Performance Analysis for Amplify-and-Forward Relay Selection with Outdated Channel Estimates

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Abstract—Performance evaluation by considering outdated channel estimates in cooperative communications systems is formulated, with only Amplify-and-Forward (AF) relaying mode being considered in this paper. The approximation of closed-form solution for the system analysis is derived. The wireless relay channels between different nodes (e.g., source to relay, relay to destination, or source to destination) are assumed to suffer from an independent and identically distributed (i.i.d.) Rayleigh fading, and the potential performance gain obtained through cooperation and relay selection is analyzed as well. In the presence of high-speed objects, autocorrelation Jakes’ Model is employed to formulate the wireless fading channels. Both theoretical analyses and simulation results indicate the validity of the proposed method in terms of both the outage probability and the symbol error probability (SEP). With channel state information being known at the source node or with the Doppler Shift being negligible, a best-relay selection scheme can be performed to optimize both the outage probability and SEP. Numerical results finally validate the proposed analyses.

Index Terms—Amplify-and-forward(AF), Relay, cooperation, outage probability, symbol error probability, outdated channel state information.

I. INTRODUCTION

Cooperative communication, regarded as a virtual Multiple-input Multiple-output (MIMO) system, is beneficial to improving the diversity order of wireless channels [1]. A deep fading due to the single-point failure can be mitigated by employing cooperative relays, and the spectral efficiency can also be improved through a relaying transmission. Among the existing relaying modes, the most well-known ones should be amplify-and-forward (AF) and decode-and-forward (DF) modes [2].

As compared to the single-relay model, employing multiple relays could further increase the diversity order. However, more bandwidth is consumed in the latter to convey the same message, if orthogonal channels among relays are required. In view of the scarcity of the spectrum resource, the idea of relay selection was introduced to solve the challenges aforementioned [3]–[5]. Many existed works on this topic have been focused on the cooperative scenarios that with a perfect channel state information (CSI) being available [6]–[8]. However, in the realistic case, an outdated CSI is usually obtained due to the effects of Doppler frequency shift and the feedback delay. In this case, the actual CSI of data transmission is different from that of the estimated value, and the diversity order may be deceased due to the imperfect CSI. The impact of outdated CSI on the degrees of freedom is studied in [9]. However, most of these existing works deal with the case of outdated CSI being available in MIMO (see [10] and reference therein). In cooperative communication, the relay selection is dependent on the outdated CSI. The DF of opportunistic relay selection with outdate CSI is studied in [11], [12]. As compared to it, the AF relaying system is no longer linear due to the convolution operation being performed on the concatenation of mutli-hop channels, and it is more cumbersome in AF mode to derive the closed-form solution than that in DF mode.

There have been several works in the literature dealing with the AF relay selection with outdated channel estimates, most of which consider the case of direct source-to-destination ($S \rightarrow D$) links being unavailable (see, e.g., [13]–[17]). In [13] performance analysis for AF opportunistic relay over Rayleigh fading channels is studied in depth, and the closed form expressions of average spectral efficiency for that scenario is derived, with the impact of outdated CSI being analyzed. The discrete-rate adaptive modulation with constant-power and adaptive-rate transmission has also been considered in that paper. Assuming that the source to destination is in a deep fading and only the end-to-end links of source-relays-destination will be considered, the SEP and outage probability analysis for both the opportunistic selection and partial relay selection in the presence of outdated CSI is studied in (14), [15], and the closed-form expression is also derived. In [15], the scenarios of partial and opportunistic relay selection with fixed/variable AF gains is analyzed. The partial relay selection with outdated channel estimates is analyzed in [16], where both the fixed gain relaying and variable gain relaying has been discussed. In [17], a very good research on no-direct-source-to-destination link is carried out, and the exact closed-form expressions for both CDF and PDF of end-to-end SNR have been given out.

