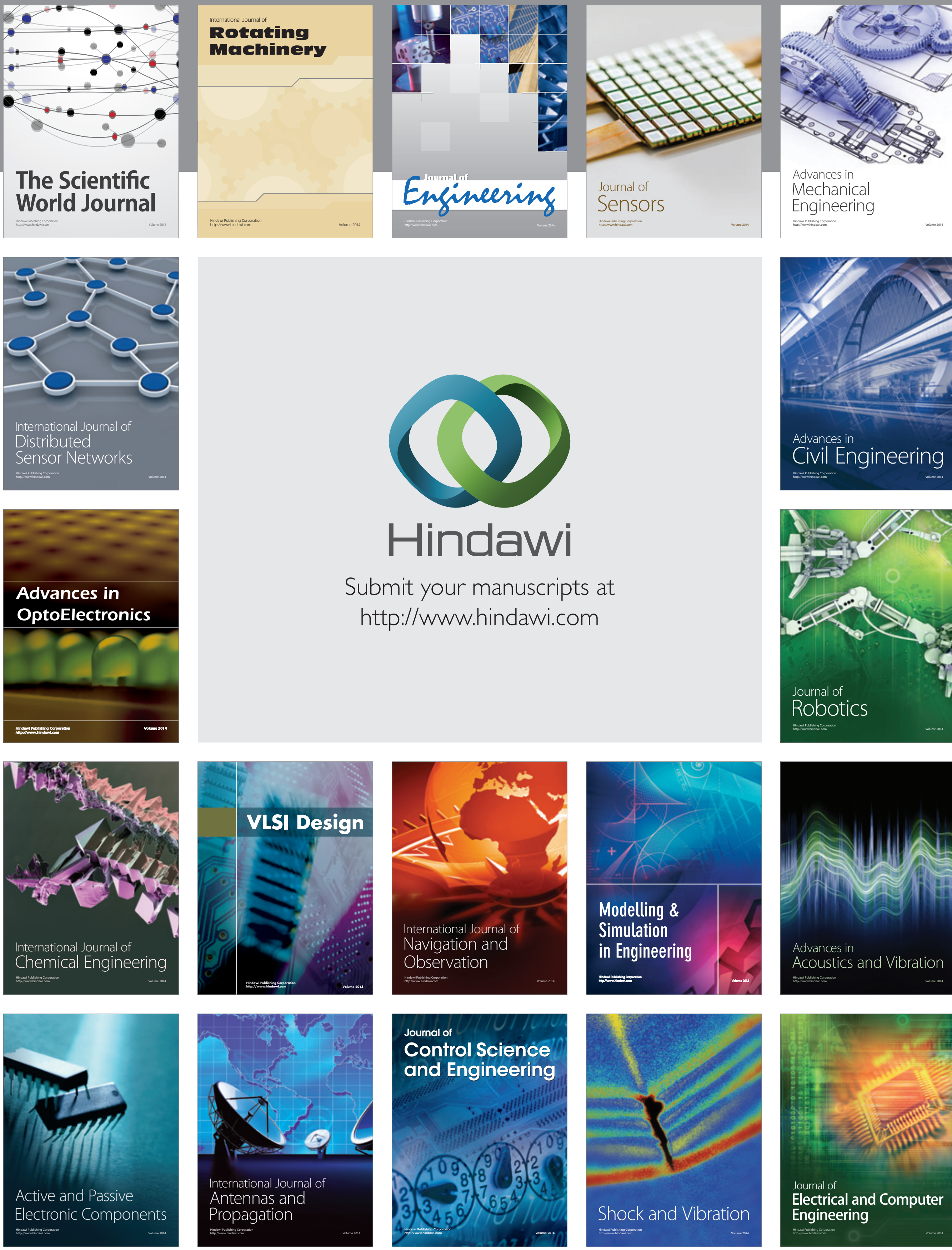
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