Relay Selection Schemes and Performance Analysis Approximations for Two-Way Networks

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***Abstract*—This paper studies relay selection schemes for two-way amplify-and-forward (AF) relay networks. For a network with two users that exchange information via multiple AF relays, we first consider a single-relay selection (SRS) scheme based on the maximization of the worse signal-to-noise ratio (SNR) of the two end users. The cumulative distribution function (CDF) of the worse SNR of the two users and its approximations are obtained, based on which the block error rate (BLER), the diversity order, the outage probability, and the sum-rate of the two-way network are derived. Then, with the help of a relay ordering, a multiple-relay selection (MRS) scheme is developed. The training overhead and feedback requirement for the implementation of the relay selection schemes are discussed. Numerical and simulation results are provided to corroborate the analytical results.**

***Index Terms*—Diversity order, error rate, outage probability, relay selection, sum-rate, two-way networks.**

I. Introduction

COOPERATIVE communications have drawn much interest due to its capability of mitigating the fading effect of wireless channels, extending coverage without enlarging transmit power, and achieving spatial diversity. The relay network, in which one or multiple pairs of users communicate with the help of a single or multiple relay nodes, is one of the most common models for cooperative communications [1]–[5]. The decode-and-forward (DF) and the amplify-and-forward (AF) are two popular relaying protocols. AF usually has a lower implementation complexity as an AF relay simply amplifies its received signal with a power coefficient and forwards it to the destination without hard decoding. Both coherent power coefficient and non-coherent power coefficient are proposed for AF relaying [3]–[5]. The coherent power coefficient, which is adaptive to the channel condition, outperforms the non-coherent one.

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The relaying concept is initiated in unidirectional or one-way relay networks, and has been extensively studied in the literature. Recently, bidirectional or two-way relay networks have gained much attention. In two-way relay networks, two end users exchange information with each other through a single or multiple common relays. Since the two-way relay network model allows the two users to exchange data simultaneously, it improves bandwidth efficiency [6]–[8]. For two-way networks with multiple antennas, precoding is considered in [9], [10]. For two-way networks with multiple relays, single-relay selection (SRS) and multiple-relay selection (MRS) schemes are two main techniques to use the available relays.

SRS schemes, in which a single relay is chosen to help the end users, have been proposed for DF relaying [11]–[15] and AF relaying [16]–[26]. For DF relaying, in [11], a selection scheme is given to maximize the weighted sum-rate capacity; in [12]–[14], the worse receive signal-to-noise ratio (SNR) of the two users is maximized; and in [15], a cross-layer relay selection metric, which depends on both the instantaneous channel conditions and the queuing status, is investigated. For AF relaying, SRS schemes are proposed to maximize the instantaneous sum-rate [16], minimize the sum symbol error rate (SER) [17], maximize the mutual information [18], minimize the outage probability based on the mutual information [19], and maximize the average receive SNR [20]. In [21], three SRS schemes based on the transmission rate maximization, equivalent channel gain maximization, and harmonic mean of channel gain minimization are proposed. Suboptimal max-min criteria are used in [22] and [23], where the maximum SER is minimized in [22], and the minimum SNR is maximized in [23]. The asymptotic SER and outage probability are also derived for high SNR in [22], [23]. Recently, a selection scheme that maximizes the worse receive SNR of the two users for a two-way AF relay network is proposed in [24]–[26]. Specifically, the outage-optimal opportunistic relaying is considered in [24], and our work in [25] and [26] focus on the error rate analysis.

While research on SRS in two-way networks is frequently available in the literature, research on MRS, in which more than one relay can be selected for cooperation, is still limited. In [14], for DF relaying, a scheme that selects two relays out of N available relays to minimize the average sum bit error rate (BER) is proposed. For AF relaying, our paper [26] reports some preliminary results on MRS based on maximization of the worse receive SNR. In [27], focusing on the achievable rate maximization, a cross-entropy (CE) method is introduced to search a near-optimal relay subset.

In this paper, we consider two-way AF relay networks and study SRS and MRS schemes that maximize the worse receive SNR of the two end users. Since this work is for AF relaying, it differs from [11]–[15], which are for DF relaying. Further, design criteria of [11] and [15] are different from our max-min design criterion. The same max-min design criterion is used in references [12]–[14], which consider DF and were published during the review process of this paper. Due to the difference in the relaying protocols (DF vs. AF), the analytical approaches and employed mathematical tools in [12]–[14] are significantly different from those in this paper. Also, while [12]–[14] analyze outage probability, diversity order, frame error-rate, and bit error-rate, in this paper, outage probability, diversity order, block error-rate (BLER), and sum-rate are analyzed. The last two measures are not considered in other papers. This paper is also different from [16]–[23] because it considers the worse receive SNR maximization while different criteria are used in [16]–[23] as discussed above. This paper is different from [24] in that outage probability is the only performance measure in [24] while outage probability, error rate, sum-rate, diversity order, and power efficiency are analyzed with different analytical approaches in this paper. Further, this paper is a broader and deeper extension of our work in [25], [26]. Only error rate and diversity order of the SRS scheme are analyzed in [25] and [26] with the former focusing on two-relay networks only. Our main contributions in this paper are summarized as follows.

- The exact cumulative distribution function (CDF) of the worse end-to-end SNR of the two users and its approximations are obtained, based on which extensive performance measures, including the error rate, diversity order, outage probability, and sum-rate, are evaluated analytically for SRS.
- An MRS scheme is developed for two-way relay networks by using the relay ordering idea proposed in [28]. The extension of the relay ordering idea to two-way relay networks is not straightforward because for two-way relay networks, there are two communication tasks each with its own bit/symbol error rate and end-to-end SNR. The relay selection depends on the overall network quality-of-service requirement and the fairness consideration. In this paper, we apply the relay ordering based on the worse receive SNR and aim at finding the subset of relays that maximizes the worse receive SNR of the two users.
- In comparing SRS and MRS schemes, two interesting advantages of the latter are observed. The MRS scheme is more power efficient, and results in a faster increase in sum-rate with respect to the increase in the number of relays in the network.

The remainder of the paper is organized as follows. The system model, the relay selection criterion, the performance metrics, and discussions on training for the channel state information (CSI) requirement are presented in Section II. The SRS and its performance analysis are studied in Section III. The MRS is considered in Section IV. Numerical and simulation results are presented in Section V, followed by concluding remarks in Section VI. Two involved proofs are provided in the appendices.

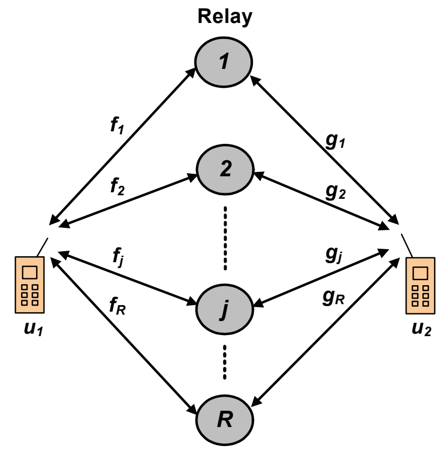


Fig. 1. A two-way multiple-relay network with two end users and R relays.

II. System Model

This section describes the network model, the relay selection criterion, and the measures used to evaluate the network performance. A training scheme for the CSI requirement and its overhead are also discussed.

A. Network Model

A two-way wireless relay network has two end users (namely, u_1 and u_2) and R relays as depicted in Fig. 1. Each node has a single antenna which can be used for both transmission and reception. The fading coefficients from u_1 to the jth relay and from u_2 to the jth relay are denoted as f_j and g_j, respectively. The channels are reciprocal such that the channels from the jth relay to the two end users are also f_j and g_j, respectively. All channels are assumed to be independent and identically distributed (i.i.d.) complex Gaussian fading with zero-mean and unit-variance, i.e., $f_j, g_j \sim \mathcal{CN}(0,1)$. Therefore, magnitudes of f_j and g_j follow a Rayleigh distribution.[1] It is assumed that the two end users know all channel coefficients, $f_1, \ldots, f_R$ and $g_1, \ldots, g_R$, and Relay j knows its own channels f_j and g_j. This channel information requirement can be satisfied through training which is discussed in detail in Section II-D. The power budget is P for each end user and Q_j for the jth relay.

For simplicity, we assume that both users use the same codebook denoted by $\mathcal{S}$. The information symbols from u_1 and u_2, randomly selected from the codebook, are denoted by s_1 and s_2, respectively. For the two users to exchange their information symbols, we use the following two-phase protocol. In the first phase, u_1 and u_2 transmit s_1 and s_2, respectively, at the same time to all relays. Relay j receives a superposition of the two signals, given as $y_j = \sqrt{P} f_j s_1 + \sqrt{P} g_j s_2 + v_j$, where v_j is the additive noise at the relay. v_j's are assumed to

[1] Although we discuss i.i.d. Rayleigh flat-fading channels only, the relay selection schemes studied in this paper work for networks with any channel statistics, because instantaneous CSI is assumed to be available at corresponding nodes.

be i.i.d. with the distribution $\mathcal{CN}(0,1)$. In the second phase, one or multiple relays are selected to forward information. Denote the set of the indices of the selected relays as $\mathcal{R}$.

