Cooperative Communications Using Reliability-Forwarding Relays

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***Abstract*—This study presents a new relay strategy and associated diversity combining technique for improving the communication performance in semi-blind cooperative networks. In constructing the network model, it is assumed that each relay can obtain the perfect channel state information (CSI) from the source to itself, and the destination can acquire the perfect CSI from all the relays to itself, but does not require the CSI from the source to the participating relays. In performing the considered semi-blind cooperative communications, the relays forward their reliability to the destination using a quantized reliability-relaying (QRR) scheme. Specifically, the relays partition their reliability into three levels in accordance with the log-likelihood ratio (LLR) value of the received signal, and forward a regenerative symbol to the destination if the quantized reliability falls within the "send +1" or "send -1" region; and remain silent otherwise. It is shown theoretically that the QRR scheme achieves a higher deflection coefficient than the regular decode-and-forward (DF) scheme, in which all the participating relays forward their regenerative messages to the destination irrespective of their reliability. Moreover, the simulation results show that given the same semi-blind model, the QRR scheme achieves a lower bit error rate (BER) than existing relay selection DF schemes for all considered values of the average input signal-to-noise ratio (SNR).**

***Index Terms*—cooperative communications, decode-and-forward, relay, reliability, detection**

I. Introduction

COOPERATIVE communications, in which multiple single-antenna relay terminals assist the source in transmitting information to the destination, provide an effective means of increasing the spatial diversity of communication networks [1]–[5]. Such a communication strategy is particularly beneficial in networks comprising low-power-consumption and portable mobile terminals, in which mounting multiple antennas is a difficult, if not impossible, task. In implementing a cooperative communication network, relay strategies and received signal combining schemes play a key role in achieving spatial diversity. The present study focuses on developing a new relay strategy and associated diversity combining technique for improving the communication performance of semi-blind cooperative networks, in which the channel state information (CSI) between the source and the participating relays is unknown to the destination.

Many relay-based strategies have been proposed for realizing cooperative diversity in wireless communication networks [6]–[9]. Among these strategies, the decode-and-forward (DF) [10] scheme is one of the most widely used due to its simplicity and intuitive design. In the DF scheme, each relay decodes the received information and generates a new message, which it then forwards to the destination. However, in many applications, the relays cannot perform channel decoding due to a lack of knowledge of the channel codebook or a limited transceiver capability. In such a scenario, the DF scheme is implemented simply by detecting or demodulating the received signals on a symbol-by-symbol basis. Note that in referring to the DF scheme hereafter in this paper, it is this uncoded DF scenario which is considered.

The literature contains many proposals for diversity combining techniques [11], [12] in DF cooperative networks. However, in implementing such schemes, each relay must know the source-to-relay channel CSI, while the destination must know not only the CSI of each relay-to-destination channel, but also the CSI of each source-to-relay channel (see Eqs. (7)–(9) in the C-MRC combining rule in [11] and Eqs. (6) and (7) in the LAR-α scheme in [12]). To satisfy this requirement, various assumptions must be made. For example, to obtain the perfect CSI of the network, the following assumptions are required:

Assumption 1. *Each relay is able to acquire the perfect CSI of the source to itself.*

Assumption 2. *The destination is able to acquire the perfect CSI of all the participating relays to itself.*

In addition, to render the CSI acquired by each relay available to the destination for diversity combining purposes, the following assumption is required:

Assumption 3. *Additional communication and resource costs are incurred by the relays in transmitting their CSI to the destination.*[1]

Several recent studies have considered the problem of cooperative communications in networks with blind relays [13]–[15]. In such networks, the relays have no knowledge of the CSI; neither between the source and each relay nor between

[1]Alternatively, a knowledge of the source-to-relay channel CSI can be obtained at the destination by using a more complicated channel estimation technique based on training signals sent from the source to the destination via a relay message forwarding scheme.

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each relay and the destination. Therefore, when blind relay is considered in the cooperative communications, it means that Assumption 1 is not required. However, in [13]–[15], the destination knows the CSI of all the source-to-relay channels and all the relay-to-destination channels. Consequently, both Assumption 2 and Assumption 3 are required.

The present study considers an alternative network model (i.e., a semi-blind model) in which each relay can obtain the perfect CSI from the source to itself, and the destination can acquire the perfect CSI from all the relays to itself. In other words, Assumptions 1 and 2 are both required. However, the destination does not require the CSI from the source to all of the participating relays. Hence, Assumption 3 is not required. It is noted that this semi-blind model is more realistic than models in which the CSI is assumed to be available at all the relays and the destination [11], [12] (see also [8, Reactive DaF]) or those based on blind relays [13]–[15]. Specifically, cooperative communication schemes based on a knowledge of the CSI at all the relays and the destination not only incur an additional communication cost, but also require a significant modification of the hardware and software (built for traditional point-to-point communications) at almost every layer of the network [16]. Furthermore, cooperative communication schemes based on blind relays do not use any of the channel estimation hardware or software incorporated within traditional non-cooperative communication transceivers, and are therefore based on an overly simplified model. In the semi-blind model considered in the present study, Assumptions 1 and 2 can be achieved using the channel estimation functionality developed for traditional point-to-point communications without the need for any modification. Furthermore, the considered model removes the need for Assumption 3, which is an overly restrictive condition.

The best-relay and Nth-best-relay selection DF schemes presented in [17], [18] are based on the same CSI knowledge assumptions as those considered in the present study (i.e., Assumptions 1 and 2 are required, while Assumption 3 is not) provided that the selection protocol is implemented in a distributed manner at the relay nodes.[2] If such an approach is not possible, the relay selection process must be performed by a centralized controller at the destination. When the centralized selection controller is implemented, the best relay or the Nth best relay can be selected only if the relay node belongs to the decoding set, i.e., the set of relays with the ability to correctly decode the source symbols. For a relay to achieve successful decoding, the channel between the source and the relay node must be sufficiently good. In practice, successful decoding at the ith relay requires the mutual information between the source and the ith relay (I_i) to be greater than a pre-determined spectral efficiency η_R, i.e.,

$$I_i = C \log_2(1 + \gamma_{sr,i}) > \eta_R, \tag{1}$$

where C depends on the number of orthogonal channels used for data transmission, and $\gamma_{sr,i}$ is the instantaneous signal-to-noise ratio (SNR) between the source and the ith relay, which depends on the instantaneous CSI of the channel between the source and the relay. Thus, for the destination to know the correct decoding set, it must first know the source-to-relay CSI for all the participating relays. (Note that binary quantized CSI is sufficient.)

