A Cooperative Phase Steering Scheme in Multi-Relay Node Environments

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***Abstract*—We propose a decode-and-forward (DF) based cooperative phase steering scheme and analyze its outage probability. The cooperative phase steering scheme is to make the received signals from multiple relay nodes co-phased at a destination node by pre-adjusting the phase differences. With a reasonable amount of feedback information from a destination node, the cooperative phase steering scheme circumvents the drawbacks of conventional cooperative diversity techniques such as maximal ratio combining (MRC) reception, maximal ratio transmission (MRT), and opportunistic relay selection schemes. Our analytical and simulation results show that the cooperative phase steering scheme outperforms the opportunistic relay selection scheme and approaches the MRT scheme known as a theoretically optimal cooperative diversity technique. It is also shown that cooperative phase steering has sufficient robustness to phase incoherence.**

***Index Terms*—Cooperative diversity, relay, outage probability, phase steering.**

I. Introduction

RECENT studies have found that significant diversity gains can be achieved through cooperation among geographically distributed nodes or terminals, namely *cooperative diversity* [1]− [8]. Based on a motivation that multiple relays can significantly increase the cooperative diversity gains, the focus of recent research has moved to multiple relay configurations. Various cooperative diversity techniques using multiple relay nodes have been proposed and studied [5]−[8]. Distributed space-time coding across multiple relay nodes was proposed in [5]. The MRC of the received signals from multiple relays was studied in [6]. The MRC reception, however, significantly sacrifices spectral efficiency because the orthogonality between the received signals from relay nodes is typically secured by frequency division or time division multiple access among nodes. On the other hand, it is known that MRT [9] achieves the theoretically optimal diversity performance if power cooperation (or power sharing) among geographically distributed relay nodes is allowed. However, power cooperation among nodes is not practically feasible since nodes are geographically distributed in cooperative communication networks. It is rather reasonable to consider individual power constraints of relay nodes. Furthermore, exploiting full channel state information at each node requires a large amount of feedback information.

To reduce the burden of the power cooperation and feedback information in cooperative communication networks, an opportunistic relay selection scheme was proposed in [7]. From an analytical point of view, the opportunistic relay selection scheme corresponds to a conventional transmit selection diversity technique. In the opportunistic relay selection scheme, however, a destination node must identify which relay nodes successfully decoded the signal from a source node, namely a decode set; the destination node selects a relay node in the decode set based on the channel quality. If the destination has no prior knowledge of the decode set, then diversity performance seriously degrades. As an alternative approach, a relay can be selected in a distributed manner [7], [8]. However, it inevitably causes additional signaling and feedback overhead. Besides the requirement of prior knowledge of the decode set at the destination node, the performance of the opportunistic relay selection scheme is limited, compared to the MRT scheme. These facts motivate us to propose a new cooperative diversity scheme whose performance is comparable to that of the MRT but free from the shortcomings of previous cooperative diversity techniques. The cooperative phase steering scheme can be a good candidate. This phase steering scheme aligns the phases of the received signals by pre-adjusting the phase differences for array antenna beamforming. The phase steering takes a big advantage over other transmission schemes using prior channel knowledge in terms of the required amount of feedback information because the channel amplitude information is not required to be fed back. In addition, channel phase values are much less sensitive to the quantization levels and errors than channel amplitudes. It should be also noted that phase steering is performed without power cooperation among nodes and is known to be the optimal transmission strategy under individual power constraints [10].

In this context, we mathematically analyze the performance of a cooperative phase steering scheme in terms of outage probability. In the cooperative phase steering scheme, each relay node which has successfully decoded the signal from a source node pre-adjusts the phase difference at the destination node and forwards the signal with its allowable full transmit power. The rest of this paper is organized as follows. In Section II, a system model is briefly described. In Section III, the performance of the cooperative phase steering scheme is mathematically analyzed in terms of outage probability and its closed-form approximation is provided. In Section IV, numerical results show the performance of the cooperative

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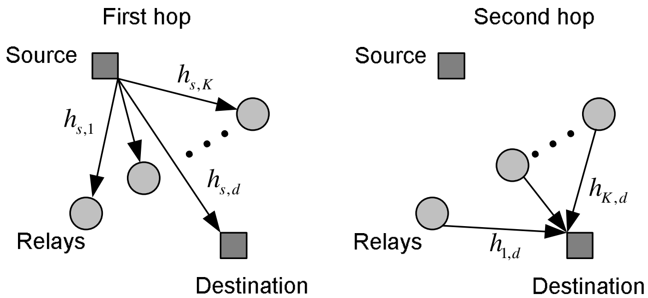

Fig. 1. A half-duplex two-hop relay system

phase steering scheme in terms of outage probability and the effect of phase incoherence. Finally, conclusions are drawn in Section V.