During the second phase of communication, each selected relay amplifies its received signal in the first phase and broadcasts it to both users. With each relay knowing its channel coefficients, it should incorporate a phase shift to cancel the phases of its channels during the amplifying process, so useful information from each relay can be added coherently at the users [28]. The amplification factor of the jth relay thus should be $\alpha_j e^{\mathbf{i}\varphi_j}$, where $\varphi_j = -(\angle f_j + \angle g_j)$, with $\angle z$ the phase of the complex value z and $\mathbf{i}$ the standard imaginary unit. The power coefficient α_j is to control the relay power. Its design is discussed later in this section. Each end user receives a superposition of the signals forwarded by the selected relays as follows:

$$\begin{aligned} y_{u_1} &= \sum_{j\in\mathcal{R}} \alpha_j \left[\sqrt{P} f_j^2 e^{\mathbf{i}\varphi_j} s_1 + \sqrt{P}|f_j g_j| s_2 + f_j \tilde{v}_j\right] + w_1, \\ y_{u_2} &= \sum_{j\in\mathcal{R}} \alpha_j \left[\sqrt{P} g_j^2 e^{\mathbf{i}\varphi_j} s_2 + \sqrt{P}|f_j g_j| s_1 + g_j \tilde{v}_j\right] + w_2, \end{aligned} \tag{1}$$

where $|z|$ denotes the magnitude of a complex value z, $\tilde{v}_j = v_j e^{\mathbf{i}\varphi_j}$, and w_1 and w_2 denote the noises at the two users, respectively. The noises w_1 and w_2 are also assumed to be i.i.d. with the distribution $\mathcal{CN}(0,1)$. The phase adjustment does not affect the statistical properties of the noises at the relays, i.e., v_j and $\tilde{v}_j$ have the same distribution. Equation (1) shows that each end user receives an observation that is a combination of the other user's symbol and its own symbol. After canceling the self-interference, u_1 and u_2 get:

$$\begin{aligned} \tilde{y}_{u_1} &= \sqrt{P}\textstyle\sum_{j\in\mathcal{R}} \alpha_j |f_j g_j| s_2 + \sum_{j\in\mathcal{R}} \alpha_j f_j \tilde{v}_j + w_1, \\ \tilde{y}_{u_2} &= \sqrt{P}\textstyle\sum_{j\in\mathcal{R}} \alpha_j |f_j g_j| s_1 + \sum_{j\in\mathcal{R}} \alpha_j g_j \tilde{v}_j + w_2, \end{aligned} \tag{2}$$

respectively. The maximum-likelihood (ML) decoding rules of u_1 and u_2 are:

$$\begin{aligned} \hat{s}_2 &= \arg\min_{s\in\mathcal{S}} \left|\tilde{y}_{u_1} - \sqrt{P}\textstyle\sum_{j\in\mathcal{R}} \alpha_j |f_j g_j| s\right|, \\ \hat{s}_1 &= \arg\min_{s\in\mathcal{S}} \left|\tilde{y}_{u_2} - \sqrt{P}\textstyle\sum_{j\in\mathcal{R}} \alpha_j |f_j g_j| s\right|, \end{aligned}$$

respectively. From the system equation (2), the receive SNRs at u_1 and u_2 when the relay subset $\mathcal{R}$ is selected are

$$\begin{aligned} \gamma_{u_1,\mathcal{R}} &= \frac{P\left(\sum_{j\in\mathcal{R}} \alpha_j |f_j g_j|\right)^2}{1+\sum_{j\in\mathcal{R}} \alpha_j^2 |f_j|^2}, \\ \gamma_{u_2,\mathcal{R}} &= \frac{P\left(\sum_{j\in\mathcal{R}} \alpha_j |f_j g_j|\right)^2}{1+\sum_{j\in\mathcal{R}} \alpha_j^2 |g_j|^2}, \end{aligned} \tag{3}$$

respectively.

We have shown in [26] that coherent power coefficient achieves better performance than non-coherent power coefficient in two-way networks. Since each relay knows its channels, only coherent power coefficient is considered in this paper, i.e., α_j is designed as $\alpha_j = \sqrt{\frac{Q_j}{1+P|f_j|^2+P|g_j|^2}}$.

B. Relay Selection Criterion

For a one-way network, the choice of the design criterion is straightforward. Optimal performance is obtained by maximizing the end-to-end SNR, which at the same time maximizes the transmission rate and minimizes the error rate. For a two-way network, however, there are two communication tasks each with its own end-to-end SNR and bit/symbol error rate. The choice of the design criterion depends on the overall network quality-of-service requirement and the fairness consideration. In this paper, we care about the reliability of both users and maximize the worse of the end-to-end SNRs of the two users, or equivalently, minimize the larger of the error rates of the two communication tasks. The general relay selection problem for a two-way network is thus to find the subset of $\{1, 2, \cdots, R\}$, denoted as $\check{\mathcal{R}}$, that results in the maximum worse end-to-end SNR. In other words,

$$\check{\mathcal{R}} = \arg\max_{\mathcal{R}\subseteq\{1,2,\cdots,R\}} \min\{\gamma_{u_1,\mathcal{R}}, \gamma_{u_2,\mathcal{R}}\}. \tag{4}$$

C. Performance Measures

As for performance measures, we consider BLER, diversity order, outage probability, sum-rate, and power efficiency of the network. In the following, we elaborate on these measures.

In a two-way relay network, the two users exchange their symbols, s_1 and s_2, with each other. We take s_1 and s_2 as a block (s_1, s_2). Thus a *block error* occurs when either of the two users makes an error, i.e., $(\hat{s}_1, \hat{s}_2) \neq (s_1, s_2)$. The BLER metric is naturally an upper bound on the symbol error rate (SER) of either user, and also a lower bound on the sum of the SERs of the two users. In addition, in the high SNR regime, the user with the smaller SNR has a higher probability of error, and dominates the block error. Thus, this metric is consistent with the relay selection idea and criterion in (4). For a given channel realization, let $\grave{u}$ be the index of the user with the worse receive SNR, i.e., $\grave{u} = 1$ if $\gamma_{u_1,\check{\mathcal{R}}} < \gamma_{u_2,\check{\mathcal{R}}}$ and $\grave{u} = 2$ otherwise. Let $\tilde{u}$ be the index of the other user. The BLER, denoted as P_{block}, can be calculated as

$$P_{block} = \mathbb{E}[\mathbb{P}(\hat{s}_{\tilde{u}} \neq s_{\tilde{u}})] + \mathbb{E}[\mathbb{P}(\hat{s}_{\grave{u}} \neq s_{\grave{u}} | \hat{s}_{\tilde{u}} = s_{\tilde{u}})], \tag{5}$$

where $\mathbb{E}[\cdot]$ and $\mathbb{P}(\cdot)$ stand for the expectation and probability functions, respectively.

The *outage probability*, denoted as P_{out}, is another important performance measure for communication systems. In a traditional wireless network, an outage occurs if the received SNR, γ, drops below a predetermined SNR threshold γ_{th}. The outage probability can then be calculated as $P_{out} = \mathbb{P}(0 \leq \gamma \leq \gamma_{th})$. In many communication models, outage probability reflects the rate of successful transmission. In the two-way relay network, there are two communication tasks. We thus define outage probability as $P_{out} = \mathbb{P}(0 \leq \min\{\gamma_{u_1,\check{\mathcal{R}}}, \gamma_{u_2,\check{\mathcal{R}}}\} \leq \gamma_{th})$, which is the probability that either user experiences an outage.

The *diversity order* shows how fast the error rate/outage probability decreases with the increase in the transmit power in the high transmit power range. It is originally defined based on the error rate as $d \triangleq -\lim_{P\to\infty} \frac{\log \text{Error rate}}{\log P}$ and is later shown to have an equivalent definition based on the outage probability as $d \triangleq -\lim_{P\to\infty} \frac{\log P_{out}}{\log P}$ where P is the transmit power [29]. When the outage probability of a system is approximated as $P_{out} \approx cP^{-d}$, c relates to the array or coding gain, and d is the diversity order.

The average *sum-rate*, denoted as C, is the highest rate at which information can be communicated. For our two-way relay network, the average sum-rate can be calculated as

$$C = \frac{1}{2}\mathbb{E}[\log_2(1+\gamma_{u_1,\check{\mathcal{R}}})] + \frac{1}{2}\mathbb{E}[\log_2(1+\gamma_{u_2,\check{\mathcal{R}}})] \text{ bits/sec/Hz.} \tag{6}$$

As each node in the network has its own power constraint, the total transmit power in the whole network changes with the number of cooperating relays. To make fair comparison among different selection schemes, we consider the average *power efficiency* defined as [28]

$$\eta \triangleq \mathbb{E}\left[\frac{\min\{\gamma_{u_1,\check{\mathcal{R}}}, \gamma_{u_2,\check{\mathcal{R}}}\}}{2P + \sum_{j\in\check{\mathcal{R}}} Q_j}\right]. \tag{7}$$

It is the average worse end-to-end SNR per unit power achieved in the network.

D. Discussions on CSI and Training

In this work, it is assumed that 1) both users know all channels $f_1, \cdots, f_R, g_1, \cdots, g_R$, and 2) Relay j knows its own channels f_j and g_j. These CSI requirements should be satisfied through training before data transmission for each coherence interval. In this section, a possible training scheme is proposed. Since the focus of our discussion is on the overhead requirement, we consider only the minimum requirement on the training interval length. Specific channel estimation rules and the effect of channel estimation errors on the network performance are not discussed. The proposed training scheme contains three steps.