The amplify-and-forward (AF) best-relay selection scheme proposed in [20] also considers a semi-blind model. Specifically, the amplitude CSI of the source-to-relay is unknown to the destination, and the relay with the best source-to-relay SNR transmits its amplified signal to the destination. However, in [20], coherent reception is assumed to be accomplished at both the relays and the destination (i.e., the phase CSI is assumed to be perfectly known by both the relays and the destination) (see [20, Eqs. (1) and (2)]). Thus, the destination must have a perfect knowledge of the phase CSI of all the source-to-relay channels (since otherwise, symbol detection will fail at the destination).[3] In other words, the semi-blind model considered in [20] differs from that considered in the present study, in which neither the amplitude CSI nor the phase CSI of the source-to-relay channels is required by the destination.

In implementing the semi-blind model proposed in this study, it is assumed that each participating relay forwards its reliability to the destination utilizing a quantized reliability-relaying (QRR) scheme. Specifically, after receiving the source symbol, each relay partitions its reliability into three levels based on the log-likelihood ratio (LLR) of the received signal, and forwards the regenerative symbol to the destination over orthogonal channels if its quantized reliability falls within the "send +1" or "send -1" region, but keeps silent otherwise.

The performance of the proposed QRR scheme is examined both theoretically and numerically in the context of a simple network based on the binary phase shift keying (BPSK) modulation technique and orthogonal channels between the relays and the destination. Note that a simplistic model is deliberately adopted here in order to facilitate a theoretical analysis of the proposed scheme. It is shown that the QRR scheme achieves a higher deflection coefficient than the regular DF scheme, in which the participating relays forward their regenerative messages to the destination irrespective of their reliability. Simulations are performed to compare the bit error rate (BER) performance of the proposed QRR scheme with that of the regular DF scheme, the best-relay selection scheme [17], and the Nth-best-relay selection scheme [18] given the same semi-blind model. The results show that the QRR scheme outperforms all three DF schemes for all considered values of the average input SNR. However, the spectral efficiency of the QRR scheme is poorer than that of the two relay selection schemes; particularly under high SNR conditions.

The remainder of this paper is organized as follows. Section II presents the system model of the considered semi-blind

[2]The distributed selection scheme could be implemented using the opportunistic carrier sensing scheme presented in [19] (see also [8]). In this scheme, each relay sets a timer at the beginning of a transmission period with a length inversely proportional to the local selection criterion (i.e., the instantaneous SNR of the relay-to-destination channel in the schemes proposed in [17], [18]). Each relay broadcasts a signal to all the other relays as soon as its timer reduces to zero. The first relay to broadcast a signal is then permitted to send its regenerative symbol to the destination.

[3]The DF relay-selection schemes presented in [17] and [18] also consider a coherent-reception signal model. However, since they are DF schemes, the relays regenerate the received symbol before forwarding it to the destination. In other words, the destination does not require the phase CSI of the source-to-relay links in order to achieve coherent signal reception.

cooperative communication network. Section III introduces the proposed reliability-relaying concept and derives the optimal design for the QRR scheme. In addition, the performance of the QRR scheme is theoretically analyzed. Section IV presents and discusses the simulation results obtained for the BER performance and spectral efficiency of the QRR, regular DF, and best-relay selection DF schemes. Finally, Section V provides some brief concluding remarks and indicates the intended direction of future research.

II. Preliminary

A. System Model

Figure 1 illustrates a typical cooperative communication network comprising M randomly placed relay nodes $\mathbb{R}_i$, $i = 1, \ldots, M$, a source node $\mathbb{S}$, and a destination node $\mathbb{D}$. Each node has only a single antenna, and thus simultaneous transmission and reception cannot be performed. In addition, it is assumed that the communication channel between each node pair is flat fading. Let the channel from the source $\mathbb{S}$ to relay $\mathbb{R}_i$ be denoted as h_i, and let the channel from relay $\mathbb{R}_i$ to the destination $\mathbb{D}$ be denoted as g_i. Furthermore, let the two sets of channels be denoted as $\boldsymbol{h} = \{h_1, \ldots, h_M\}$ and $\boldsymbol{g} = \{g_1, \ldots, g_M\}$, respectively. Assume that all the communication channels are drawn from a Rayleigh distribution, i.e., $h_i \sim \mathcal{CN}(0, \sigma_h^2)$ and $g_i \sim \mathcal{CN}(0, \sigma_g^2)$. As described in Section I, in implementing the semi-blind model, Assumptions 1 and 2 are retained, but Assumption 3 is discarded. In other words, the CSI from $\mathbb{S}$ to $\mathbb{R}_i$ is unknown to the destination.

Assume that $\mathbb{S}$ wishes to transmit symbol s to $\mathbb{D}$ using the considered semi-blind model. The present study assumes the use of a BPSK modulation technique, and hence $s \in \{+\sqrt{P_s}, -\sqrt{P_s}\}$, where P_s is the power of the symbol transmitted by the source. As described in the following, the transmission is accomplished by means of a two-phase process. In Phase I, the source $\mathbb{S}$ broadcasts s to all the relays in the network. Under the flat fading assumption, the received complex signal at $\mathbb{R}_i$ is expressed as

$$y_i = h_i s + n_i, \tag{2}$$

where n_i is a zero mean circular symmetric complex Gaussian (ZMCSCG) variable with variance σ_n^2, i.e., $n_i \sim \mathcal{CN}(0, \sigma_n^2)$. In addition, $n_i, i = 1, \ldots, M$ are assumed to be independent. In Phase II, having received y_i, relay $\mathbb{R}_i$ generates an output x_i in accordance with a pre-defined relaying approach. In the regular uncoded DF scheme, the relays make hard decisions based on the signal received from $\mathbb{S}$, and then transmit these decisions to the destination. The output of relay $\mathbb{R}_i$ has the form

$$x_i = \begin{cases} +\sqrt{P_r}, & \text{if } \gamma_{\mathrm{DF}}(y_i) > \eta_{\mathrm{DF}}; \\ -\sqrt{P_r}, & \text{otherwise,} \end{cases}$$

where P_r is the power of the symbol transmitted by the relays, and γ_{DF} is a function of y_i and is designed in accordance with certain performance criteria.

B. Proposed QRR Scheme

In the QRR scheme proposed in this study, the relays transmit (or mute) their signals in accordance with their reliability, as determined by, the LLR of the relay observations, y_i. Under the considered assumptions, the density function of y_i given h_i and s can be expressed as

$$p(y_i|h_i, s) = \frac{1}{\pi\sigma_n^2} \exp\left(-\frac{(y_i - h_i s)^*(y_i - h_i s)}{\sigma_n^2}\right).$$

Thus, the LLR of y_i is given by

$$\begin{aligned} \mathcal{L}(y_i) &= \log \frac{p(y_i|h_i, s = +\sqrt{P_s})}{p(y_i|h_i, s = -\sqrt{P_s})} \\ &= \frac{4\sqrt{P_s}\Re(h_i^* y_i)}{\sigma_n^2}, \end{aligned}$$

where $\Re(c)$ denotes the real part of complex variable c. Since $\frac{4\sqrt{P_s}}{\sigma_n^2}$ of $\mathcal{L}(y_i)$ is a constant for all i, the reliability of y_i can be defined as

$$\mathrm{Rel}(y_i) = \Re(h_i^* y_i), \tag{3}$$

thereby $-\infty < \mathrm{Rel}(y_i) < \infty$.