It worth pointing out that even with multiple parallel relays being employed, the $S \rightarrow D$ link can still be utilized to increase the system diversity order. Moreover, the effect of source-to-destination link cannot be neglected, especially in the underlay cognitive networks, where the secondary source user results in an interference to the primary user due to its relay transmission, and once the secondary source drops to
use the relays, it will have only the $S \rightarrow D$ link to use [18].

In this paper, both the partial relay selection and best relay selection with the outdated channel estimation are studied, with the $S \rightarrow D$ link being utilized. We assume that the average signal-to-noise ratio (SNR) of $S \rightarrow D$ links is different from that of the other relaying links. We provide closed-form expressions for the outage probability and SEP of the AF relaying selections (including the best relay selection and the partial relay selection). Numerical results validate the proposed analysis. It is also demonstrated that the performance of cooperative networks highly depends on the SNR of the $S \rightarrow D$ link. Besides, that performance of the relay selections is also highly impacted by the correlation between the actual CSI and its estimation value.

The remainder of this paper is organized as follows. Section II introduces the channel model with outdated CSI. Close-form expressions for outage probability with outdated CSI are derived in Section III, followed by close-form expressions for symbol error probability being derived in Section IV. Numerical results are given out by Section V. Finally, section VI concludes this paper.

Notation: $\mathbb{R}\{x\}$ and $\mathbb{S}\{x\}$ are the real and imaginary part of $x$, respectively. A circularly symmetric complex Gaussian random variable (RV) $w$ with mean 0 and variance $\sigma^2$ is denoted by $w \sim CN(0, \sigma^2)$. $\mathbb{E}\{x\}$ and $\text{Var}\{x\}$ are the mean and variance of $x$. $\gamma_{ab}$ is the instantaneous SNR of link $a \rightarrow b$. $f_X(.)$ and $F_X(.)$ are the random variable $X$’s probability density function (PDF) and cumulative distribution function (CDF), respectively. $M_X(s)$ denotes the Moment generation function (MGF) of RV $X$. $\otimes$ denotes the convolution operation.

II. OUTDATED CHANNEL STATE INFORMATION ESTIMATION MODEL

In this section, we consider two kinds of relays selection scheme (the partial relay selection and the best relay selection), and introduce the channel mode as follow. Furthermore, we will depict the work mode of the two kinds of schemes, respectively.

A. Channel Mode

Considering a scenario of the single cooperating network with source, relay and destination nodes being represented as $S$, $R_i$, and $D$, respectively (please see Fig. 1), the wireless channels for source-relay, relay-destination and source-destination are represented as $h_{SR_i}$, $h_{R_iD}$ and $h_{SD}$, respectively, where $i \in \{1, ..., N\}$. Without loss of generality, we assume that $\mathbb{R}\{h_{ab}\}$ and $\mathbb{S}\{h_{ab}\}$ are independent and identically distributed (i.i.d.) Gaussian random variables with zero means and a common variance $\sigma^2/2$ according to the Rayleigh distribution, where $\sigma^2$ stands for the channel variance with $a,b \in \{S, R_1, ..., R_N, D\}$. Therefore, we have $h_{ab} \sim CN(0, \sigma^2)$. In brief, we assume that all nodes transmit with unit power and the spectral density of additive white Gaussian noise (AWGN) terms is $N_0$, and, therefore, the effective Signal-to-Noise (SNR) is given by

$$\gamma_{ab} = \frac{|h_{ab}|^2}{N_0} = \frac{\mathbb{R}\{h_{ab}\}^2}{N_0} + \frac{\mathbb{S}\{h_{ab}\}^2}{N_0}.$$  From [19, Eq.(2.3-27)], $\gamma_{ab}$ can be formulated as a chi-square $(\chi^2)$ random variable with 2 degrees of freedom, and the probability density function (PDF) of $\gamma_{ab}$ is given by $f_{\gamma_{ab}}(\gamma) = \frac{1}{\sqrt{\pi \delta_x}} e^{-\frac{\delta_x}{\pi \delta_x} \gamma}$, where $\hat{\gamma}_{ab} = \mathbb{E}\{\gamma_{ab}\}$ denotes the expectation of $\gamma_{ab}$.