Step 1 needs R time slots for the two end users to obtain their channel gain information with the relays. For the jth time slot of this step, Relay j broadcasts a pilot. Each user can thus estimate its channel with Relay j based on its received signal by using common estimation rules, such as ML or minimum mean square error (MMSE) estimations. After this step, u_1 knows $f_1, \cdots, f_R$ and u_2 knows $g_1, \cdots, g_R$.

Step 2 needs $(R+1)$ time slots, for Relay j ($j \in \{1, 2, ..., R\}$) to estimate f_j and u_2 to estimate $f_1, \cdots f_R$. It has two phases. In Phase 1, u_1 sends one pilot and all relays receive, which takes one time slot. Relay j can thus estimate f_j, its channel with u_1, from the signal it receives. In Phase 2, the relays amplify and forward their received signals in Phase 1 in turn, which takes R time slots. For simplicity, non-coherent amplification factor can be used. u_2, at Slot j of Phase 2, receives

$$y_j^{(t,2)} = \sqrt{\frac{PQ_j}{P+1}} f_j g_j s^{(t,2)} + \sqrt{\frac{PQ_j}{P+1}} g_j v_j^{(t,2)} + w_2^{(t,2)},$$

where $v_j^{(t,2)}$ is the noise at Relay j in Phase 1, $w_2^{(t,2)}$ is the noise at u_2, and $s^{(t,2)}$ is the pilot (sent by u_1 in Phase 1). We use superscript 't' to indicate the training phase and use superscript '2' to indicate Step 2. Since u_2 knows g_j from Step 1, it can thus estimate f_j from $y_j^{(t,2)}$. After Step 2, Relay j knows f_j and u_2 knows $f_1, \cdots, f_R$.

Step 3 needs $(R+1)$ time slots, for Relay j to estimate g_j and u_1 to estimate $g_1, \cdots g_R$. It is symmetric to Step 2. It also has two phases. In Phase 1, u_2 sends one pilot and all relays receive, which takes one time slot. Relay j can thus estimate g_j, its channel with u_2, from the signal it receives. In Phase 2, the relays amplify and forward their received signals in Phase 1 in turn, which takes R time slots. u_1, at Slot j of Phase 2, receives

$$y_j^{(t,3)} = \sqrt{\frac{PQ_j}{P+1}} g_j f_j s^{(t,3)} + \sqrt{\frac{PQ_j}{P+1}} f_j v_j^{(t,3)} + w_1^{(t,3)},$$

where $v_j^{(t,3)}$ is the noise at Relay j in Phase 1, $w_1^{(t,3)}$ is the noise at u_1, $s^{(t,3)}$ is the pilot (sent by u_2 in Phase 1). Since u_1 knows f_j from Step 1, it can thus estimate g_j from $y_j^{(t,3)}$. After Step 3, Relay j knows g_j and u_1 knows $g_1, \cdots, g_R$.

Thus, after all three steps of the training scheme, all nodes in the two-way relay network obtain their required CSI. The total overhead required for the training is $(3R+2)$, which is linear in the network size. No cross talks between the relays and between the two end users are required. No channel coefficient, which is a complex number, needs to be communicated between nodes.

III. Single-Relay Selection and its Performance Analysis

In this section, we consider SRS, i.e., only one of the multiple available relays in the network is chosen to cooperate. An advantage of this scheme over MRS is that during the second phase of communication, the phase adjustment at the selected relay is unnecessary and only the channel amplitude information is required at the relay. Assuming that the jth relay is chosen, the received signals at u_1 and u_2 after self-interference cancelation are:

$$\tilde{y}_{u_1} = \sqrt{P}\alpha_j f_j g_j s_2 + \alpha_j f_j v_j + w_1,$$
$$\tilde{y}_{u_2} = \sqrt{P}\alpha_j f_j g_j s_1 + \alpha_j g_j v_j + w_2,$$

respectively. The end-to-end receive SNRs of u_1 and u_2 are thus

$$\begin{aligned}\gamma_{u_1,\{j\}} &= \tfrac{PQ_j|f_jg_j|^2}{1+(P+Q_j)|f_j|^2+P|g_j|^2},\\ \gamma_{u_2,\{j\}} &= \tfrac{PQ_j|f_jg_j|^2}{1+P|f_j|^2+(P+Q_j)|g_j|^2},\end{aligned} \tag{8}$$

respectively. The relay selection problem in (4) reduces to

$$\check{j} = \arg\max_j \ \min\left\{\gamma_{u_1,\{j\}}, \gamma_{u_2,\{j\}}\right\}, \tag{9}$$

that is, finding the relay that results in the maximum worse SNR.

The relay selection can be performed at either end user, who knows all channels. The user can find the index of the relay, $\check{j}$, with the highest worse end-to-end SNR, and broadcast the index information to the relays. $\log_2 R$ bits are needed.

A. CDF Analysis of the Worse End-to-End SNR

Define $\gamma_j \triangleq \min\left\{\gamma_{u_1,\{j\}}, \gamma_{u_2,\{j\}}\right\}$. The CDF of γ_j, denoted as $F_{\gamma_j}(x)$, is rigorously derived in the following theorem.

Theorem 1: The CDF of γ_j is

$$\begin{aligned}F_{\gamma_j}(x) = &\ 1 - e^{-\frac{\theta_j(x)}{P}} \frac{\kappa_j(x)}{P}\mathcal{K}_1\left(\frac{\kappa_j(x)}{P}\right)\\ &+ e^{-\frac{\theta_j(x)}{P}} \int_{a_j-(1+\xi_j)\frac{x}{P}}^{a_j-\xi_j\frac{x}{P}} e^{-\left(y+\frac{\kappa_j(x)^2}{4P^2y}\right)} dy,\end{aligned} \tag{10}$$

where $a_j \triangleq \frac{(\xi_j+\frac{1}{2})x+\sqrt{(\xi_j+\frac{1}{2})^2x^2+\xi_j x}}{P}$, $\xi_j \triangleq \frac{P}{Q_j}$, $\kappa_j(x) \triangleq 2\sqrt{\xi_j x(1+(1+\xi_j)x)}$, $\theta_j(x) \triangleq (1+2\xi_j)x$, and $\mathcal{K}_1(\cdot)$ is the modified first-order Bessel function of the second kind.

Proof: See Appendix A. ■

The CDF formula in Theorem 1 is rigorous and applies for any values of the powers P and Q_j. However, the integration and the modified Bessel function make it complicated for further performance (e.g., outage probability, BLER, and sum-rate) analysis. Thus, we derive several approximations of the CDF, which are mathematically more tractable, to facilitate further performance analysis.

Approximation 1 ($F_{\gamma_j}^{apx1}(x)$): We first look for an approximation on the integral term in (10). Let $\Lambda \triangleq [a_j-(1+\xi_j)\frac{x}{P}, a_j-\xi_j\frac{x}{P}]$. With the mean value theorem, there exists a $\mu \in \Lambda$ such that

$$\int_{a_j-(1+\xi_j)\frac{x}{P}}^{a_j-\xi_j\frac{x}{P}} e^{-\left(y+\frac{\kappa_j(x)^2}{4P^2y}\right)}dy = \frac{x}{P}e^{-\left(\mu+\frac{\kappa_j(x)^2}{4P^2\mu}\right)}.$$

Noticing that $\frac{\kappa_j(x)}{2P} \in \Lambda$ and the length of Λ is $\frac{x}{P}$, we have $\left|\frac{\kappa_j(x)}{2P}-\mu\right| \leq \frac{x}{P}$. When P is large, $\frac{x}{P}$ is small, thus $\mu \approx \frac{\kappa_j(x)}{2P}$. By using this, an approximate CDF $F_{\gamma_j}^{apx1}(x)$ is obtained as

$$F_{\gamma_j}^{apx1}(x)= 1-\frac{\kappa_j(x)}{P}e^{-\frac{\theta_j(x)}{P}}\mathcal{K}_1\left(\frac{\kappa_j(x)}{P}\right)+\frac{x}{P}e^{-\frac{\theta_j(x)+\kappa_j(x)}{P}}. \tag{11}$$

Note that Approximation 1 is obtained by approximating the third term in (10) only. From the above derivation, it can be seen that Approximation 1 is accurate for large P. Since the outage probability can be written in the form of $F_{\gamma_j}(\gamma_{th})$, we use Approximation 1 to analyze the outage probability for large P, the details of which will be shown in Section III-B.

In addition, we are interested in the BLER and sum-rate analysis. If we use Approximation 1, the calculations involve derivative and integration of $\mathcal{K}_1(\cdot)$ with complicated arguments, which are intractable. Therefore, we propose two further approximations for the second term in (10), to analyze the BLER in Section III-C and the sum-rate in Section III-E.