In the QRR scheme, the real-valued reliability given in (3) is partitioned into three regions by means of the following detector:

$$x_i = \delta_{\mathrm{Q},i} \hat{s}_i(y_i), \tag{4}$$

where

$$\hat{s}_i(y_i) = \begin{cases} 1, & \text{if } \Re(h_i^* y_i) > \eta_u; \\ 0, & \text{if } \eta_l < \Re(h_i^* y_i) < \eta_u; \\ -1, & \text{if } \Re(h_i^* y_i) < \eta_l, \end{cases} \tag{5}$$

in which η_u and η_l are upper and lower threshold values, respectively. In (4), $x_i = 0$ indicates that $\mathbb{R}_i$ mutes its decision (i.e., it transmits nothing to the destination), and the coefficient $\delta_{\mathrm{Q},i}$ is chosen such that the relay power is normalized to P_r. It can be shown that

$$\delta_{\mathrm{Q},i} = \sqrt{\frac{P_r}{1-q}},$$

where

$$\begin{aligned} q &:= \Pr(x_i = 0) \\ &= \frac{1}{2}\left\{\Pr(x_i = 0|s = +\sqrt{P_s}) + \Pr(x_i = 0|s = -\sqrt{P_s})\right\}. \end{aligned} \tag{6}$$

In addition, let $p(q)$ be denoted as

$$p(q) := \Pr(x_i = 1|s = +\sqrt{P_s}). \tag{7}$$

In other words, probability p is a function of probability q because p is a function of η_u and η_l. (Note that in the remainder of this paper, $p(q)$ is written simply as p when the emphasis on the function of q is unimportant.) In developing the QRR scheme, it is assumed that $\eta_u = -\eta_l = \eta$. (Note that this assumption is consistent with the common detector used in the channel model given in (2) [21].) As a result, it follows that $q = \Pr(x_i = 0|s = +\sqrt{P_s}) = \Pr(x_i = 0|s = -\sqrt{P_s})$ and $p = \Pr(x_i = 1|s = +\sqrt{P_s}) = \Pr(x_i = -1|s = -\sqrt{P_s})$.

In Phase II of the transmission process, it is assumed that the relays transmit their output signals $x_i, i = 1, \ldots, M$ to the destination over orthogonal channels using either a time division multiplexing (TDM) scheme or a frequency

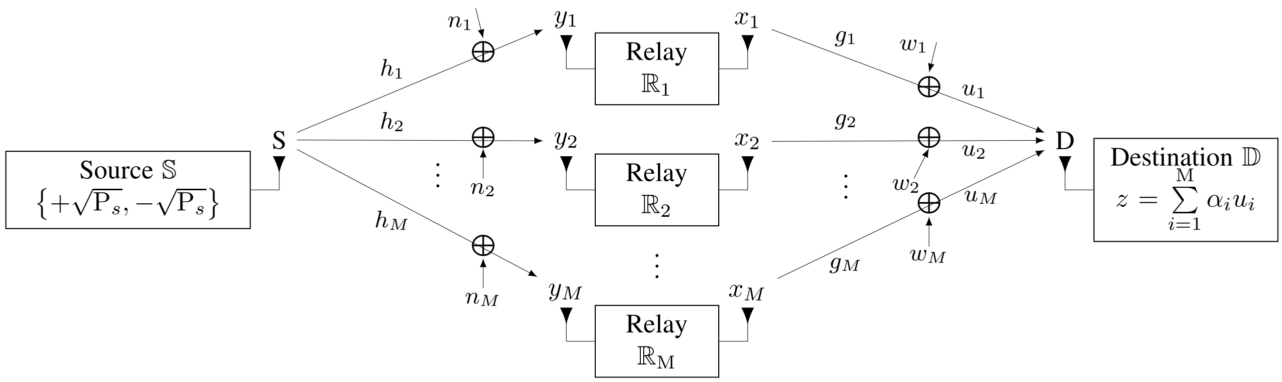

Fig. 1. Typical wireless relay network without direct path.

division multiplexing (FDM) scheme. The received signal corresponding to signal x_i from $\mathbb{R}_i$ therefore has the form

$$u_i = g_i x_i + w_i, \tag{8}$$

where w_i is a ZMCSCG variable with variance σ_w^2, i.e., $w_i \sim \mathcal{CN}(0, \sigma_w^2)$. For the sake of convenience, it is assumed that the destination utilizes a linear combiner detection rule, i.e.,

$$z = \sum_{i=1}^{M} \alpha_i u_i, \tag{9}$$

where α_i is optimally determined for the QRR scheme. The statistic z is then used to infer the symbol sent from the source.

In the QRR scheme, the active relays ($x_i = 1$ or -1) and the inactive relays ($x_i = 0$) are determined in a fully distributed manner (see (5)). Moreover, the data transmissions from the active relays can also be implemented in a completely distributed manner by using a scheme similar to the opportunistic carrier sensing scheme described in Footnote 2. Specifically, once a relay determines itself to be an active node, it turns on its timer; else it leaves its timer in the off condition. If the timers of all the relays are properly set, the destination will simply stop receiving signals from the relays at a particular moment during the transmission period. In other words, the destination does not need to know which relays are active (or inactive), and thus no feedback channel is required.

III. Design and Analysis of QRR Scheme

This section commences by describing the design of the linear-combining coefficients for the QRR scheme given a no-send probability q. The performance of QRR is then compared theoretically with that of the regular DF scheme. Finally, the optimal value of q is derived.

A. Linear-combining rule used in QRR scheme

In developing the QRR scheme, this study adopts the deflection coefficient [22]; a widely used performance metric in detection theory. For a given relay-to-destination CSI $\boldsymbol{g}$, the conditional deflection coefficient is given by

$$\mathcal{D}_{\text{def}}^2 := \frac{(\mathbf{E}_{\boldsymbol{x},\boldsymbol{w}}[z|s=+\sqrt{P_s},\boldsymbol{g}] - \mathbf{E}_{\boldsymbol{x},\boldsymbol{w}}[z|s=-\sqrt{P_s},\boldsymbol{g}])^2}{\mathbf{Var}_{\boldsymbol{x},\boldsymbol{w}}[z|s=-\sqrt{P_s},\boldsymbol{g}]}. \tag{10}$$