II. A Cooperative Communication System Model

We consider a DF based cooperative communication model employing a repetition-based two-hop half-duplex relaying protocol, as shown in Fig. 1. The system consists of a source node, a destination node, and K relay nodes denoted by s, d, and $r \in \{1, \cdots, K\}$, respectively. In the first-hop, the source node broadcasts its data to relay nodes and the destination node. Then, in the second hop, only relay nodes that successfully decoded the source message from the source node forward the source message to the destination. Since this cooperative communication is performed over two-hop periods, the required data rate should be double the data rate of direct communication without relaying to compensate for the spectral efficiency loss by the transmit duty cycle. It is possible for the source to transmit its message to the destination in the second-hop to increase data rate or improve diversity performance, especially when a decoding set is empty. This scenario, however, requests the source to secure an orthogonal channel or cooperate with relays in the second-hop, which increases the system overhead or reduces efficiency. Thus, we consider a simple DF protocol as in [11], where the source does not re-transmit its message in the second-hop when all relays fail to decode their received messages from the source. Assuming channels between nodes are static over two-hop periods, the received signal at node B from node A is represented by

$$y_B = h_{A,B} x_A + n_B \tag{1}$$

where x_A is the signal transmitted from node A, $h_{A,B}$ representing the channel gain from node A to node B is a complex Gaussian random variable $\sim \mathcal{CN}(0, \sigma_{A,B}^2)$, and n_B denoting the additive white Gaussian noise (AWGN) at node B follows a complex Gaussian distribution $\sim \mathcal{CN}(0, N_0)$. The terms A and B can be either source (s) and relay (r) or relay and destination (d), respectively. $\mathbb{E}\{|x_A|^2\}$ is the transmit power of the source node or the relay node (P_s or P_r). Each node, regardless of the source and relay, is assumed to have the same power constraint P for simplicity. The channels in each hop are assumed to be independent and identically-distributed (i.i.d.).

III. Outage Probability of The Cooperative Phase Steering Scheme

A decode set ($\mathcal{D}$) is defined as a set of relay nodes that successfully decode the source message and is given by

$$\mathcal{D} = \left\{ k \in \mathcal{S} : |h_{s,k}|^2 \geq R' \right\}, \tag{2}$$

where R' is determined as

$$R' \triangleq \frac{2^{2R} - 1}{\rho}$$

and R is the required spectral efficiency of a cooperative communication system, and $\rho (\triangleq P/N_0)$ is the transmit SNR. The decode set is obviously a subset of a whole relay set, $\mathcal{S}$, containing all the relay nodes. When a source node broadcasts its signal to a destination and relay nodes in the first hop, the received signal at the destination node is given by

$$y_d = h_{s,d} x_s + n_d. \tag{3}$$

Relay nodes also decode the source signal during the first hop. At the second hop, relay nodes that successfully decoded at the first hop forward the source message to the destination node. Then, the received signal at the destination from relay nodes in the second hop is given by

$$y_d = \begin{cases} 0\,, & |\mathcal{D}| = 0 \\ \sum_{i=1}^{|\mathcal{D}|} |h_{i,d}| x_s + n_d, & |\mathcal{D}| \neq 0, \end{cases} \tag{4}$$

where $|\mathcal{D}|$ is the cardinality of a decode set $\mathcal{D}$ and $\mathbb{E}\left[|x_s|^2\right] = P$ since each node is assumed to have the same power constraint P. Note that the relays in the decoding set repeat the codeword to improve diversity performance at the destination. Even though an incremental redundancy method can increase the achievable data rate, this paper simply considers the repetition based scheme to focus on the ways of exploiting multiple relay nodes.