In the presence of outdated information, the imperfect CSI is modelled as [14, Eq.(1)]. $\hat{h}_{ab} = \mu h_{ab} + \sqrt{1-\mu^2} w_{ab}$, where $\mu \in \{1, 2, 3\}$, and $h_{ab}$ denotes the estimation of $a \rightarrow b$ channel at the time of $t$. Jake’s autocorrelation mode, as given by [17, Eq.(3)], is used in this paper. $\rho_1$, $\rho_2$ and $\rho_3$ stand for the correlation coefficients between the actual value and the estimation of $h_{SR_i}$, $h_{R_iD}$ and $h_{SD}$, respectively, with $\rho_1 = J_0(2\pi f_{\text{ab}})$ and $J_0(.)$ denoting the zeroth Bessel function of the first kind. $f_{\text{ab}}$ here stands for the maximum Doppler Shift on the $a \rightarrow b$ link due to the relative motion between two nodes. $w_{ab}$ is a circularly symmetric complex Gaussian RVs with variance of $\sigma^2$.

Once the estimation of outdated CSI (i.e., $\hat{h}_{ab}$ for the link of $a \rightarrow b$) is available, the SNR of that link can be represented as $\gamma_{ab} = |\hat{h}_{ab}|^2/N_0$. Based on it, the performance of relay selections will be analyzed in the following subsections.

1) Partial Relay Selection: As compared to the best relay selection, the feedback information required by partial relay selection can be decreased considerably. In this scheme, only the CSI of $S \rightarrow R_i$ or $R_i \rightarrow D$ link is required the central unit, and the relay $k$ is selected, subject to [17, Eq.(8)].

$$k = \begin{cases} \arg\max_i (\hat{\gamma}_{SR_i}) , & h_{SR_i} \text{ is known} \\ \arg\max_i (\hat{\gamma}_{R_iD}) , & h_{R_iD} \text{ is known}. \end{cases} \quad (1)$$

2) Best Relay Selection: This scheme requires the outdated CSI of all the links to be known. A central unit is needed to perform the control of relay selection activity. With this information being available, the best relay will be chosen. Best relay selection is performed as follows. In the first step, the central unit compares the estimated SNR of $(S \rightarrow R_i)$ and $(R_i \rightarrow D)$ links for each candidate relay in the presence of outdated CSI (as performed in [17, Eq.(6)]), i.e.,

$$\hat{\gamma}_i = \min (\hat{\gamma}_{SR_i}, \hat{\gamma}_{R_iD}). \quad (2)$$

An upper-bound SNR of the $S \rightarrow R_i \rightarrow D$ link is exhibited in (2). The optimum relay $k$ is therefore chosen as

$$k = \arg\max (\hat{\gamma}_i). \quad (3)$$

The optimum relay in terms of SNR optimization can be obtained, however, at the cost of a heavily increased feedback information.

III. OUTAGE PROBABILITY ANALYSIS

In this section, the approximations of closed-form expressions for the outage probability in the relay selection are
Likewise, the outage probability can be expressed as \( F_\gamma (\gamma_T) = \int_{\gamma_T}^{\infty} f_\gamma(x) dx \), where \( \gamma \) stands for the SNR at destination terminal after maximal ratio combining (MRC). Like in [21, Eq.(2)], \( \gamma = \gamma_{SD} + \gamma_k \) and \( \gamma_k = \frac{\gamma_{SR} \gamma_{RD} D}{1 + \gamma_{SR} \gamma_{RD} D} \), \( \gamma_k \) stands for the SNR of end-to-end \( S \rightarrow R_k \rightarrow D \) link.

### A. Partial Relay Selection

In this scheme, in order to obtain the outage probability, the PDF of \( \gamma \) is first derived as follow. Since \( \gamma_{SD} \) and \( \gamma_k \) are independent, the PDF of \( \gamma \) can be represented as \( f_\gamma(x) = f_{\gamma_{SD}}(x) \otimes f_{\gamma_k}(x) \).