Given the assumptions adopted in the present study, $\mathcal{D}_{\text{def}}^2$ has the form of a closed-form expression, and thus the problem of designing the linear-combining coefficients used at the destination is significantly reduced. It can be shown that

$$\begin{aligned}
&\mathbf{E}_{\boldsymbol{x},\boldsymbol{w}}[z|s=+\sqrt{P_s},\boldsymbol{g}] \\
&= \sum_{i=1}^{M} \alpha_i \mathbf{E}[u_i|s=+\sqrt{P_s},g_i] \\
&= \sum_{i=1}^{M} \alpha_i g_i \mathbf{E}[x_i|s=+\sqrt{P_s},g_i] + \alpha_i \mathbf{E}[w_i|s=+\sqrt{P_s},g_i] \\
&= \sum_{i=1}^{M} \alpha_i g_i (2p+q-1)\sqrt{\frac{P_r}{1-q}}.
\end{aligned} \tag{11}$$

Similarly, it follows that

$$\mathbf{E}_{\boldsymbol{x},\boldsymbol{w}}[z|s=-\sqrt{P_s},\boldsymbol{g}] = \sum_{i=1}^{M} \alpha_i g_i (1-2p-q)\sqrt{\frac{P_r}{1-q}}. \tag{12}$$

Moreover, it can be shown that

$$\begin{aligned}
&\mathbf{E}_{\boldsymbol{x},\boldsymbol{w}}\left[|z|^2|s=-\sqrt{P_s},\boldsymbol{g}\right] \\
&= \mathbf{E}_{\boldsymbol{x},\boldsymbol{w}}\left[\left|\sum_{i=1}^{M} \alpha_i g_i x_i + \alpha_i w_i\right|^2 |s=-\sqrt{P_s},\boldsymbol{g}\right] \\
&= \sum_{i=1}^{M} \left(|\alpha_i|^2|g_i|^2\mathbf{E}[x_i^2] + |\alpha_i|^2\mathbf{E}[w_i^2]\right) \\
&\qquad + \sum_{i=1}^{M}\sum_{j\neq i} \alpha_i\alpha_j g_i g_j \mathbf{E}[x_i|s=-\sqrt{P_s}]\mathbf{E}[x_j|s=-\sqrt{P_s}] \\
&\overset{(a)}{=} \sum_{i=1}^{M} |\alpha_i|^2(|g_i|^2 P_r + \sigma_w^2) \\
&\qquad + \sum_{i=1}^{M}\sum_{j\neq i} \alpha_i\alpha_j g_i g_j P_r \frac{(1-2p-q)^2}{1-q},
\end{aligned} \tag{13}$$

where (a) follows from the fact that

$$\mathbf{E}\left[x_i|s=-\sqrt{P_s}\right]=p\left(-\sqrt{\frac{P_r}{1-q}}\right)+(1-p-q)\sqrt{\frac{P_r}{1-q}}$$
$$=(1-2p-q)\sqrt{\frac{P_r}{1-q}}.$$

From (12) and (13), the variance of z given $\boldsymbol{g}$ and $s=-\sqrt{P_s}$ can be obtained as

$$\begin{aligned}&\mathbf{Var}_{\boldsymbol{x},\boldsymbol{w}}[z|s=-\sqrt{P_s},\boldsymbol{g}]\\&=\mathbf{E}_{\boldsymbol{x},\boldsymbol{w}}\left[|z|^2|s=-\sqrt{P_s},\boldsymbol{g}\right]-\left(\mathbf{E}_{\boldsymbol{x},\boldsymbol{w}}\left[z|s=-\sqrt{P_s},\boldsymbol{g}\right]\right)^2\\&=\sum_{i=1}^{M}|\alpha_i|^2\left(|g_i|^2P_r\left(\frac{4p(1-p-q)}{1-q}\right)+\sigma_w^2\right)\end{aligned}\tag{14}$$

It immediately follows from (10), (11), (13) and (14) that

$$\mathcal{D}_{\rm def}^2=\frac{\left(\sum_{i=1}^{M}2\alpha_i g_i(2p+q-1)\sqrt{\frac{P_r}{1-q}}\right)^2}{\sum_{i=1}^{M}|\alpha_i|^2\left(|g_i|^2P_r\left(\frac{4p(1-p-q)}{1-q}\right)+\sigma_w^2\right)}.\tag{15}$$

Denoting

$$\psi_i:=\alpha_i^*\sqrt{|g_i|^2P_r\left(\frac{4p(1-p-q)}{1-q}\right)+\sigma_w^2}$$

and

$$\phi_i:=\frac{2g_i(2p+q-1)\sqrt{\frac{P_r}{1-q}}}{\sqrt{|g_i|^2P_r\left(\frac{4p(1-p-q)}{1-q}\right)+\sigma_w^2}},$$

(15) can be rewritten as

$$\mathcal{D}_{\rm def}^2=\frac{\left|\sum_{i=1}^{M}\psi_i^*\phi_i\right|^2}{\sum_{i=1}^{M}|\psi_i|^2}.$$

Applying the Cauchy-Schwartz inequality [23] to the numerator of the equation above, it follows that

$$\left|\sum_{i=1}^{M}\psi_i^*\phi_i\right|^2\le\sum_{i=1}^{M}|\psi_i|^2\sum_{i=1}^{M}|\phi_i|^2.$$

Therefore, it is shown that

$$\mathcal{D}_{\rm def}^2\le\mathcal{D}_{\rm def,max}^2,\tag{16}$$

where

$$\begin{aligned}\mathcal{D}_{\rm def,max}^2&:=\sum_{i=1}^{M}|\phi_i|^2\\&=\sum_{i=1}^{M}\frac{4|g_i|^2P_r(2p+q-1)^2}{4|g_i|^2P_rp(1-p-q)+\sigma_w^2(1-q)}.\end{aligned}\tag{17}$$

The equality in (16) holds when $\psi_i=c\phi_i$, where c is a constant. Thus, the optimal combining coefficient $\alpha_{{\rm MDC},i}$ which yields the maximum value of $\mathcal{D}_{\rm def,max}^2$ is given by

$$\alpha_{{\rm MDC},i}=\frac{2cg_i^*(2p+q-1)\sqrt{\frac{P_r}{1-q}}}{|g_i|^2P_r\left(\frac{4p(1-p-q)}{1-q}\right)+\sigma_w^2},\qquad 1\le i\le M.\tag{18}$$

Remark 1. *The optimal combining coefficient $\alpha_{{\rm MDC},i}$ and corresponding $\mathcal{D}_{\rm def,max}^2$ given in* (18) *and* (17)*, respectively, also apply to the regular DF scheme since this scheme is simply a special case of the QRR scheme for which $q=0$.*

B. Performance analysis of QRR scheme

In this section, it is shown that the QRR scheme outperforms the regular DF-relaying scheme in terms of a higher deflection coefficient. The analysis commences by establishing the proposition below to show that under quite mild conditions, a local optimum $\mathcal{D}_{\rm def}^2$ is attained at a non-zero value of q. Define $p'(q):=\frac{\partial p(q)}{\partial q}$.