Approximation 2 ($F_{\gamma_j}^{apx2}(x)$): First, we look for a simple approximation for $\frac{\kappa_j(x)}{P}$. Notice that

$$2\sqrt{\xi_j(1+\xi_j)}\frac{x}{P} \leq \frac{\kappa_j(x)}{P} \leq 2\sqrt{\xi_j(1+\xi_j)}\frac{x}{P}+\frac{1}{P}\sqrt{\frac{\xi_j}{1+\xi_j}}.$$

The difference between the lower and the upper bound in the above formula is $\frac{1}{P}\sqrt{\frac{\xi_j}{1+\xi_j}}$, which is small for large P. Therefore, we have $\frac{\kappa_j(x)}{P} \approx \tilde{\kappa}_j\frac{x}{P}$ where $\tilde{\kappa}_j \triangleq 2\sqrt{\xi_j(1+\xi_j)}$. Second, we use $x\mathcal{K}_1(x) \approx 1$, which is valid for small x [30]. $F_{\gamma_j}^{apx2}(x)$ is thus obtained from (11) as:

$$F_{\gamma_j}^{apx2}(x) = 1-e^{-\frac{\tilde{\theta}_j}{P}x}+\frac{x}{P}e^{-\frac{\tilde{\theta}_j+\tilde{\kappa}_j}{P}x}, \tag{12}$$

where $\tilde{\theta}_j = 1+2\xi_j$. This approximation is expected to be tight for small x only.

Approximation 3 ($F_{\gamma_j}^{apx3}(x)$): For the second term in (11), we first use $\frac{\kappa_j(x)}{P} \approx \tilde{\kappa}_j\frac{x}{P}$ to simplify the argument of the modified Bessel function. Then we use $\mathcal{K}_1(y) \approx \sqrt{\frac{\pi}{2}}\frac{e^{-y}}{y}$, which is valid for moderate and high y [31].[2] $F_{\gamma_j}^{apx3}(x)$ is thus obtained as

$$F_{\gamma_j}^{apx3}(x) = 1-\sqrt{\frac{\pi}{2}}e^{-\frac{\tilde{\theta}_j+\tilde{\kappa}_j}{P}x}+\frac{x}{P}e^{-\frac{\tilde{\theta}_j+\tilde{\kappa}_j}{P}x}. \tag{13}$$

So the approximation $F_{\gamma_j}^{apx3}(x)$ is expected to be tight for moderate and large x.

Fig. 2(a) shows the comparison of the three approximations with the exact CDF, while Fig. 2(b) and Fig. 2(c) are enlarged portions of Fig. 2(a) in small x range and large x range, respectively, for $P = Q_j = 10$ dB. The exact CDF is generated using Monte-Carlo simulation. As shown in Fig. 2(a), $F_{\gamma_j}^{apx1}(x)$ well matches the exact CDF for all x. As shown in Fig. 2(b) and Fig. 2(c), $F_{\gamma_j}^{apx2}(x)$ matches well with the exact CDF for small x and $F_{\gamma_j}^{apx3}(x)$ matches well with the exact CDF for moderate and large x, as expected.

With the SRS scheme given in (9), the maximum worse end-to-end SNR of the network is $\gamma_{\tilde{j}} = \max_j \gamma_j$. Since all channels are independent, the CDF of $\gamma_{\tilde{j}}$, denoted as $F_{\gamma_{\tilde{j}}}(x)$, can be calculated as $F_{\gamma_{\tilde{j}}}(x) = \prod_{j=1}^R F_{\gamma_j}(x)$.

B. Outage Probability Analysis

In this subsection, the outage probability is analyzed. For the sake of brevity, we assume that all relays have the same power. From the definition in Section II-C, the outage probability of the two-way network with our SRS scheme can be calculated as $P_{out} = \mathbb{P}(0 \leq \gamma_{\tilde{j}} \leq \gamma_{th}) = F_{\gamma_{\tilde{j}}}(\gamma_{th})$. Using $F_{\gamma_j}^{apx1}(x)$, the outage probability can be approximated as

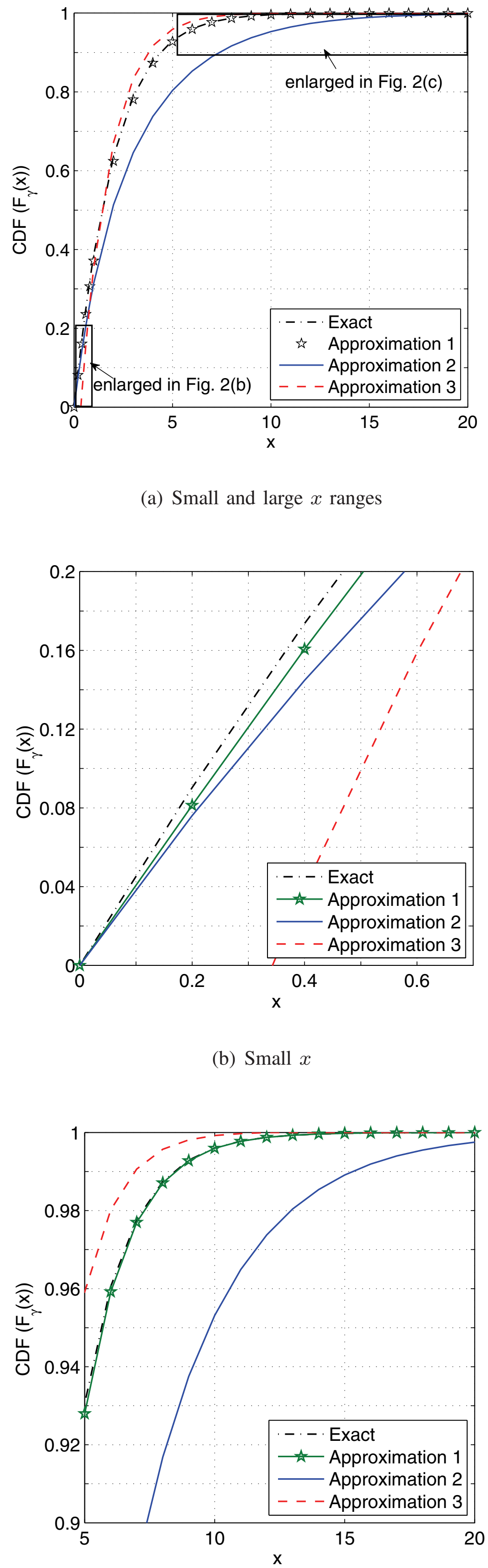
$$\begin{aligned} P_{out} \approx \prod_{j=1}^R \quad &\left(1-\tfrac{\kappa_j(\gamma_{th})}{P}e^{-\frac{\theta_j(\gamma_{th})}{P}}\mathcal{K}_1\left(\tfrac{\kappa_j(\gamma_{th})}{P}\right)\right. \\ &\left.+\tfrac{\gamma_{th}}{P}e^{-\frac{\theta_j(\gamma_{th})+\kappa_j(\gamma_{th})}{P}}\right), \end{aligned} \tag{14}$$

which can be calculated numerically. Interestingly, although Approximation 1 is valid for large P only, simulation results in Section V show that the outage probability formula (14) is accurate even for small P (e.g., $P = 0$ dB in Fig. 3). This is because in (10), the third term is not significant, compared with the first and second terms.

C. BLER Analysis

In this subsection, we analyze the BLER of the two-way relay network with the SRS scheme. A BLER formula is provided in (5), in which the first term is the average probability that the user with the lower receive SNR makes an error and the second term is the average probability that the user with the higher receive SNR makes an error given that the other user decodes correctly. When the transmit power is high, the second term is expected to be much smaller than the first. Thus, we approximate the BLER by ignoring the second

[2]This is through truncating high order terms of $\mathcal{K}_\nu(y) = \sqrt{\frac{\pi}{2}}\frac{e^{-y}}{y}\left[\sum_{k=0}^n \frac{(\nu+\frac{1}{2})_k(\frac{1}{2}-\nu)_k}{k!}\left(-\frac{1}{2y}\right)^k+\mathcal{O}\left(\frac{1}{y^{n+1}}\right)\right]$, where n is a positive integer and $(\cdot)_k$ is the Pochhammer function.



(a) Small and large x ranges

(b) Small x

(c) Large x

Fig. 2. Comparison of proposed CDF approximations with the exact CDF of γ_j, $P = Q_j = 10$dB.

term, i.e., $P_{block} \approx P_{appro} \triangleq \mathbb{E}[\mathbb{P}(\hat{s}_{\tilde{u}} \neq s_{\tilde{u}})]$. Since the second term is non-negative, P_{appro} is actually a lower bound on the BLER of the network.