After receiving the signals over the first and the second hops, the destination node coherently combines the signals. Then, the effective received SNR at the destination node for a given decode set $\mathcal{D}$ is given by

$$\gamma(\mathcal{D}) = \begin{cases} \rho |h_{s,d}|^2, & |\mathcal{D}| = 0 \\ \rho \left[|h_{s,d}|^2 + \frac{1}{N_{norm}} \left(\sum_{i=1}^{|\mathcal{D}|} |h_{i,d}| \right)^2 \right], & |\mathcal{D}| > 0, \end{cases} \tag{5}$$

where N_{norm} denotes the transmit power normalization term introduced for fair performance comparison with other cooperative diversity techniques because the total power consumed by relay nodes is different according to given cooperative diversity techniques using multiple relay nodes. In a long-term average sense, the cooperative phase steering consumes $\mathbb{E}[|\mathcal{D}|] P$ in the second hop, while the opportunistic relay selection and the MRT schemes consume $\Pr[|\mathcal{D}| \neq 0] P$. Thus, in order to set the average power consumption in the second hop to be P, the transmit power normalization factor for the cooperative phase steering scheme is determined by

$$\begin{aligned} N_{norm} &\triangleq \mathbb{E}[|\mathcal{D}|] \\ &= \sum_{k=1}^{K} k \binom{K}{k} \left(e^{-\frac{R'}{\sigma_{s,r}^2}} \right)^k \left(1 - e^{-\frac{R'}{\sigma_{s,r}^2}} \right)^{K-k}. \end{aligned} \tag{6}$$

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It should be again noted that cooperative phase steering does not require any power sharing among relays.

Let $Z_{\mathcal{D}}$ be the effective channel gain for a given $|\mathcal{D}|$ in Eq. (5) such that

$$Z_{\mathcal{D}} \triangleq \begin{cases} X = |h_{s,d}|^2, & |\mathcal{D}| = 0 \\ X + Y_{\mathcal{D}}^2 = |h_{s,d}|^2 + \frac{\left(\sum_{i=1}^{|\mathcal{D}|} |h_{i,d}|\right)^2}{N_{norm}}, & |\mathcal{D}| > 0, \end{cases} \tag{7}$$

where X is an exponentially distributed random variable and $Y_{\mathcal{D}}$ is the sum of $|\mathcal{D}|$ Rayleigh-distributed random variables. Then, the conditional CDF of $Z_{\mathcal{D}}$ conditioned on $\mathcal{D}$ can be derived as

$$\begin{aligned} F_{Z_{\mathcal{D}}}(z) &= \begin{cases} 1 - e^{-\frac{z}{\sigma_{s,d}^2}}, & |\mathcal{D}| = 0 \\ \int_{y=0}^{\sqrt{z}} \int_{x=0}^{z-y^2} f_{X,Y_{\mathcal{D}}}(x,y)dxdy, & |\mathcal{D}| > 0. \end{cases} \\ &= \begin{cases} 1 - e^{-\frac{z}{\sigma_{s,d}^2}}, & |\mathcal{D}| = 0 \\ \int_{y=0}^{\sqrt{z}} \left(1 - e^{-\frac{z-y^2}{\sigma_{s,d}^2}}\right) f_{Y_{\mathcal{D}}}(y)dy, & |\mathcal{D}| > 0, \end{cases} \end{aligned} \tag{8}$$

where $f_{Y_{\mathcal{D}}}(y)$ is the PDF of the sum of $|\mathcal{D}|$ Rayleigh-distributed random variables, $Y_{\mathcal{D}}$. Even though the closed form $f_{Y_{\mathcal{D}}}(y)$ is not known, a close approximation has been developed as [12]

$$f_{Y_{\mathcal{D}}}(y) \approx \frac{\left(\frac{y}{\sqrt{|\mathcal{D}|}}\right)^{2|\mathcal{D}|-1} e^{-\left(\frac{y}{\sqrt{|\mathcal{D}|}}\right)^2/2b_{\mathcal{D}}}}{\sqrt{|\mathcal{D}|}2^{|\mathcal{D}|-1}(b_D)^{|\mathcal{D}|}\left(|\mathcal{D}|-1\right)!}, \tag{9}$$