Evidently, the convolution operation is cumbersome. In view of Laplace transform changes the convolution to product operation for the nonnegative value random variables, i.e.,

\[
M_\gamma (s) = M_{\gamma_{SD}} (s)M_{\gamma_k} (s),
\]

(4)

According to (1), in [17, Eq.(17)], the CDF of \( \gamma_k \) is given by

\[
F_{\gamma_k}(\gamma) = 1 - 2N \sum_{m=0}^{N-1} [(-1)^m \binom{N-1}{m}] \times \frac{K_1 \left( \frac{2(m + 1)\gamma + 1}{\gamma_{RD} \gamma_{SR} [1 + m(1 - \rho_1^2)]} \right)}{\sqrt{(m + 1)\gamma_{RD} \gamma_{SR} [1 + m(1 - \rho_1^2)]}} \gamma,
\]

(5)

where \( K_1(x) \) is the first order modified Bessel function of the second kind. We obtain an approximation expression for the CDF by using \( K_1(x) = \frac{1}{x} \) [23, Eq.9.6.9)] in (5). After differentiation, we obtain

\[
f_{\gamma_k}(x) = A_1 e^{-B_1 x},
\]

(6)

where \( A_1 \) and \( B_1 \) are defined as

\[
A_1 = N \sum_{m=0}^{N-1} (-1)^m \frac{\binom{N-1}{m} m + 1}{m + 1} \left( \frac{m + 1}{m(1 - \rho_1^2)} \right) \frac{1}{\gamma_{SD}} + \frac{1}{\gamma_{RD}} \gamma,
\]

(7)

and

\[
B_1 = \frac{m + 1}{m(1 - \rho_1^2)} \frac{1}{\gamma_{SD}} + \frac{1}{\gamma_{RD}},
\]

(8)

respectively. Since the links are i.i.d., the average SNR in all \( S \rightarrow R_k \) and \( R_k \rightarrow D \) links are the same as \( \gamma_{SD} \), and \( \gamma_{RD} \), respectively. The Laplace transform of (6) is then given by

\[
M_{\gamma_k} (s) = A_1 \frac{1}{s + B_1}.
\]

(9)

Likewise, the PDF of \( \gamma_{SD} \) is given by

\[
f_{\gamma_{SD}}(x) = \frac{1}{\gamma_{SD}} e^{-\frac{x}{\gamma_{SD}}},
\]

which leads to the MGF of \( \gamma_{SD} \) being derived as

\[
M_{\gamma_{SD}} (s) = \frac{1}{s + 1/\gamma_{SD}}.
\]

(10)

Equation (4) is therefore rewritten as

\[
M_\gamma (s) = A_1 \frac{1}{s + B_1} \frac{1/\gamma_{SD}}{s + 1/\gamma_{SD}}.
\]

(11)

After performing inverse Laplace transform on (11), the PDF of \( \gamma \) is derived as

\[
f_\gamma(x) = A_1 \frac{1}{B_1} \frac{1}{\gamma_{SD}} - 1 \left\{ e^{-x/\gamma_{SD}} - e^{-B_1 x} \right\},
\]

(12)

which leads to the CDF of \( \gamma \) as

\[
F_\gamma(x) = A_1 \left( \frac{1}{B_1} + \frac{1}{\gamma_{SD} - 1/\gamma_{SD}} \frac{e^{-x/\gamma_{SD}} - e^{-B_1 x}}{B_1 - 1/\gamma_{SD}} \right).
\]

(13)

When \( x = \gamma_T \), (13) denoted the outage probability of the partial relay selection.