From the definition, P_{appro} is exactly the average SER of a single-source communication system with receive SNR $\gamma_{\tilde{j}}$. With digital modulations, the SER can be approximated as (the nearest neighbor approximation) $P_{appro} \approx M_{d_{\min}} \mathbb{E}\left[\mathcal{Q}\left(\frac{\beta}{\sqrt{2}}\sqrt{\gamma_{\tilde{j}}}\right)\right]$, where $M_{d_{\min}}$ is the number of neighbors a constellation point has at the minimum distance $d_{\min}$, β is a constant depending on the modulation, and $\mathcal{Q}(x)$ is the probability that a standard normal random variable takes a value larger than x. Using integration by parts, we have

$$P_{appro} \approx \frac{\beta M_{d_{\min}}}{4\sqrt{\pi}} \int_0^{\infty} x^{-\frac{1}{2}} e^{-\frac{\beta^2}{4}x} F_{\gamma_{\tilde{j}}}(x) dx. \tag{15}$$

For the sake of brevity, we assume that all relays have the same power, i.e., $Q_j = Q$, for $j = 1, \cdots, R$. Therefore, the CDF of $\gamma_{\tilde{j}}$ can be calculated as $F_{\gamma_{\tilde{j}}}(x) = \left[F_{\gamma_j}(x)\right]^R$. Using Approximation 2, $F_{\gamma_j}^{apx2}(x)$ given in (12), for $F_{\gamma_j}(x)$ and the binomial series expansion, we have

$$F_{\gamma_{\tilde{j}}}(x) \approx \sum_{i=0}^{R}\sum_{j=0}^{i} \frac{(-1)^j \binom{R}{i}\binom{i}{j}}{P^{i-j}} x^{i-j} e^{-\frac{i\tilde{\theta}+(i-j)\tilde{\kappa}}{P}x}, \tag{16}$$

where $\xi = \xi_j$, $\tilde{\theta} = \tilde{\theta}_j$ and $\tilde{\kappa} = \tilde{\kappa}_j$ since all relays have the same power. By using (16) in (15), the BLER can be approximated as

$$P_{appro} \approx \frac{\beta M_{d_{\min}}}{4\sqrt{\pi}} \sum_{i=0}^{R}\sum_{j=0}^{i} \frac{(-1)^j \binom{R}{i}\binom{i}{j}\Gamma(i-j+\frac{1}{2})}{P^{i-j}\left(\frac{i\tilde{\theta}+(i-j)\tilde{\kappa}}{P} + \frac{\beta^2}{4}\right)^{i-j+\frac{1}{2}}}, \tag{17}$$

where $\Gamma(\cdot)$ is the Gamma function. The BLER for networks with non-uniform relay powers (i.e., with $Q_i \neq Q_j$ for $i \neq j$) can be evaluated similarly in closed-form but with a much more complicated expression. Simulation results in Section V show that the BLER approximation is tight for a wide range of transmit power P.

Remark: Approximation 2 is obtained by approximating Approximation 1 for small SNR, and is used to analyze the BLER. The network BLER is mostly contributed by small x region, due to the exponential function in the integration in (15). Thus, an approximation of the CDF that is precise for small x is useful, while its tightness at medium to high x is less important. This motivates Approximation 2, which is accurate in small SNR region as shown in Section III-A. The derived BLER formula is accurate compared with simulation results (to be shown in Section V).

D. Diversity Order Analysis

In this subsection, we analyze the achievable diversity order of the SRS scheme using the outage probability. The following theorem is proved.

Theorem 2: The outage probability, P_{out}, is evaluated to be

$$P_{out}(\gamma_{th}) = \frac{2^R \prod_{j=1}^{R}(1+\xi_j)\gamma_{th}^R}{P^R} + \mathcal{O}\left(\gamma_{th}, \frac{1}{P^{R+1}}\right), \tag{18}$$

where γ_{th} is the SNR threshold.

Proof: See Appendix B. ■

As we explained in Section II-C, from (18), we conclude that the SRS achieves the diversity order of R, which is the full spatial diversity order provided by the network for both users. The P_{out} formula given in (18) is rigorous and valid for any values of P and Q_j. No approximation is made in its derivation. Note that, if we use Approximation 1 and Approximation 2 of the CDF in (11) and (12), the same result as in (18) can be derived.

Remark: Although equations (14) and (18) are both for outage probability, they have different purposes. Equation (18) is used for the diversity order analysis. From the definition of diversity order, it only depends on the highest order term of P in the outage probability formula. Thus, equation (18) provides the highest order term of P, while all other terms are included in $\mathcal{O}\left(\gamma_{th}, \frac{1}{P^{R+1}}\right)$. On the other hand, equation (14) is based on Approximation 1. It contains not only the highest order term, but also lower order terms of P (via the $\mathcal{K}_1(x)$ function). Thus, when used to evaluate outage probability, equation (14) is expected to be more precise than equation (18) especially when P is not very high.

E. Sum-Rate Analysis

In this subsection, the average sum-rate of the SRS scheme is analyzed. Again, we assume that all relays have the same power. From (6), a lower bound on the average sum-rate can be defined as

$$C_{\text{lb}} \triangleq \mathbb{E}[\log_2(1+\gamma_{\breve{j}})] = \int_0^\infty \log_2(1+x) f_{\gamma_{\breve{j}}}(x) dx, \quad (19)$$

where $f_{\gamma_{\breve{j}}}(x)$ is the probability density function of $\gamma_{\breve{j}}$ which is given as $f_{\gamma_{\breve{j}}}(x) = \frac{dF_{\gamma_{\breve{j}}}(x)}{dx}$. Using Approximation 3, $F_{\gamma_j}^{apx3}(x)$, we have

$$\begin{aligned} f_{\gamma_{\breve{j}}}(x) \approx \quad & R\left(F_{\gamma_j}^{apx3}(x)\right)^{R-1} \\ & \times \left(\tfrac{1}{P} + \sqrt{\tfrac{\pi}{2}}\tfrac{(\tilde{\theta}+\tilde{\kappa})}{P} - \tfrac{(\tilde{\theta}+\tilde{\kappa})}{P^2}x\right) e^{-\frac{\tilde{\theta}+\tilde{\kappa}}{P}x}. \end{aligned}$$

With the help of the binomial series expansion, an approximation for C_{lb} is derived as (20) on the top of the next page, where $\mu \triangleq \frac{(i+1)(\tilde{\theta}+\tilde{\kappa})}{P}$, $\mathcal{J}_n(\mu) \triangleq (n-1)! e^{\mu} \sum_{l=1}^{n} \frac{\Gamma(l-n,\mu)}{\mu^l}$, and $\Gamma(\cdot,\cdot)$ is the upper incomplete gamma function [32].

Remark: Approximation 3 is obtained by approximating Approximation 1 for moderate and large SNR, and is used to analyze the sum-rate. For the sum-rate, Approximation 2 cannot be used because the sum-rate of the network is mostly contributed by the high x region, due to the log-function in the integration in (19). Thus, we need an approximation that is precise for high x, while its tightness at low x is less important. This motivates Approximation 3, which is accurate in high SNR region as shown in Section III-A. The derived sum-rate matches well with simulation results (to be shown in Section V). This is because transmission rates of the moderate and large SNR ranges contribute more to the average transmission rate than that of the low SNR range.

IV. Multiple-Relay Selection

In this section, we generalize the relay selection scheme from SRS to MRS; in other words, more than one relay is allowed to participate in the second phase of the communication. For one-way relay networks, MRS is proposed in [28] and is shown to have a much better performance than SRS with a small amount of extra cost on the overhead. A disadvantage is that when more than one relay is allowed to cooperate, for the relay signals to be added coherently at the two end users, the cooperative relays must adjust the phases of their transmission signals precisely, which requires carrier-level synchronization. The relay selection problem, as explained in Section II-B, is finding the subset of relays, denoted as $\breve{\mathcal{R}}$, that maximizes the worse of the two end-to-end SNRs given in (3).

As there are R relays and each relay has two choices, there are $(2^R - 1)$ possibilities (the case that no relay cooperates is obviously not optimal). One can always solve the relay selection problem by exhaustive search. But the computational complexity is exponential in R, and the number of required overhead bits is R since one bit for each relay is needed. For networks with a large number of relays, having the amount of overhead bits linear in the network size is undesirable. Thus, the same as one-way relay networks, the real challenge of the problem is to find MRS schemes with low complexity, good performance, and, at the same time, low overhead. This motivates the relay ordering idea in one-way relay networks [28]. With a relay ordering, one can find the cooperating relays sequentially. In this paper, we apply the idea to two-way networks and develop the worse end-to-end SNR as the relay ordering function. The MRS scheme is described in Algorithm 1. This algorithm can be performed by either end user, who has perfect and global CSI.

Algorithm 1 MRS algorithm for two-way relay networks.

1: Calculate $\gamma_j = \min(\gamma_{u_1,\{j\}}, \gamma_{u_2,\{j\}})$, using (8) for all $j = 1, ..., R$.
2: Sort γ_j in descending order to get a relay ordering $(i_1, \cdots, i_R)$.
3: **for** $k = 1 : R$ **do**
4: Calculate $\gamma_{u_1,\{i_1,\ldots,i_k\}}$ and $\gamma_{u_2,\{i_1,\ldots,i_k\}}$ using (3).
5: Find $\check{k} = \arg\max_k \min(\gamma_{u_1,\{i_1,\ldots,i_k\}}, \gamma_{u_2,\{i_1,\ldots,i_k\}})$.
6: Broadcast a number that is between $\min\{\gamma_{u_1,\{i_{\check{k}}\}}, \gamma_{u_2,\{i_{\check{k}}\}}\}$ and $\min\{\gamma_{u_1,\{i_{\check{k}+1}\}}, \gamma_{u_2,\{i_{\check{k}+1}\}}\}$.

Upon receiving the broadcasted value (in Step 6 of Algorithm 1) from the end user that conducts relay selection, each relay, who knows its own γ_j, decides whether to cooperate or not by comparing its γ_j with the broadcasted value. If γ_j is larger, the jth relay cooperates; otherwise, it does not cooperate. The MRS scheme requires the feedback of one positive number that is common to all relays. Thus, the number of feedback bits is fixed whose value depends on the required precision, independent of the number of relays.