where $b_{\mathcal{D}} = \frac{\sigma_{r,d}^2}{2|\mathcal{D}|N_{norm}}\left[(2|\mathcal{D}|-1)!!\right]^{\frac{1}{|\mathcal{D}|}}$ and $(2|\mathcal{D}|-1)!! = (2|\mathcal{D}|-1)(2|\mathcal{D}|-3)\cdots 3\cdot 1$. By substituting $f_{Y_{\mathcal{D}}}(y)$ in Eq. (9) into Eq. (8), the closed form approximation of $F_{Z_{\mathcal{D}}}(z)$ can be obtained as Eq. (10), where $c = \frac{\sigma_{s,d}^2 - 2b_{\mathcal{D}}|\mathcal{D}|}{2b_{\mathcal{D}}|\mathcal{D}|\sigma_{s,d}^2}$, $\Gamma(\alpha,\beta)$ denotes an incomplete gamma function, and $\mathrm{M}(\lambda,\mu,z)$ is a Whittaker function given by

$$\mathrm{M}(\lambda,\mu,z) \triangleq z^{\mu+\frac{1}{2}}e^{-\frac{z}{2}}\Phi(\mu-\lambda+\frac{1}{2}, 2\mu+1; z),$$

where $\Phi(\alpha,\gamma;z)$ is a confluent hypergeometric function defined as $\Phi(\alpha,\gamma;z) \triangleq 1 + \frac{\alpha z}{\gamma\cdot 1!} + \frac{\alpha(\alpha+1)z^2}{\gamma(\gamma+1)2!} + \cdots$.

Using the CDF of $Z_{\mathcal{D}}$, the outage probability for a given decode set $\mathcal{D}$ is obtained as

$$\begin{aligned} P_{out}(\mathcal{D}) &\triangleq \Pr\left[\frac{1}{2}\log_2\left(1+\gamma(\mathcal{D})\right) < R\right] \\ &= \Pr\left[Z_{\mathcal{D}} < \frac{2^{2R}-1}{\rho}\right] \\ &= F_{Z_{\mathcal{D}}}(R'). \end{aligned} \tag{11}$$

The (unconditional) outage probability is obtained by averaging the conditional outage probability in Eq. (11) over all possible decode sets such as

$$\begin{aligned} P_{out} &= \sum_{k=0}^{K} \Pr\left[|\mathcal{D}| = k\right] P_{out}(\mathcal{D}) \\ &= \sum_{k=0}^{K} \binom{K}{k} \left(e^{-\frac{R'}{\sigma_{s,r}^2}}\right)^k \left(1 - e^{-\frac{R'}{\sigma_{s,r}^2}}\right)^{K-k} F_{Z_{\mathcal{D}}}(R'). \end{aligned} \tag{12}$$

This formula enables us to numerically evaluate the outage probability. However, the simple closed form of the outage probability is still required to identify key parameters and intuitively understand their effects. In this context, we now derive a close approximation of the outage probability in the high SNR region.

Theorem 1 (Outage probability in the high SNR region): The outage probability derived in Eq. (12) is approximated in the high SNR region by

$$\begin{aligned} P_{out} \approx \frac{R'^{K+1}}{\left(\sigma_{s,r}^2\right)^K \sigma_{s,d}^2} + \sum_{k=1}^{K} \binom{K}{k} \left(1 - \frac{R'}{\sigma_{s,r}^2}\right)^k \left(\frac{R'}{\sigma_{s,r}^2}\right)^{K-k} \times \\ \left[\left(\frac{R'}{2b_k k}\right)^k \frac{1}{k!} - \right. \\ \left. \left(\frac{\sigma_{s,d}^2}{\sigma_{s,d}^2 - 2b_k k}\right)^k e^{-\frac{R'}{\sigma_{s,d}^2}} \left(1 - \frac{\Gamma(k, cR')}{(k-1)!}\right)\right]. \end{aligned} \tag{13}$$

Proof: Refer to Appendix A. ■

Using upper and lower bounds on $\lim_{\text{SNR}\to\infty} P_{out}$, it can be shown that the achievable diversity order of the cooperative phase steering is $K+1$ although the details are omitted due to the limit of the length.