Proposition 1. *If $p(0)>\frac{1}{2}$ and*

$$p'(0)>\max_{1\le i\le M}-\frac{4|g_i|^2P_rp(0)+\sigma_w^2(1+2p(0))}{4|g_i|^2P_r+4\sigma_w^2},\tag{19}$$

then the optimal $q_{\rm opt}$ which yields the maximum value of $\mathcal{D}_{\rm def,max}^2$ is located at $0<q_{\rm opt}<1$.

Proof: Firstly, it can be shown that

$$\lim_{q\to0}\mathcal{D}_{\rm def,max}^2=\sum_{i=1}^{M}\frac{4|g_i|^2P_r(2p-1)^2}{4|g_i|^2P_rp(1-p)+\sigma_w^2}.\tag{20}$$

By applying L'Hospital's rule [24], the optimal $\mathcal{D}_{\rm def,max}^2$ when $q\to1$ is given by (21) (see top of next page). As q approaches 1, $p(q)$ approaches 0. Thus, (21) becomes

$$\lim_{q\to1}\mathcal{D}_{\rm def,max}^2=0.\tag{22}$$

From (20) and (22), it follows that $\lim_{q\to0}\mathcal{D}_{\rm def,max}^2\ge\lim_{q\to1}\mathcal{D}_{\rm def,max}^2$. In proving Proposition 1, it suffices to show that $\lim_{q\to0}\mathcal{D}_{\rm def,max}^2$ increases when q increases from zero since this guarantees the existence of a local maximum at a non-zero value of q. It is easily shown that $\frac{\partial\mathcal{D}_{\rm def,max}^2}{\partial q}$ when $q\to0$ is given by (23) (see top of next page). Therefore, as long as $p(0)>\frac{1}{2}$ and the condition given in (19) holds, then $\lim_{q\to0}\frac{\partial\mathcal{D}_{\rm def,max}^2}{\partial q}>0$. Finally, the assertion given in Proposition 1 then follows from the fact that $\mathcal{D}_{\rm def,max}^2$ is a continuous function of q. ■

Proposition 1 implies that if condition (19) holds, the QRR scheme achieves a higher deflection coefficient than the regular DF-relaying scheme since the optimal no-send probability $q_{\rm opt}$ is not located at $q=0$ (see Remark 1).

It can be shown that condition (19) given in Proposition 1 easily holds for most cooperative communication systems. However, the condition is quite general, and thus it is difficult to interpret its practical implications. However, the following two corollaries demonstrate that the QRR scheme outperforms the regular DF scheme for relay-to-destination communications over high-SNR and low-SNR channels, respectively, given much simpler conditions than those given in (19).

Corollary 1. *Assume that the relay-to-destination channel noise variance approaches zero, i.e., $\sigma_w^2\to0$. Given $p(0)>\frac{1}{2}$ and*

$$p'(0)>-p(0),\tag{24}$$

$$\lim_{q\to 1} \mathcal{D}^2_{\mathrm{def,max}} = \lim_{q\to 1} \sum_{i=1}^{M} \frac{\partial\{4|g_i|^2 P_r (2p+q-1)^2\}/\partial q}{\partial\{4|g_i|^2 P_r p(1-p-q) + \sigma_w^2(1-q)\}/\partial q}$$
$$= \lim_{q\to 1} \sum_{i=1}^{M} \frac{8|g_i|^2 P_r (2p(q)+q-1)(2p'(q)+1)}{4|g_i|^2 P_r p'(q)(1-p(q)-q) + 4|g_i|^2 P_r p(q)(-p'(q)-1) - \sigma_w^2}. \tag{21}$$

$$\lim_{q\to 0} \frac{\partial \mathcal{D}^2_{\mathrm{def,max}}}{\partial q} = \sum_{i=1}^{M} \frac{4|g_i|^2 P_r (2p(0)-1)\left[4|g_i|^2 P_r (p'(0)+p(0)) + \sigma_w^2(4p'(0)+2p(0)+1)\right]}{\left(4|g_i|^2 P_r p(0)(1-p(0)) + \sigma_w^2\right)^2}. \tag{23}$$

the optimal q_{opt} which yields the maximum value of $\mathcal{D}^2_{\mathrm{def,max}}$ is located in the range of $0 < q_{\mathrm{opt}} < 1$.

Proof: The proof is straightforward and is therefore omitted here. ■

Corollary 2. *Assume that the relay-to-destination channel noise variance approaches infinity, i.e., $\sigma_w^2 \to \infty$. Given $p(0) > \frac{1}{2}$ and*

$$p'(0) > -\frac{1}{4} - \frac{p(0)}{2}, \tag{25}$$

the optimal q_{opt} which yields the maximum value of $\mathcal{D}^2_{\mathrm{def,max}}$ is located in the range of $0 < q_{\mathrm{opt}} < 1$.

Proof: Again, the proof is trivial and is therefore omitted here. ■

By defining $\epsilon := -\frac{1}{2} + p(0) > 0$, the conditions for $0 < q_{\mathrm{opt}} < 1$ given in Corollaries 1 and 2 are equivalent to $p'(0) > -\frac{1}{2} - \epsilon$ and $p'(0) > -\frac{1}{2} - \frac{1}{2}\epsilon$, respectively. Since $p(q)$ can be interpreted as the probability of a correct detection result at the relay node, Corollaries 1 and 2 imply that as long as the decreasing rate of the correct detection probability is less than $\frac{1}{2}$ when $q = 0$, the QRR scheme outperforms the regular DF scheme. The lemma below further investigates the decreasing rate of the correct detection probability for a widely employed local detector.

Lemma 1. *Assuming that the received signal model at each relay has the form shown in* (2) *and the breakpoints of the reliability detector are set as $\eta_u = -\eta_l = \eta$, then $p'(0) = -\frac{1}{2}$.*

Proof: For the received signal model given in (2), probabilities p and q can be expressed respectively as

$$p(\eta) = \int_{\eta}^{\infty} \mathbf{E}_{h_i}\left[\frac{1}{\sqrt{\pi}|h_i|\sigma_n} \exp\left\{-\frac{\left(t - |h_i|^2\sqrt{P_s}\right)^2}{|h_i|^2\sigma_n^2}\right\}\right] dt, \tag{26}$$

and

$$q(\eta) = \int_{-\eta}^{\eta} \mathbf{E}_{h_i}\left[\frac{1}{\sqrt{\pi}|h_i|\sigma_n} \exp\left\{-\frac{\left(t - |h_i|^2\sqrt{P_s}\right)^2}{|h_i|^2\sigma_n^2}\right\}\right] dt. \tag{27}$$