### B. Best Relay Selection

According to (2) and (3), we derive the formula of CDF like in [17, Eq.(12)], the CDF of \( \gamma_k \) is derived as

\[
F_{\gamma_k}(x) = \begin{cases} \left( \frac{2x}{\gamma} \right)^N & \text{if } \rho_1 = \rho_2 = 1 \\ A_2 \frac{x}{\gamma} + B_2 \frac{x}{\gamma} & \text{if } \rho_1 < 1 \text{ or } \rho_2 < 1, \end{cases}
\]

(14)

where assuming that \( \gamma_{SR} = \gamma_{RD} = \gamma \) for simplify, and \( A_2 \) and \( B_2 \) are SNR-independent constants and can be defined as

\[
A_2 = N \sum_{n=0}^{N-1} \frac{(-1)^n (N-1)!}{2n + 1} \left( 1 + \frac{2n}{\gamma \left( 1, 1, n, \rho_1 \right)} \right)
\]

(15)

and

\[
B_2 = N^2 \sum_{n=0}^{N-1} \sum_{m=0}^{N-1} \frac{(-1)^{n+m} (N-1)! (N-1)! (2 - \rho_1^2)}{m + 1} \left( 1 + \frac{2n}{\gamma \left( 1, 1, n, \rho_1 \right)} \right)
\]

(16)

respectively, and \( \gamma(x, y, n, \rho) = x \left[ 1 + n(1 - \rho^2) \right] + y(n + 1)(1 - \rho^2) \).

The PDF of \( \gamma_k \) can be derived from (14) as

\[
f_{\gamma_k}(x) = \begin{cases} N \left( \frac{2}{\gamma} \right)^N x^{N-1} & \text{if } \rho_1 = \rho_2 = 1 \\ A_2 \frac{x}{\gamma} + B_2 \frac{x}{\gamma} & \text{if } \rho_1 < 1 \text{ or } \rho_2 < 1. \end{cases}
\]

(17)

After performing Laplace transform on (17), the MGF of \( \gamma_k \) can be derived as

\[
M_{\gamma_k} (s) = \left( \frac{2}{\gamma} \right)^N \frac{(N-1)!}{s^{N}} \left( 1 + \frac{A_2 \frac{1}{\gamma} + B_2 \frac{1}{\gamma}}{s} \right),
\]

(18)

By substituting (18) and (10) into (4), we have

\[
M_\gamma(s) = \begin{cases} \left( \frac{2N}{\gamma} \right)^N \frac{(N-1)!}{s^{N}} \frac{1/\gamma_{SD}}{s + 1/\gamma_{SD}} & \text{if } \rho_1 = \rho_2 = 1 \\ \left( A_2 \frac{1}{\gamma} + B_2 \frac{1}{\gamma} \right) \frac{1/\gamma_{SD}}{s(s + 1/\gamma_{SD})} & \text{if } \rho_1 < 1 \text{ or } \rho_2 < 1. \end{cases}
\]

(19)
After performing inverse Laplace transform on (19), and simplifying through [24, eq.(3.461.2)], the PDF of $\gamma$ can be finally derived as

$$f_\gamma(x) = \begin{cases} N \left( \frac{2}{\gamma} \right)^N (-\bar{\gamma}_{SD})^{N-1} e^{-x/\bar{\gamma}_{SD}} & \text{if } \rho_1 = \rho_2 = 1 \\
\times \left( \Gamma \left( N, -\frac{x}{\bar{\gamma}_{SD}} \right) - \Gamma(N, 0) \right) & \text{if } \rho_1 < 1 \text{ or } \rho_2 < 1. \\
\left( A_2 \frac{1}{\gamma} + B_2 \frac{1}{\gamma} \right) \left( 1 - e^{-x/\bar{\gamma}_{SD}} \right) & \text{if } \rho_1 < 1 \text{ or } \rho_2 < 1. \end{cases}$$  \hspace{1cm} (20)

The CDF of $\gamma$ then derived as

$$F_\gamma(x) = \int_0^\infty \left( N \left( \frac{2}{\gamma} \right)^N (-\bar{\gamma}_{SD})^{N-1} e^{-x/\bar{\gamma}_{SD}} \times \left( \Gamma \left( N, -\frac{x}{\bar{\gamma}_{SD}} \right) - \Gamma(N, 0) \right) \right) \right. dx$$

$$\left. \left( A_2 \frac{1}{\gamma} + B_2 \frac{1}{\gamma} \right) \left( 1 - e^{-x/\bar{\gamma}_{SD}} \right) \right)$$

$$\text{if } \rho_1 < 1 \text{ or } \rho_2 < 1. \hspace{1cm} (21)$$

When $x = \gamma_T$, (21) denoted the outage probability of the best relay selection.