IV. Numerical Results

A. Outage Probability

Fig. 2 shows the outage probability of three different schemes: MRT, opportunistic relay selection, and phase steering for varying transmit SNR values when $R = 0.5$ bps/Hz. The number of relay nodes K is set to three or five. The channel gains of a direct path, source-to-relay path, and relay-to-destination path are set to $\sigma_{s,d}^2 = -30\ dB$, $\sigma_{s,r}^2 = -10\ dB$, and $\sigma_{r,d}^2 = -20\ dB$, respectively, to reflect the geometric characteristics of relay networks. Monte-Carlo simulation results are presented for verification of the accuracy of the analytical results. The result shows that the derived approximation of outage probability agrees very well with both the simulation results and numerical evaluations in the high SNR region. The outage probability of the cooperative phase steering scheme is lower than that of the opportunistic relay selection scheme, but higher than that of the MRT scheme which is known to be theoretically optimal. However, it should be noted here that the cooperative phase steering scheme requires a much smaller amount of feedback information than the MRT scheme. Furthermore, the cooperative phase steering scheme does not require power cooperation among relay nodes and, thus, it works well under individual power constraints.

Fig. 3 shows the outage probabilities versus the number of relay nodes K when the transmit SNR is 20 dB or 25 dB. The cooperative phase steering scheme outperforms the opportunistic relay selection scheme and achieves comparable performance to the optimal MRT scheme. As the number of relay nodes, K, increases, the performance difference between the cooperative phase steering and opportunistic relay selection schemes becomes large. The high SNR approximation results also show good accuracy regardless of the number of relay nodes K when the SNR value is high.

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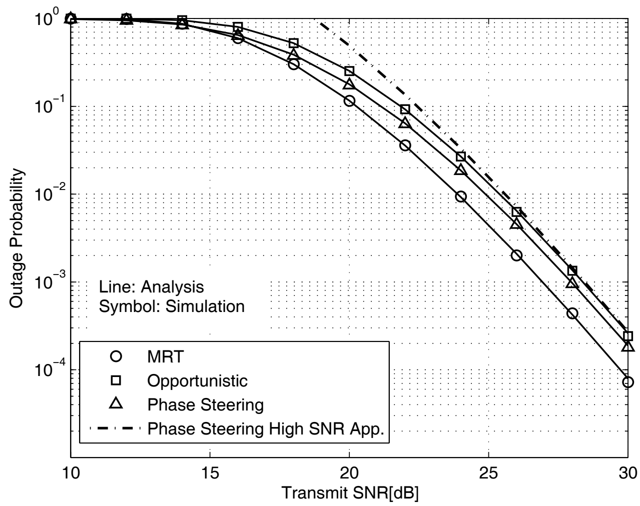
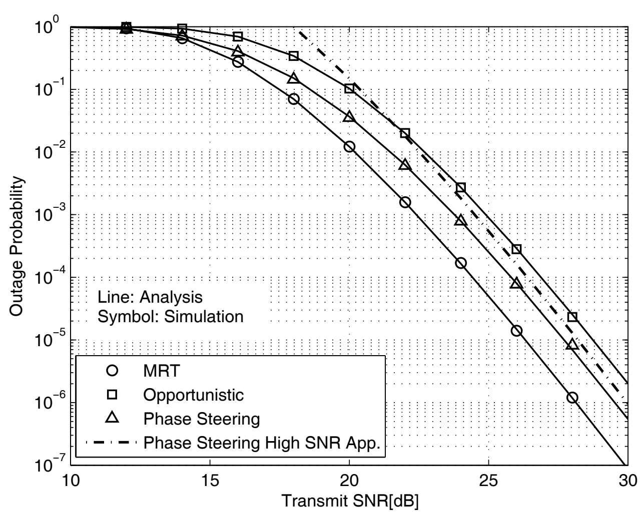
$$F_{Z_{\mathcal{D}}}(z) \approx \begin{cases} 1 - e^{-\frac{z}{\sigma_{s,d}^2}}, & |\mathcal{D}| = 0 \\ \frac{1}{(2b_{\mathcal{D}}|\mathcal{D}|)^{|\mathcal{D}|}(|\mathcal{D}|+1)!} z^{\frac{|\mathcal{D}|}{2}} e^{-\frac{z}{4b_{\mathcal{D}}|\mathcal{D}|}} \left[\left(\sqrt{2b_{\mathcal{D}}|\mathcal{D}|} \right)^{|\mathcal{D}|} \mathrm{M}\left(\frac{|\mathcal{D}|}{2}, \frac{|\mathcal{D}|}{2} + \frac{1}{2}, \frac{z}{2b_{\mathcal{D}}|\mathcal{D}|} \right) \right. & |\mathcal{D}| > 0, \\ \quad \left. + e^{-\frac{z}{4b_{\mathcal{D}}|\mathcal{D}|}} z^{\frac{|\mathcal{D}|}{2}} (1 + |\mathcal{D}|) \right] - \left(\frac{\sigma_{s,d}^2}{\sigma_{s,d}^2 - 2b_{\mathcal{D}}|\mathcal{D}|} \right)^{|\mathcal{D}|} e^{-\frac{z}{\sigma_{s,d}^2}} \left[1 - \frac{\Gamma(|\mathcal{D}|, cz)}{(|\mathcal{D}|-1)!} \right], & \end{cases} \quad (10)$$