Therefore, it follows that

$$\frac{\partial p(\eta)}{\partial \eta} = -\mathbf{E}_{h_i}\left[\frac{1}{\sqrt{\pi}|h_i|\sigma_n} \exp\left\{-\frac{\left(\eta - |h_i|^2\sqrt{P_s}\right)^2}{|h_i|^2\sigma_n^2}\right\}\right] \tag{28}$$

and

$$\frac{\partial q(\eta)}{\partial \eta} = \mathbf{E}_{h_i}\left[\frac{1}{\sqrt{\pi}|h_i|\sigma_n} \exp\left\{-\frac{\left(\eta - |h_i|^2\sqrt{P_s}\right)^2}{|h_i|^2\sigma_n^2}\right\}\right] + \mathbf{E}_{h_i}\left[\frac{1}{\sqrt{\pi}|h_i|\sigma_n} \exp\left\{-\frac{\left(\eta + |h_i|^2\sqrt{P_s}\right)^2}{|h_i|^2\sigma_n^2}\right\}\right]. \tag{29}$$

Applying the chain rule, it follows from (28) and (29) that

$$\lim_{q\to 0} \frac{\partial p}{\partial q} = \lim_{\eta\to 0} \frac{\partial p}{\partial \eta}\frac{\partial \eta}{\partial q} = -\frac{1}{2}. \tag{30}$$

■

It is straightforward to verify that $p'(0) = -0.5$ satisfies both condition (24) in Corollary 1 and condition (25) in Corollary 2. More importantly, $p'(0) = -0.5$ satisfies condition (19) in Proposition 1, i.e., the condition for the more general case in which the communication channels have neither a high-SNR nor a low-SNR. Therefore, in accordance with Lemma 1 and Proposition 1, the following proposition immediately follows.

Proposition 2. *If the received signal model at each relay has the form given in* (2) *and the breakpoints of the reliability detector are set as $\eta_u = -\eta_l = \eta$, then the optimal q_{opt} which yields the maximum value of $\mathcal{D}^2_{\mathrm{def,max}}$ is located at $0 < q_{\mathrm{opt}} < 1$.*

Proposition 2 implies that the proposed QRR scheme outperforms the regular DF scheme given the use of the widely-used channel model in (2) and a common detector in which the breakpoints are set as $\eta_u = -\eta_l = \eta$.

C. Determination of optimal q_{opt}

Since $\mathcal{D}^2_{\mathrm{def,max}}$ in (17) is dependent on the relay-to-destination CSI $\boldsymbol{g}$, the optimal $\eta_{\mathrm{opt}} := \eta(q_{\mathrm{opt}})$, which maximizes $\mathcal{D}^2_{\mathrm{def,max}}$ may be a function of $\boldsymbol{g}$, which is inconsistent with the semi-blind model adopted in the present study. However, the following two lemmas suggest that $\mathcal{D}^2_{\mathrm{def,max}}$ can be well approximated by another performance measure which does not require knowledge of $\boldsymbol{g}$. Note that the proofs of both lemmas are trivial and are therefore omitted.

Lemma 2. *For the case where $\frac{|g_i|^2 P_r}{\sigma_w^2} \gg 1 - q$, i.e., the relay-to-destination instantaneous CSI is very large, the deflection coefficient $\mathcal{D}^2_{\mathrm{def,max}}$ given in* (17) *can be approximated as*

$$\mathcal{D}^2_{\mathrm{def,max}} \approx \frac{M(2p+q-1)^2}{p(1-p-q)}.$$

Lemma 3. *For the case where* $\frac{|g_i|^2 P_r}{\sigma_w^2} \ll 1-q$*, i.e., the relay-to-destination instantaneous CSI is very small, the deflection coefficient* $\mathcal{D}^2_{\text{def,max}}$ *given in* (17) *can be approximated as*

$$\mathcal{D}^2_{\text{def,max}} \approx \left(\sum_{i=1}^{M} |g_i|^2\right) \frac{4P_r(2p+q-1)^2}{\sigma_w^2(1-q)}.$$

It can be seen from Lemmas 2 and 3 that finding the optimal η_{opt} which maximizes $\mathcal{D}^2_{\text{def,max}}$ is independent of the CSI $\boldsymbol{g}$ and the total number of relays provided that the relay-to-destination instantaneous CSI is sufficiently high or sufficiently low. Therefore, in determining the optimal η_{opt}, the following deflection coefficient per sensor is proposed as the objective function for the optimization problem. That is, the optimal η_{opt} is found in accordance with

$$\eta_{\text{opt}} = \arg\max_{\eta} d^2_{\text{def,max}}, \tag{31}$$

where

$$d^2_{\text{def,max}} := \frac{4P_r(2p+q-1)^2}{4P_r p(1-p-q) + \sigma_w^2(1-q)}. \tag{32}$$

IV. Performance Evaluation

This section evaluates the performance of the QRR scheme and compares it with that of three existing DF schemes. In conducting the performance evaluations, it is assumed that the source and relays have an equal power (i.e., $P_s = P_r = P_0$) and all the channels have a unit variance (i.e., $\sigma_h^2 = \sigma_g^2 = 1$). As a result, the average input source-to-relay SNR is equal to $\bar{\gamma}_{sr} = P_0/\sigma_n^2$, while the average input relay-to-destination SNR is equal to $\bar{\gamma}_{rd} = P_0/\sigma_w^2$. In addition, in evaluating the performance of QRR, it is assumed that the thresholds of the reliability detector employed at each relay are set as $\eta_u = -\eta_l = \eta$.

The evaluations commence by investigating the variations of the deflection coefficient per relay $d^2_{\text{def,max}}$ (defined in (32)) and the probability p with the no-send probability q given $\bar{\gamma}_{sr} = \bar{\gamma}_{rd} = \bar{\gamma}$. Figures 2 and 3 present the corresponding results for SNRs of $\bar{\gamma} = 0$ dB and $\bar{\gamma} = 5$ dB, respectively. It is observed that the optimal no-send probability q_{opt} has a value of $0 < q_{\text{opt}} < 1$ in both cases. In other words, the assertion of Proposition 2 in Section III is confirmed. In addition, it is seen that the no-send probability for the low SNR case (Fig. 2) has a greater value than that for the high SNR case (Fig. 3). Note that this finding is reasonable since the range of the unreliable signal received at the relays under low SNR condition is broader than that under high SNR conditions.