From the relay ordering in Step 2 and the maximization in Step 5, the performance of the MRS is always no worse than that of the SRS. It improves the end user SNRs, and also achieves full diversity. However, the total power utilization in the whole network increases as more relays cooperate. Other

$$
\begin{aligned}
C_{\text{lb}} &\approx \frac{R}{\ln 2}\sum_{i=0}^{R-1}\sum_{j=0}^{i}\frac{(-1)^j\binom{R-1}{i}\binom{i}{j}\left(\frac{\pi}{2}\right)^{\frac{j}{2}}}{P^{i-j+1}}\int_0^\infty\left[\ln(1+x)\left(\sqrt{\frac{\pi}{2}}(\tilde{\theta}+\tilde{\kappa})+1-\frac{(\tilde{\theta}+\tilde{\kappa})}{P}x\right)x^{i-j}e^{-\frac{(i+1)(\tilde{\theta}+\tilde{\kappa})}{P}x}\right]dx \\
&= \frac{R}{\ln 2}\sum_{i=0}^{R-1}\sum_{j=0}^{i}\frac{(-1)^j\binom{R-1}{i}\binom{i}{j}\left(\frac{\pi}{2}\right)^{\frac{j}{2}}\left[\left(\sqrt{\frac{\pi}{2}}(\tilde{\theta}+\tilde{\kappa})+1\right)\mathcal{J}_{i-j+1}(\mu)-\frac{(\tilde{\theta}+\tilde{\kappa})\mathcal{J}_{i-j+2}(\mu)}{P}\right]}{P^{i-j+1}}.
\end{aligned} \tag{20}
$$

than the worse SNR, a more sensible measure in comparing the MRS with the SRS is thus the power efficiency, defined in (7). The power efficiency is the average SNR achieved per unit power. With this measure, one can tell whether the performance improvement obtained by having more relays cooperate in the MRS scheme is worthy of the extra power spent. As will be shown by simulation in Section V, the MRS achieves much higher power efficiency. In addition, it achieves a faster sum-rate increase as the network size increases.

V. Numerical and Simulation Results

In this section, we give numerical and simulation results to justify our analysis and to evaluate the performance of the relay selection schemes. Quadrature phase-shift keying (QPSK) is used as the modulation scheme by which $\beta=\sqrt{2}$ and $M_{d_{\min}}=2$.

A. Performance of SRS

Fig. 3 shows the outage probability of the SRS scheme for $R=2$ and $R=4$ at $\gamma_{th}=-5$ dB and $\gamma_{th}=5$ dB. The continuous curves and discrete markers show the analytical results given in approximation (14) and the simulation results, respectively. This figure shows the tightness of the approximation and also the diversity order in the sense of outage probability, which are 2 and 4 for $R=2$ and $R=4$, respectively. We can see that for both threshold values (-5dB and 5 dB), the derived outage expression (14) is tight for all simulated power levels even for $P=0$ dB. This is because the third term in the CDF formula (10) is insignificant, compared with the other two terms.

In Fig. 4, we show BLERs of the SRS scheme for relay networks with $R=1,2,3,4$ with respect to P, the power of the end users. All nodes have the same power, i.e., $P=Q_1=Q_2=\cdots=Q_R$. The analytical BLER curves in this figure are based on the approximation in (17). First, it can be seen that the diversity order changes from 1 to 4 when R varies from 1 to 4. This is consistent with our result in Theorem 2 that diversity order R can be achieved. Further, the BLER approximation in (17) tightly matches the simulated BLER for the entire simulated range of P (12 dB $\sim$ 40 dB), especially for large P. For all networks, the gaps between the simulation curve and the approximation curve are less than 0.3 dB at 10^{-6} BLER level. The approximation is a lower bound, which is consistent with our discussion in Section III.

In Fig. 5, we show the average sum-rate of the SRS scheme for $R=2$ and $R=10$. We set the power such that $P=Q_1=Q_2=\ldots=Q_R$. Four curves are plotted: 1) the exact sum-rate of the SRS by simulation, with legend "Exact"; 2) the sum-rate of random relay selection, in which a

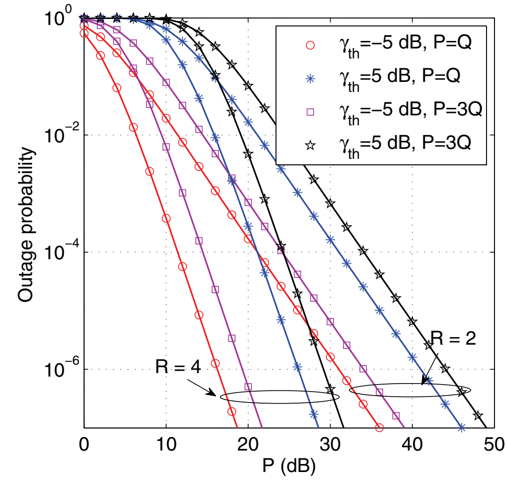


Fig. 3. Outage probability of the SRS scheme ($R=2,4$).

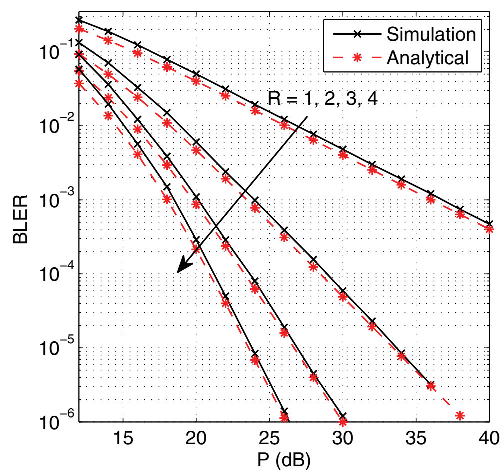


Fig. 4. BLER of the SRS scheme ($R=1,2,3,4$ and $P=Q_j$).

relay is randomly chosen to cooperate, with legend "Random"; 3) the sum-rate of the best sum-rate selection, in which the relay giving the best sum-rate is selected, with legend "Best sum-rate"; and 4) our analytical lower bound on the sum-rate given in (20), with legend "Analytical lower bound". First, this figure shows that the SRS, although aiming at maximizing the worse end-to-end SNR, achieves almost the same sum-rate as the best sum-rate relay selection in our simulated network example. Its advantage over random relay selection is evident. Since the sum-rate of random relay selection does not depend

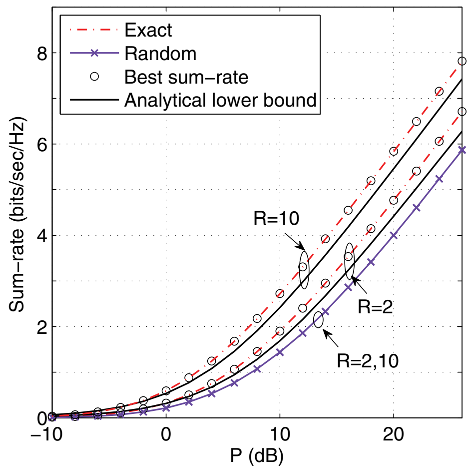


Fig. 5. Average sum-rate of the SRS, random relay selection, and best sum-rate relay selection ($R = 2, 10$).

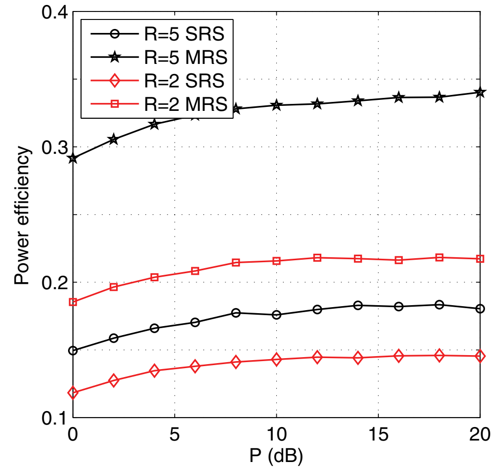


Fig. 7. Power efficiency of the SRS scheme and the MRS scheme ($R = 2, 5$).

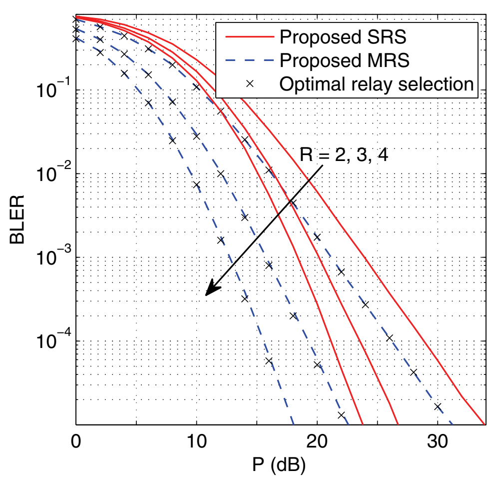


Fig. 6. BLER of of the SRS, MRS, and exhaustively searched optimal relay selection.

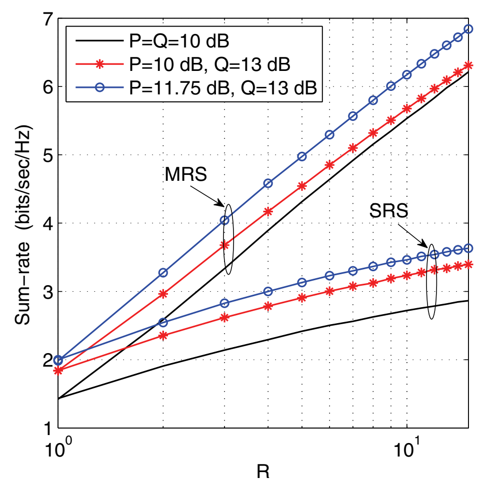


Fig. 8. Sum-rate versus R of the SRS and MRS schemes.

on the number of relays and the sum-rate of our selection scheme increases with R, this advantage increases as more relays are available in the network. The derived analytical sum-rate approximation (20) works well. Its gaps with the exact (simulated) sum-rate are about 1.0 dB and 1.2 dB at sum-rates 2 bits/sec/Hz and 5 bits/sec/Hz, respectively, for both network settings.