IV. Symbol Error Probability Analysis

In this section, we derived the approximation of close-form expressions for the SEP of both best relay selection and partial relay selection schemes. Like in [19, Eq.(2.3-10)] [21, Eq.(3)], the SEP can be represented as

$$P_e = \mathbb{E}_\gamma \left\{ B Q \left( \sqrt{\bar{\gamma}_T} \right) \right\} = \frac{B}{\sqrt{2\pi}} \int_0^\infty F_\gamma \left( \frac{x^2}{\bar{\beta}} \right) e^{-x^2/2} dx,$$

$$\text{where } B \text{ and } \beta \text{ are modulation specified constants, and } Q(.).$$

is the Gaussian Q-function $(Q(x) = (1/\sqrt{2\pi}) \int_x^\infty e^{-t^2/2} dt)$. In the following subsections, the SEP for both relay selection schemes will be derived.

A. Partial relay selection

In this case, by substituting (13) into (22) using [24, eq.(3.461.2)], we have

$$P_e = A_1 \frac{B}{2} \frac{1}{B_1} + \frac{1/\bar{\gamma}_{SD}}{B_1 (B_1 - 1/\bar{\gamma}_{SD})^{\beta/\beta + 2B_1}} \sqrt{\frac{\beta}{\beta + 2B_1}}$$

$$- \frac{1}{(B_1 - 1/\bar{\gamma}_{SD})^{\beta/\beta + 2/\bar{\gamma}_{SD}}}.$$  \hspace{1cm} (23)

B. Best Relay Selection

In this case, if $\rho_1 = \rho_2 = 1$, (22) can be rewritten as

$$P_e = B \int_0^\infty Q \left( \sqrt{\bar{\beta}} \right) \left( N \left( \frac{2}{\gamma} \right)^N (-\bar{\gamma}_{SD})^{N-1} e^{-\gamma/\bar{\gamma}_{SD}} \right.$$  \hspace{1cm} (24)

$$\left. \times \left( \Gamma \left( N, -\frac{\gamma}{\bar{\gamma}_{SD}} \right) - \Gamma(N, 0) \right) d\gamma. \right)$$

If $\rho_1 < 1$ or $\rho_2 < 1$, by substituting (21) into (22), and simplifying through [24, eq.(3.461.2)], it yields

$$P_e = B \left( \frac{A_2 + B_2}{\gamma} \right) \left( 1 + \frac{\bar{\gamma}_{SD}}{\beta \bar{\gamma}_{SD}} \left( \sqrt{\frac{\beta \bar{\gamma}_{SD}}{\beta + 2\bar{\gamma}_{SD}} - 1} \right) \right).$$

(25)

V. Numerical Results

System performance of the proposed models is evaluated in this section. In the proposed simulation, the constant $\beta$ depends on the type of modulation (e.g., $\beta = 2$, $B = 1$ for Binary phase shift keying (BPSK)). Maximum ratio combiner (MRC) is applied to multiple copies of received signals at the destination.

Both the source and relays are assumed to have unit signal power, and the channel is defined as $h_{ab} \sim CN(0, 1)$. The gain of relay is assumed to be adaptively variant. For different relays, the average SNR of the $S \rightarrow R_i \rightarrow D$ links is assumed to be different. To simplify the analysis, a symmetric scenario of i.i.d. fading is assumed, i.e., $\bar{\gamma}_{SR} = \bar{\gamma}_{RD}$, parameter $\rho_1$ could be changed in the simulation.