In the following discussions, the BER performance of the QRR scheme is compared with that of the regular DF scheme, the best-relay selection scheme [17], and the 2nd-best-relay selection scheme [18] by means of numerical simulations. For all four schemes, the variation of the BER with the average input SNR is investigated for both $\bar{\gamma}_{sr} = \bar{\gamma}_{rd}$ and $\bar{\gamma}_{sr} \neq \bar{\gamma}_{rd}$, respectively. In every case, the network is assumed to contain $M = 5$ relays. For the QRR scheme, the threshold η_{opt} is found by numerically maximizing the conditional deflection coefficient $d^2_{\text{def,max}}$ given in (32). In addition, for the best-relay and 2nd-best-relay selection schemes, successful decoding (or otherwise) at each relay node is determined in accordance with (1) by setting $C = 1$ and $\eta_R = 1, 2,$ or 3 (see Figs. 4, 5, and 6, respectively). Figures 4, 5, and 6 compare the BER performance of the QRR scheme with that of the three DF schemes for the case of $\bar{\gamma}_{sr} = \bar{\gamma}_{rd} = \bar{\gamma}$. It is seen that QRR outperforms the other DF schemes for all considered values of the average input SNR. In addition, it is noted that the BER performance of the best-relay and 2nd-best-relay selection schemes is strongly dependent on the value assigned to η_R. For example, given a small value of η_R, the BER of both schemes is higher than that of the regular DF scheme, and thus full diversity cannot be achieved (see Fig. 4). Note that the improved BER performance of the regular DF scheme stems from its information combining of all the reliable and unreliable received messages. Moreover, the performance of the best-relay and 2nd-best-relay schemes is degraded under high SNR conditions since the low value of η_R results in a significant error propagation effect. For a high value of η_R, the best-relay selection scheme achieves full diversity

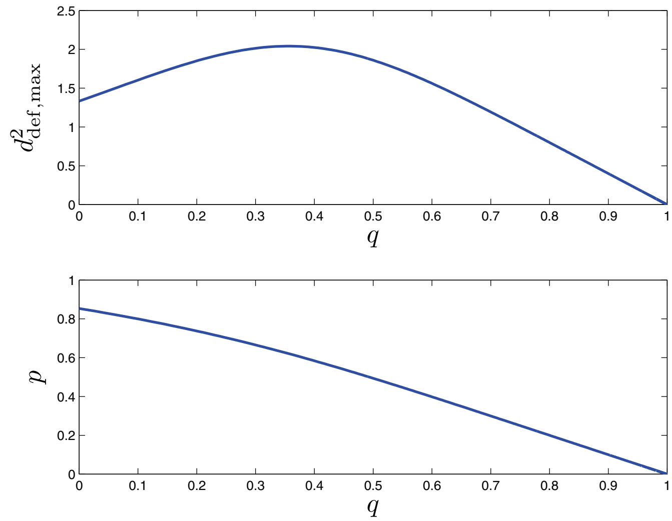

Fig. 2. Deflection coefficient per relay, $d^2_{\text{def,max}}$, and probability p versus probability q for scenario in which $\bar{\gamma}_{sr} = \bar{\gamma}_{rd} = 0$ dB.

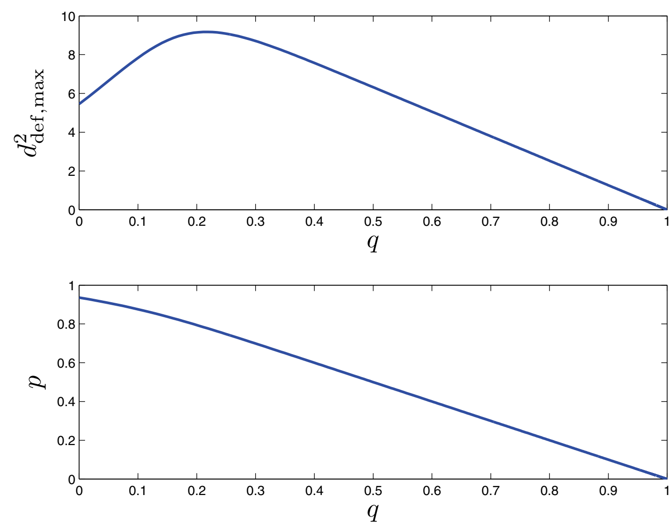

Fig. 3. Deflection coefficient per relay, $d^2_{\text{def,max}}$, and probability p versus probability q for scenario in which $\bar{\gamma}_{sr} = \bar{\gamma}_{rd} = 5$ dB.

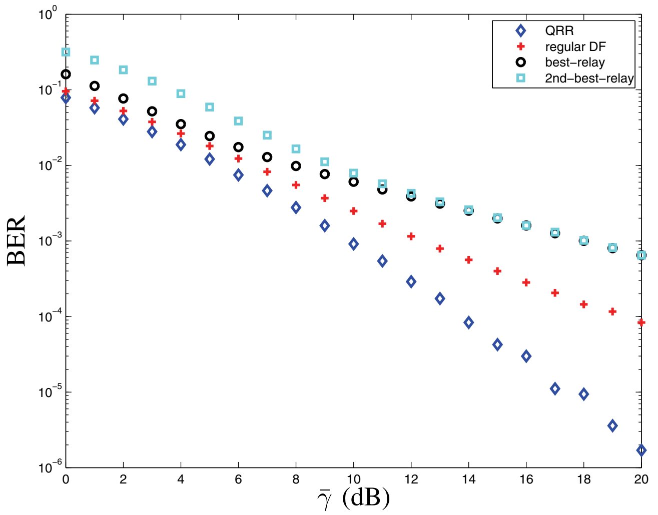

Fig. 4. BER performance of QRR, regular DF, best-relay selection, and 2nd-best-relay selection schemes for scenario in which $\bar{\gamma}_{sr} = \bar{\gamma}_{rd} = \bar{\gamma}$ and $\eta_R = 1$ is set for both selection schemes.

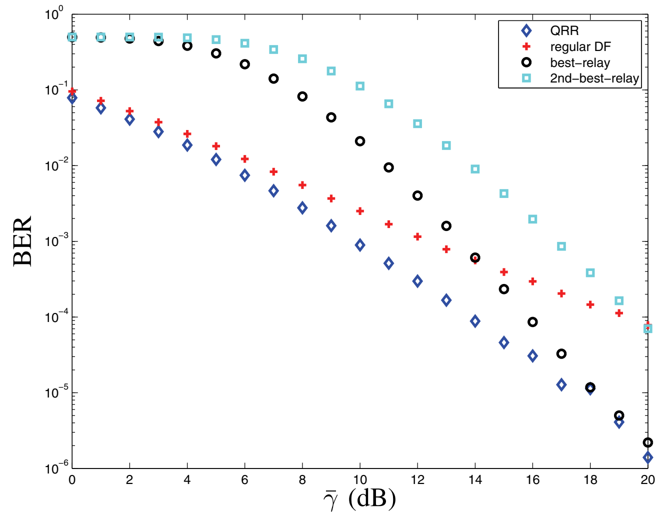

Fig. 6. BER performance of QRR, regular DF, best-relay selection, and 2nd-best-relay selection schemes for scenario in which $\bar{\gamma}_{sr} = \bar{\gamma}_{rd} = \bar{\gamma}$ and $\eta_R = 3$ is set for both selection schemes.