B. Performance of MRS and Comparison with SRS

In this subsection, we show performance of our developed MRS in Algorithm 1 and its comparison with SRS. The results shown in Figs. 6-8 are simulation results only.

Due to the nature of the MRS, it will not perform worse (in the sense of every metric considered in the work) than the SRS. Fig. 6 shows the BLERs of the MRS scheme and comparison with that of the SRS for $R = 2$, 3, and 4. Again, all nodes are assumed to have the same power. Note that although both schemes have the same diversity order R, MRS has a larger array gain. The array gain improvement increases as the number of relays increases. At the 10^{-5} BLER level, MRS outperforms the SRS by approximately 3 dB, 4.5 dB, and 6 dB for $R = 2$, 3, and 4, respectively. For comparison, we also show the performance of the optimal relay selection, i.e., choosing (among all possible relay subsets) the subset of the relays that results in the maximum worse receive SNR. This optimal relay selection requires exhaustive search. Note that the gap between the MRS and the optimal relay selection is negligible. Importantly, the complexity of optimal relay selection is exponential in R while the complexity of the MRS is $R \log R$.

As discussed in Section IV, allowing multiple relays to cooperate improves the performance, but the total transmit power of the network also increases. A more sensible measure is thus the power efficiency. In Fig. 7, the power efficiencies of SRS and MRS are compared. It shows that the MRS scheme is much more power efficient. The power efficiency improvement also increases as the number of relays increases.

Another prominent advantage of MRS over SRS we have observed through simulation is in the sum-rate. In Fig. 8, the sum-rates of the SRS and MRS schemes are plotted for different values of R at different power levels, with all relay having the same power Q. Sum-rates of both schemes increase linearly in $\log R$. But the MRS scheme results in a much larger slope, which shows a faster increase in sum-rate as the network size increases. At R =10, the sum-rate improvements of the MRS over SRS are about 77%, 70%, and 100%, respectively for the three power settings ($P = 11.75$ dB, $Q = 13$ dB), ($P = 10$ dB, $Q = 13$ dB), and ($P = 10$ dB, $Q = 10$ dB).

VI. Conclusion

A two-way relay network with multiple AF relays is considered. An SRS scheme which chooses the relay that results in the highest worse receive SNR of the two users is studied. The exact CDF of the worse end-to-end SNR and its approximations are derived, based on which the SRS is analyzed extensively in terms of the BLER, diversity order, outage probability, and sum-rate. Simulation results are shown, which justify the validity of the analytical results. The approximate CDFs are obtained via finding appropriate approximations on the modified Bessel function of the second kind, $\mathcal{K}_1(x)$, for different performance measures. They can be used in similar analysis, where $\mathcal{K}_1(x)$ appears. Examples include one-way relay networks, two-way relay networks with different relay selection schemes, and multiply-user multiple-relay networks under relay selection schemes. An MRS algorithm is also introduced in this paper by ordering the relays in descending order of the worse end-to-end SNR. Both the SRS and the MRS schemes achieve full diversity, while the latter achieves a larger array gain. Our analysis and simulation results show that the MRS scheme has the following advantages. 1) For both SRS and MRS, the sum-rate grows as $O(\log R)$, where R is the number of relays. But MRS has much higher growth rate; 2) While the search complexity of MRS is $O(R\log R)$, its performance is virtually indistinguishable from that of optimal relay selection, which has search complexity $O(2^R)$; 3) MRS is much more power efficient than the SRS scheme, and the power efficiency improvement grows with the number of relays.

Appendix

A. Proof of Theorem 1

Let $\alpha \triangleq |f_j|^2$ and $\zeta \triangleq |g_j|^2$, which have exponential distributions. For any $x > 0$, we define $b_j \triangleq (1+\xi_j)\frac{x}{P}$ and $a_j \triangleq \frac{(\xi_j+\frac{1}{2})x+\sqrt{(\xi_j+\frac{1}{2})^2x^2+\xi_j x}}{P}$. We have $0 \le b_j \le a_j$. Let $f_\alpha(t) = e^{-t}$ denote the PDF of α. The probability of $\gamma_j \ge x$ can be calculated as

$$\begin{aligned}\mathbb{P}(\gamma_j \ge x) &= \textstyle\int_0^\infty \mathbb{P}(\gamma_j \ge x|\alpha = t) f_\alpha(t)dt\\ &= \textstyle\int_0^{b_j} \mathbb{P}(\gamma_j \ge x|\alpha = t)e^{-t}dt\\ &\quad + \textstyle\int_{b_j}^\infty \mathbb{P}(\gamma_j \ge x|\alpha = t)e^{-t}dt.\end{aligned} \tag{21}$$

The integral in the second line of (21) considers the probability of $\gamma_j \ge x$ when $\alpha \in [0, b_j)$. Since $\alpha < b_j$, we have

$$\begin{aligned}P\alpha - (1+\xi_j)x &< Pb_j - (1+\xi_j)x\\ &= P(1+\xi_j)\tfrac{x}{P} - (1+\xi_j)x\\ &= 0 < \tfrac{x(1+P\alpha)}{\zeta Q_j},\end{aligned}$$

based on which we have $x > \frac{PQ_j\alpha\zeta}{1+(P+Q_j)\alpha+P\zeta}$. From (3), we have $\gamma_{u_1,\{j\}} = \frac{PQ_j\alpha\zeta}{1+(P+Q_j)\alpha+P\zeta}$. Therefore, $\gamma_j = \min\{\gamma_{u_1,\{j\}}, \gamma_{u_2,\{j\}}\} \le \gamma_{u_1,\{j\}} < x$, which means that the integral in the second line in (21) is zero.

Next we look at the integral in the third line in (21), which considers the probability of $\gamma_j \ge x$ when $\alpha \ge b_j$. From the definition of $\gamma_{u_1,\{j\}}$ in (3), when $\alpha \ge b_j$, the following equivalence can be proved:

$$\begin{aligned}\gamma_{u_1,\{j\}} \ge x \quad &\Longleftrightarrow \quad PQ_j\alpha\zeta \ge (1+(P+Q_j)\alpha + P\zeta)x\\ &\Longleftrightarrow \quad \zeta \ge \tfrac{(1+\xi_j)\alpha+\frac{\xi_j}{P}}{P\alpha-\xi_j x}x \triangleq c_{1,j}.\end{aligned}$$

Similarly, we can prove that

$$\gamma_{u2,\{j\}} \ge x \Longleftrightarrow \zeta \ge \frac{\xi_j\alpha + \frac{\xi_j}{P}}{P\alpha - (\xi_j+1)x}x \triangleq c_{2,j}.$$

Therefore, the event $\gamma_j = \min\{\gamma_{u_1,\{j\}}, \gamma_{u_2,\{j\}}\} \ge x$ is equivalent to event $\zeta \ge \max\{c_{1,j}, c_{2,j}\}$.

We can further show that event $c_{1,j} \gtreqless c_{2,j}$ is equivalent to event $PQ_j\alpha^2 - (Q_j+2P)\alpha x - x \gtreqless 0$. The only positive root of $PQ_j\alpha^2 - (Q_j+2P)\alpha x - x = 0$ is $\alpha = a_j$. Thus, we can conclude that event $PQ_j\alpha^2 - (Q_j+2P)\alpha x - x \gtreqless 0$ is equivalent to event $\alpha \gtreqless a_j$.

In summary, when $\alpha \le a_j$, event $\gamma_j \ge x$ is equivalent to event $\zeta \ge c_{2,j}$; when $\alpha > a_j$, event $\gamma_j \ge x$ is equivalent to event $\zeta \ge c_{1,j}$. Since the integral in the second line in (21) is zero, we have

$$\begin{aligned}\mathbb{P}(\gamma_j \ge x) &= \textstyle\int_{b_j}^\infty \mathbb{P}(\gamma_j \ge x)e^{-\alpha}d\alpha\\ &= \textstyle\int_{b_j}^{a_j} \mathbb{P}(\zeta \ge c_{2,j})e^{-\alpha}d\alpha\\ &\quad + \textstyle\int_{a_j}^\infty \mathbb{P}(\zeta \ge c_{1,j})e^{-\alpha}d\alpha\\ &= \textstyle\int_{b_j}^{a_j} e^{-c_{2,j}}e^{-\alpha}d\alpha + \int_{a_j}^\infty e^{-c_{1,j}}e^{-\alpha}d\alpha\\ &= e^{-(1+2\xi_j)\frac{x}{P}} \textstyle\int_0^{a_j-b_j} e^{-\left(y+\frac{\kappa_j(x)^2}{4P^2}\frac{1}{y}\right)}dy\\ &\quad + e^{-(1+2\xi_j)\frac{x}{P}} \textstyle\int_{a_j-\frac{\xi_j x}{P}}^\infty e^{-\left(y+\frac{\kappa_j(x)^2}{4P^2}\frac{1}{y}\right)}dy,\end{aligned} \tag{22}$$

where $\kappa_j(x) = 2\sqrt{\xi_j x\,(1+(1+\xi_j)x)}$. The third equality of (22) is because ζ is exponentially distributed, and the fourth equality of (22) is because of the definitions of $c_{1,j}$ and $c_{2,j}$, and the transformation $y = \alpha - \frac{(\xi_j+1)x}{P}$. With some straightforward algebraic manipulations and with the aid of [30, eq. 3.324.1], (22) can be simplified to get

$$\begin{aligned}\mathbb{P}(\gamma_j \ge x) =& \frac{\kappa_j(x)}{P}e^{-(1+2\xi_j)\frac{x}{P}}\mathcal{K}_1\left(\frac{\kappa_j(x)}{P}\right)\\ &- e^{-(1+2\xi_j)\frac{x}{P}}\int_{a_j-(1+\xi_i)\frac{x}{P}}^{a_j-\frac{\xi_j x}{P}} e^{-\left(y+\frac{\kappa_j(x)^2}{4P^2}\frac{1}{y}\right)}dy.\end{aligned}$$

The CDF of γ_j is $F_{\gamma_j}(x) = \mathbb{P}(\gamma_j \le x) = 1 - \mathbb{P}(\gamma_j \ge x)$, from which (10) is obtained.