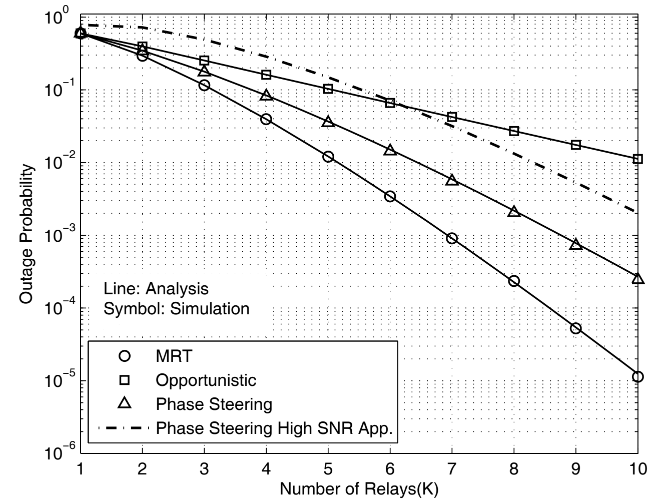


(a) $K = 3$

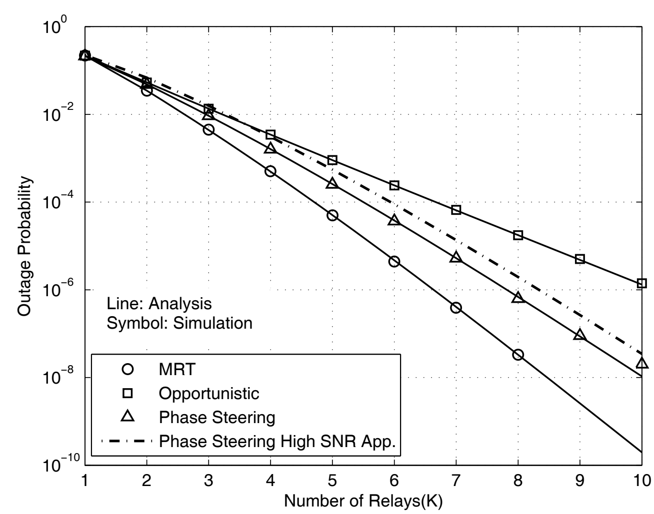


(b) $K = 5$

Fig. 2. Outage probabilities versus transmit SNR. $R = 0.5$ bps/Hz, $\sigma_{s,d}^2 = -30$ dB, $\sigma_{r,d}^2 = -20$ dB, and $\sigma_{s,r}^2 = -10$ dB.



(a) SNR=20 dB



(b) SNR=25 dB

Fig. 3. Outage probabilities versus K. $R = 0.5$ bps/Hz, $\sigma_{s,d}^2 = -30$ dB, $\sigma_{r,d}^2 = -20$ dB, and $\sigma_{s,r}^2 = -10$ dB.