Fig. 2 and Fig. 3 illustrate the outage probabilities of partial relay selection and best relay selection, respectively, with $N = 3$ and $\gamma_T = 1$ being assumed. In the upper group curves, the $S \rightarrow D$ links is assumed to be in a deep fading, and the source can communicate with destination only via the relays. In the lower group curves, when $\bar{\gamma}_{SD} = \bar{\gamma}_{SR} = \bar{\gamma}_{RD}$ is assumed, the performance of the relay selection can be significantly increased, if $S \rightarrow D$ link is utilized. It is depicted in Fig. 3 that the slope of all curves is identical for $\rho_1 = 0.5$ and $\rho_1 = 0.707$, while the slope becomes steep when $\rho_1 = 2$. It’s also shown that the outage probability of networks with $S \rightarrow D$ links ($\bar{\gamma}_{SD} = \bar{\gamma}_{SR} = \bar{\gamma}_{RD}$) being utilized is significantly lower than that without using $S \rightarrow D$ links ($\bar{\gamma}_{SD} \rightarrow 0$).

Fig. 4 and Fig. 5 depict the SEP performance of partial and best relay selections, respectively, with $\bar{\gamma}_{SR} = \bar{\gamma}_{RD}$ and $N = 3$ being considered. The gap between different correlation coefficient is a constant function of $\bar{\gamma}_{SD}$, because the PDF of $\bar{\gamma}_{SD}$ is uncorrelated with channel correlation coefficient.

Fig. 6 and Fig. 7 show the SEP parameterized by $\rho_1$. The slope of the curve is change a little when $\rho_1$ is relatively small, but will change significantly as $\rho_1$ increases to a certain value, because obtaining the perfect CSI can decrease SEP. The comparison of Fig. 6 and Fig. 7 shows that the slope changes more obviously when $\rho_1$ approaches 1. This result also indicates that when the perfect CSI is obtained, the
performance of best relay selection is more superior to that of the partial relay selection.

In Fig. 8 and Fig. 9, as the increases of the number of relays, the opportunity of selecting the optimal relay is increased accordingly and, therefore, the SEP decreases as the increases of relays. However, this performance improvement may be degraded by the imperfect CSI.

Fig. 10 shows the SEP of both relay selections, and it’s shown that with the perfect CSI being assumed, best relay selection has an advantage over the partial relay selection. The outage probability of the best relay selection is obviously lower than that of the partial relay selection, as illustrated in Fig. 11.

VI. CONCLUSION

The cooperative communications with optimal relay selection was studied, and the source-to-destination link was utilized. The approximation of closed-form expressions for the outage probability and SEP were derived, and those theoretical analysis was verified through simulation. It was proved that in the presence of an imperfect CSI, the performance improvement brought by the $S \rightarrow D$ link is far beyond the increases of diversity order. The partial relay selection scheme may also outperform the best relay selection scheme in the presence of imperfect CSI. However, the best selection scheme will always hold its advantage over the partial selection scheme if the SNR of the relay links is relative high and a perfect CSI is assumed at the same time.

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Fig. 4. SEP of the partial relay selection versus the average SNR of the $S \to R_i$ and $R_i \to D$ links, for BPSK modulation, $\gamma_{SR} = \gamma_{RD}$, and $N = 3$.

Fig. 5. SEP of the best relay selection versus the average SNR of the $S \to R_i$ and $R_i \to D$ links, for BPSK modulation, $\gamma_{SR} = \gamma_{RD}$, $\rho_1 = \rho_2$, and $N = 3$.

Fig. 6. SEP of the partial relay selection versus $\rho_1$, for BPSK modulation, $\gamma_{SR} = \gamma_{RD}$, and $N = 3$.

Fig. 7. SEP of the best relay selection versus $\rho_1$, for BPSK modulation, $\rho_1 = \rho_2$, $\gamma_{SR} = \gamma_{RD}$, and $N = 3$.


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