B. Proof of Theorem 2

Consider the following infinite series expansions:

$$\mathcal{K}_1(x) = \frac{1}{x} + \ln\frac{x}{2}\mathcal{I}_1(x) - \frac{x}{4}\sum_{k=0}^\infty \frac{[\psi(k+1)+\psi(k+2)]x^{2k}}{k!(k+1)!4^k},$$

$$\mathcal{I}_1(x) = \frac{x}{2}\sum_{k=0}^\infty \frac{x^{2k}}{k!(k+1)!4^k}, \ln(x) = \sum_{k=1}^\infty \frac{(-1)^{k-1}(x-1)^k}{k},$$

$$G_{\gamma_j}(x) = \frac{(1+2\xi_j)x}{P} - \sum_{k=2}^{\infty} \frac{(-1)^k (1+2\xi_j)^k x^k}{k! P^k} - \frac{2}{P^2} \sum_{m=1}^{\infty} \sum_{n=0}^{\infty} \sum_{w=0}^{\infty} \sum_{q=0}^{m} \frac{(-1)^{m+q+w-1} \binom{m}{q} (1+2\xi_j)^w x^w \phi_j(x)^{n+1+\frac{m-q}{2}}}{n! w! (1+n)! m P^{2n+m+w-q}}$$
$$+ \frac{1}{P^2} \sum_{l=0}^{\infty} \sum_{v=0}^{\infty} \sum_{s=0}^{l+1} \frac{\binom{1+l}{s} [\psi(1+k) + \psi(2+k)] \xi_j^{l+1} (1+2\xi_j)^v (1+\xi_j)^s x^{l+v+s+1}}{l!(1+l)! v! P^{2l+v}}. \tag{23}$$

for $0 < x < 1$, where $\mathcal{I}_1(\cdot)$ is the modified first-order Bessel function of the first-kind and $\psi(\cdot)$ is the digamma function [30]. Let $G_{\gamma_j}(x) \triangleq 1 - \frac{\kappa_j(x)}{P} e^{-(1+2\xi_j)\frac{x}{P}} \mathcal{K}_1\left(\frac{\kappa_j(x)}{P}\right)$. It can be expanded using the exponential and the above series expansions as (23) on the top of this page, where $\phi_j(x) \triangleq \xi_j x(1+(1+\xi_j)x)$. Note that $G_{\gamma_j}(x)$ is a power series of $1/P$. Its highest order term is the first term in (23).

Define $H_{\gamma_j}(x) \triangleq e^{-(1+2\xi_j)\frac{x}{P}} \int_{a_j-(1+\xi_j)\frac{x}{P}}^{a_j-\xi_j\frac{x}{P}} e^{-\left(y+\frac{\kappa_j(x)^2}{4P^2 y}\right)} dy$. Using the exponential and the binomial expansions, $H_{\gamma_j}(x)$ can be written as

$$H_{\gamma_j}(x) = e^{-(1+2\xi_j)\frac{x}{P}} \int_{a_j-(1+\xi_j)\frac{x}{P}}^{a_j-\xi_j\frac{x}{P}} \left[1 - \left(y + \frac{\kappa_j(x)^2}{4P^2 y}\right) + \sum_{r=2}^{\infty} \frac{(-1)^r}{r!} \left(y + \frac{\kappa_j(x)^2}{4P^2 y}\right)^r\right] dy.$$

After some mathematical manipulations, $H_{\gamma_j}(x)$ can be evaluated as

$$H_{\gamma_j}(x) = e^{-(1+2\xi_j)\frac{x}{P}} \left[\frac{x}{P} - \frac{x h_j(x)}{2P^2} + \frac{\kappa_j(x)^2}{4P^2} \ln\left(\frac{h_j(x)-x}{h_j(x)+x}\right) + \mathcal{L}_1\right], \tag{24}$$

where $h_j(x) \triangleq \sqrt{(2\xi_j+1)^2 x^2 + 4\xi_j x}$ and $\mathcal{L}_1 \triangleq \int_{a_j-(1+\xi_j)\frac{x}{P}}^{a_j-\xi_j\frac{x}{P}} \sum_{r=2}^{\infty} \frac{(-1)^r}{r!} \left(y + \frac{\kappa_j(x)^2}{4P^2 y}\right)^r dy$. With the binomial expansion, $\mathcal{L}_1$ can be given as

$$\begin{aligned}
\mathcal{L}_1 &= \sum_{r=2}^{\infty} \sum_{t=0}^{r} \frac{(-1)^r \binom{r}{t}}{r!} \left(\frac{\kappa_j(x)^2}{4P^2}\right)^t \int_{a_j-(1+\xi_j)\frac{x}{P}}^{a_j-\xi_j\frac{x}{P}} y^{r-2t} dy \\
&= \ln\left(\frac{h_j(x)-x}{h_j(x)+x}\right) \sum_{r=2}^{\infty} \frac{\phi_j(x)^r}{r!(r-1)! P^{2r}} \\
&\quad + \sum_{r=2}^{\infty} \sum_{\substack{t=0 \\ t \neq \frac{1+r}{2}}}^{r} \frac{(-1)^r \phi_j(x)^t}{2^{1+r-2t} t!(r-t)!(1+r-2t) P^{r+1}} \\
&\quad \times \left[(h_j(x)+x)^{1+r-2t} - (h_j(x)-x)^{1+r-2t}\right].
\end{aligned} \tag{25}$$

Using (24), (25) and expanding $e^{-(1+2\xi_j)\frac{x}{P}}$ as infinite series, $H_{\gamma_j}(x)$ is given as (26) on the top of the next page. Note that $F_{\gamma_j}(x) = G_{\gamma_j}(x) + H_{\gamma_j}(x)$. Thus, $F_{\gamma_j}(x)$ is a function of $1/P$ in which the minimum order of $1/P$ is one. Since the CDF of $\gamma_{\tilde{j}}$ is $F_{\gamma_{\tilde{j}}}(x) = \prod_{j=1}^{R} F_{\gamma_j}(x)$, $x \geq 0$, by using multinomial series expansion, $F_{\gamma_{\tilde{j}}}(x)$ can be given as

$$F_{\gamma_{\tilde{j}}}(x) = \frac{2^R \prod_{j=1}^{R} (1+\xi_j) x^R}{P^R} + \mathcal{O}\left(x, \frac{1}{P^{R+1}}\right). \tag{27}$$

The outage probability, $P_{out} = \mathbb{P}(0 \leq \gamma \leq \gamma_{th})$, of the SRS scheme is $P_{out} = F_{\gamma_{\tilde{j}}}(\gamma_{th})$, which proves Theorem 2.

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$$
\begin{aligned}
H_{\gamma_j}(x) =& \frac{x}{P} + \sum_{\nu=1}^{\infty} \frac{(-1)^{\nu}(1+2\xi_j)^{\nu} x^{\nu}}{\nu! P^{\nu}} - \sum_{\nu=0}^{\infty} \frac{(-1)^{\nu}(1+2\xi_j)^{\nu} h_j(x) x^{\nu+1}}{2\nu! P^{2+\nu}} \\
&+ \ln\left(\frac{h_j(x)-x}{h_j(x)+x}\right) \sum_{\nu=0}^{\infty} \frac{(-1)^{\nu}(1+2\xi_j)^{\nu} x^{\nu}}{\nu! P^{\nu}} \left[\frac{\phi_j(x)}{P^2} + \sum_{r=2}^{\infty} \frac{\phi_j(x)^r}{r!(r-1)! P^{2r}}\right] \\
&+ \sum_{\nu=0}^{\infty} \sum_{r=2}^{\infty} \sum_{\substack{t=0 \\ t\neq \frac{1+r}{2}}}^{r} \frac{(-1)^{r+\nu}(1+2\xi_j)^{\nu} x^{\nu} \phi_j(x)^t \left[(h_j(x)+x)^{1+r-2t} - (h_j(x)-x)^{1+r-2t}\right]}{2^{1+r-2t} \nu! t! (r-t)! (1+r-2t) P^{\nu+r+1}}.
\end{aligned} \tag{26}
$$

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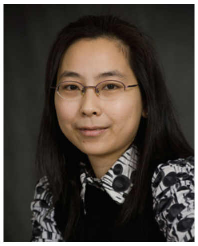

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