B. The Effect of Imperfect Phase Coherence

Distributed beamforming systems are vulnerable to phase incoherence at a destination because it is difficult to synchronize distributed nodes' oscillators [17], [18]. The phase incoherence degrades the performance of beamforming systems because the phase incoherence reduces the effective SNR at the destination. Fig. 4 shows the performance degradation according to the amount of phase incoherence when the phase incoherence from each relay node is assumed to be uniformly distributed random variable on the interval $\left[-\frac{\Delta}{2}, \frac{\Delta}{2}\right]$. Although we do not present the closed form SNR losses of MRT and phase steering schemes due to phase incoherence

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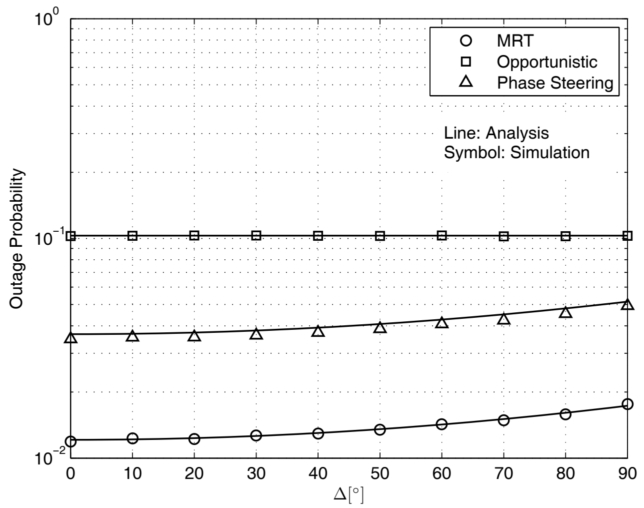

Fig. 4. Performance degradation due to imperfect phase coherence. SNR=20dB, $K=5$, $\sigma_{s,d}^2=-30$ dB, $\sigma_{r,d}^2=-20$ dB, and $\sigma_{s,r}^2=-10$ dB.

for the conciseness of this paper, they can be derived by taking a similar approach in [18]. Fig. 4 verifies that the performance of both the MRT and the cooperative phase steering schemes is degraded as the phase error increases, but the cooperative phase steering scheme still substantially outperforms the opportunistic relay selection scheme.

V. Conclusions

We proposed a DF-based cooperative diversity technique using phase steering in a multi-relay node environment and derived a closed-form analytical approximation of outage probability. The analytical and simulation results showed that the cooperative phase steering scheme outperforms the opportunistic relay selection scheme and approaches the MRT scheme in terms of outage probability. It was also shown that the cooperative phase steering achieves a large fraction of its ideal gain even when phase errors are moderately large as the MRT scheme does and still substantially outperforms the opportunistic relay selection scheme. Considering the amount of feedback information and performance, the analytical and simulation results show that the cooperative phase steering scheme can be a good candidate circumventing the limits of conventional cooperative diversity schemes in cooperative communication networks with multiple relay nodes.

Appendix A
Proof of Theorem 1

First, the outage probability for a given decode set $\mathcal{D}$ ($|\mathcal{D}| \neq 0$) is obtained from Eq. (10) as Eq. (A.1), where $\mathrm{M}(\lambda,\mu,z)$ is the Whittaker function and it can be approximated for small z by

$$\begin{aligned}\mathrm{M}(\lambda,\mu,z) &= z^{\mu+\frac{1}{2}}\left(1-\frac{z}{2}+O\left(z^2\right)\right)\\ &\quad\left(1+\frac{\left(\mu-\lambda+\frac{1}{2}\right)z}{2\mu+1}+O\left(z^2\right)\right)\\ &\approx z^{\mu+\frac{1}{2}}.\end{aligned}$$

Since $R'\left(\triangleq \frac{2^{2R}-1}{\rho}\right)$ becomes small in the high SNR region, the Whittaker function $\mathrm{M}\left(\frac{|\mathcal{D}|}{2},\frac{|\mathcal{D}|}{2}+\frac{1}{2},\frac{R'}{2b_{\mathcal{D}}|\mathcal{D}|}\right)$ in Eq. (A.1) is approximated by $\left(\frac{R'}{2b_{\mathcal{D}}|\mathcal{D}|}\right)^{\frac{|\mathcal{D}|}{2}+1}$. Thus, $P_{out}\left(\mathcal{D},|\mathcal{D}|\neq 0\right)$ is approximated by Eq. (A.2).