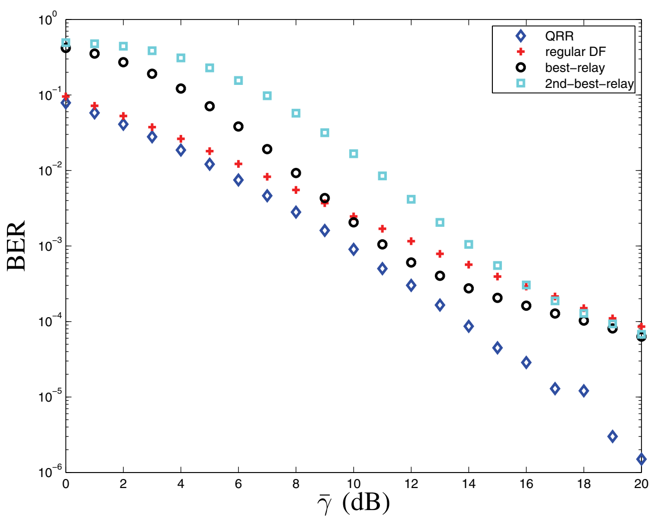

Fig. 5. BER performance of QRR, regular DF, best-relay selection, and 2nd-best-relay selection schemes for scenario in which $\bar{\gamma}_{sr} = \bar{\gamma}_{rd} = \bar{\gamma}$ and $\eta_R = 2$ is set for both selection schemes.

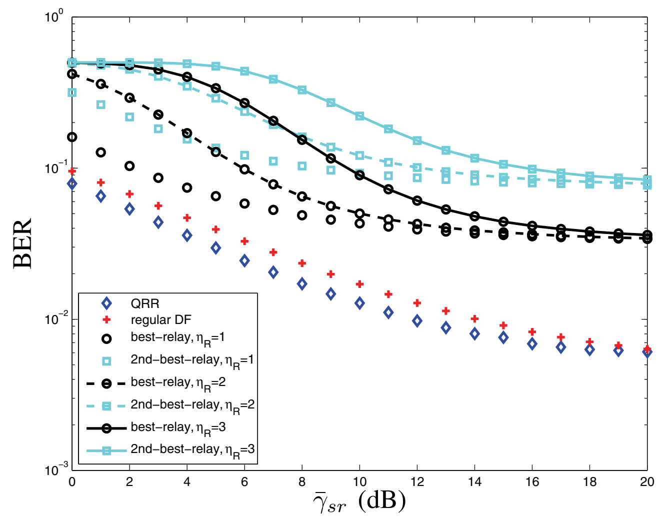

Fig. 7. BER performance of QRR, regular DF, best-relay selection, and 2nd-best-relay selection schemes for scenario in which $\bar{\gamma}_{rd} = 1$ and $\bar{\gamma}_{sr}$ varies.

and outperforms the regular DF scheme under high SNR conditions (see Fig. 6). However, under low SNR condition, the BER performance of both relay selection schemes is significantly degraded and is poorer than that obtained under a small value of η_R.

Figure 7 compares the BER performance of the four schemes for $\bar{\gamma}_{rd} = 1$ and various values of $\bar{\gamma}_{sr}$. It is again seen that the QRR scheme outperforms the DF schemes for all considered values of the SNR. (Note that the simulation results for the case in which $\bar{\gamma}_{sr}$ is fixed and $\bar{\gamma}_{rd}$ varies yield a similar finding. Hence, the results are deliberately omitted here for the sake of brevity.)

Figure 8 plots the average number of orthogonal channels required by each of the considered schemes. It is seen that the two relay selection schemes have the best spectral efficiency, i.e., they both require only one orthogonal channel. By contrast, the regular DF scheme incurs the greatest bandwidth penalty of the four schemes, i.e., M orthogonal channels (where M is the number of relays in the network). It is noted that the average number of orthogonal channels required by the proposed QRR scheme falls between that of the two relay selection schemes and the regular DF scheme, respectively. In addition, it is seen that the number of orthogonal channels required by the QRR scheme increases as the SNR increases due to the corresponding reduction in the number of unreliable signals received at each relay.

V. Conclusions and Future Work

This study has presented a quantized reliability-relaying (QRR) scheme for improving the communication performance in cooperative semi-blind networks. In implementing the proposed scheme, it is assumed that each relay can obtain the perfect CSI from the source to itself, and the destination can acquire the perfect CSI from all the relays to itself.

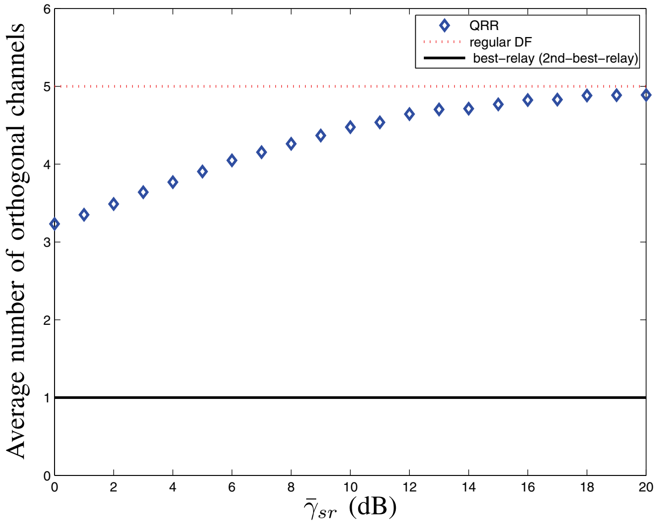

Fig. 8. Average number of orthogonal channels required by QRR, regular DF, and two relay selection schemes for scenario in which $\bar{\gamma}_{sr} = \bar{\gamma}_{rd} = \bar{\gamma}$.

Importantly, the destination does not require the CSI from the source to the participating relays, and thus the resource and communication costs are significantly reduced. In contrast to the regular DF scheme, the relays in the QRR scheme forward their quantized reliability (as determined by the LLR of the received signal) to the destination. The theoretical and numerical results have shown that the QRR scheme outperforms the regular DF scheme in terms of both a higher deflection coefficient and an improved BER. In addition, given the same semi-blind model, the simulation results have shown that the QRR scheme achieves a lower BER than the best-relay selection scheme [17] or 2nd-best selection scheme [18]. However, the QRR scheme has a poorer spectral efficiency than the two best-relay selection schemes.

Future studies will extend the QRR scheme to a cooperative communication network based on a higher-order modulation technique and non-orthogonal channels between the relays and the destination. The feasibility of the proposed QRR scheme given a higher order modulation technique will be examined by using the "worst-case distances among points in the constellation" concept described in [11] and then applying the same analysis technique as that used in the present study for the BPSK modulation scheme. Similarly, the feasibility of the QRR scheme given non-orthogonal channels between the relays and the destination will be examined using an error bound technique. In wireless cooperative networks, the relays can be distributed in many different ways. As a result, future studies might usefully examine the effects of different relay distribution strategies on the design of the QRR scheme. Furthermore, a future study might consider extending the QRR concept proposed in this study to the case of an AF relay network, in which the real-valued reliability rather than the quantized reliability is computed and forwarded to the destination. Finally, the results presented in Fig. 8 suggest that a future study should attempt to find the optimal trade-off between the BER performance and the spectral efficiency of cooperative DF schemes.

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