On the other hand, the approximated outage probability for an empty decode set in high SNR region is obtained as

$$\begin{aligned}P_{out}\left(\mathcal{D},|\mathcal{D}|=0\right) &= \left(1-e^{-\frac{R'}{\sigma_{s,d}^2}}\right)\\ &\approx \frac{R'}{\sigma_{s,d}^2}.\end{aligned} \tag{A.3}$$

The approximated outage probability in the high SNR region is derived as described in Eq. (13) by averaging as Eq. (12) over all possible decode sets of which approximated probabilities can be obtained as

$$Pr\left[|\mathcal{D}|=k\right] \approx \binom{K}{k}\left(1-\frac{R'}{\sigma_{s,r}^2}\right)^k\left(\frac{R'}{\sigma_{s,r}^2}\right)^{K-k}.$$

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$$P_{out}(\mathcal{D}, |\mathcal{D}| \neq 0) = \frac{1}{(2b_{\mathcal{D}}|\mathcal{D}|)^{|\mathcal{D}|}(|\mathcal{D}|+1)!} R'^{\frac{|\mathcal{D}|}{2}} e^{-\frac{R'}{4b_{\mathcal{D}}|\mathcal{D}|}} \left[\left(\sqrt{2b_{\mathcal{D}}|\mathcal{D}|}\right)^{|\mathcal{D}|} \mathbf{M}\left(\frac{|\mathcal{D}|}{2}, \frac{|\mathcal{D}|}{2}+\frac{1}{2}, \frac{R'}{2b_{\mathcal{D}}|\mathcal{D}|}\right) + e^{-\frac{R'}{4b_{\mathcal{D}}|\mathcal{D}|}} R'^{\frac{|\mathcal{D}|}{2}} (1+|\mathcal{D}|) \right] - \left(\frac{\sigma_{s,d}^2}{\sigma_{s,d}^2 - 2b_{\mathcal{D}}|\mathcal{D}|}\right)^{|\mathcal{D}|} e^{-\frac{R'}{\sigma_{s,d}^2}} \left(1 - \frac{\Gamma(|\mathcal{D}|, cR')}{(|\mathcal{D}|-1)!}\right) \quad \text{(A.1)}$$

$$\approx \frac{1}{(2b_{\mathcal{D}}|\mathcal{D}|)^{|\mathcal{D}|}(|\mathcal{D}|+1)!} R'^{\frac{|\mathcal{D}|}{2}} e^{-\frac{R'}{4b_{\mathcal{D}}|\mathcal{D}|}} \left[\frac{1}{2b_{\mathcal{D}}|\mathcal{D}|} R'^{\frac{|\mathcal{D}|}{2}+1} + (1+|\mathcal{D}|) e^{-\frac{R'}{4b_{\mathcal{D}}|\mathcal{D}|}} R'^{\frac{|\mathcal{D}|}{2}} \right] - \left(\frac{\sigma_{s,d}^2}{\sigma_{s,d}^2 - 2b_{\mathcal{D}}|\mathcal{D}|}\right)^{|\mathcal{D}|} e^{-\frac{R'}{\sigma_{s,d}^2}} \left(1 - \frac{\Gamma(|\mathcal{D}|, cR')}{(|\mathcal{D}|-1)!}\right)$$

$$= \left(\frac{R'}{2b_{\mathcal{D}}|\mathcal{D}|}\right)^{|\mathcal{D}|} \frac{1}{|\mathcal{D}|!} - \left(\frac{\sigma_{s,d}^2}{\sigma_{s,d}^2 - 2b_{\mathcal{D}}|\mathcal{D}|}\right)^{|\mathcal{D}|} e^{-\frac{R'}{\sigma_{s,d}^2}} \left(1 - \frac{\Gamma(|\mathcal{D}|, cR')}{(|\mathcal{D}|-1)!}\right). \quad \text{(A.2)}$$

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