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Cooperative Communications with Partial Channel State Information: When to Cooperate?

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Abstract— **In this paper we propose a new cooperative protocol, which takes into consideration the partial channel state information (CSI) available at the source. With such protocol a significant improvement in the transmission rate can be achieved in decode-and-forward cooperative transmission, while guaranteeing full diversity order. We derive closed-form expressions for the transmission rate and the symbol error rate (SER) for the M-PSK and the M-QAM signalling. Moreover, we consider two optimization metrics in the protocol design to enhance the system performance; the first is based on minimizing the SER only, while the second is based on minimizing a joint function of both the SER and the transmission rate. Finally, the obtained analytical results are verified through computer simulations.**

I. INTRODUCTION

Recently, cooperative communication for wireless networks has gained much interest due to its ability to mitigate fading in wireless networks through achieving spatial diversity, while resolving the difficulties of installing multiple antennas on small communication terminals. In cooperative communication relays are assigned to help a source in forwarding its information to its destination. Thus, the destination receives several replicas of the same information via independent channels. In other words, the source and the relays behave as a virtual antenna array.

Various cooperative diversity protocols were proposed and analyzed in [1]-[6]. In [1] Laneman *et al.* described various techniques of cooperative communication such as decode-and-forward and amplify-and-forward. In decode-and-forward cooperative protocol each relay decodes the information received from the source, re-encodes it, then forwards it to the destination. In amplify-and-forward cooperative protocol each relay simply forwards the received information after amplifying it. In [2] a distributed space-time coded cooperative scheme was proposed by Laneman *et al.*, where the relays decode the received symbols from the source and utilize a distributed space-time code. In [3] and [4] Sendonaris *et al.* introduced user cooperation diversity. A two-user CDMA cooperative system, where both users are active and use orthogonal codes, was implemented in this two-part series. The symbol error rate (SER) performance analysis was provided for the single-relay and multi-node decode-and-forward schemes in [5] and [6], respectively. It was shown that diversity order of $N+1$ is achieved, where N is the number of helping relays. However, the data rate drops to $\frac{1}{N+1}$ symbols per channel use (SPCU), as $N+1$ phases are required to complete the transmission of one symbol.

In this paper we propose a cooperative protocol when partial channel state information (CSI) is available at the source side. The main objective of this scheme is to achieve higher data rate while guaranteeing the same diversity order as that of the conventional cooperative scheme. The rational behind this protocol is that no need for the relay to forward the information if the direct link, between the source and the destination, is of high quality. In particular, we answer the question: *"When to cooperate?"*. The source needs to decide when to cooperate, by taking the ratio between the source-destination channel gain and the source-relay channel gain, and comparing it to a threshold, which is referred to as the *cooperation threshold*. we derive closed-form expressions for both the transmission rate and the SER for M-PSK and M-QAM signalling. Moreover, we present two optimization metrics for optimum choices of the cooperation threshold and the power allocation. The first is based on optimizing the SER only, while the second considers the ratio between the SER and the transmission rate.

The rest of this paper is organized as follows. In section II we present the system model for decode-and-forward cooperative wireless network. In section III closed-form expressions for both the SER and the transmission rate are derived. Section IV presents the two optimization metrics and the simulation results. Finally, section V concludes the paper.

II. SYSTEM MODEL

In this section we present the system model and the transmission protocol of the single-relay decode-and-forward cooperative communication. The communication system, as shown

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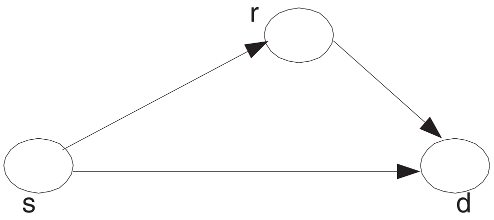

Fig. 1. Single-relay cooperative communication system.

in Fig. 1, consists of a source s and its destination d. In addition, a relay r is used to decode and forward the source's information to its destination, if necessary. Let $h_{s,d}, h_{s,r}$, and $h_{r,d}$ represent the source-destination, source-relay, and relay-destination channel coefficients, respectively. Flat quasi-static fading channels are considered, hence, the channel coefficients are assumed to be constant during a complete frame, and may vary from a frame to another. Moreover, it is assumed that the channels are reciprocal as in the Time Division Duplex (TDD) mode, hence, the source knows its source-relay and source-destination instantaneous channels gain. In other words, the source has partial transmit CSI. Let $\beta_{i,j} = |h_{i,j}|^2$ represents the source-relay, source-destination, and relay-destination channels gain.

The transmission protocol can be described as follows. In the first phase the source computes the ratio $\beta_{s,d}$ / $\beta_{s,r}$ and compares it to the cooperation threshold α. If $\frac{\beta_{s,d}}{\beta_{s,r}} \geq \alpha$, then the source decides to employ direct transmission and the received symbol at the destination can be modeled as

$$y^{\phi}_{s,d} = \sqrt{P}\, h_{s,d}\, x + \eta_{s,d}\ , \tag{1}$$

where P is the total transmitted power, x is the transmitted symbol, $\eta_{s,d}$ is an additive noise, and $\phi = \{\ \beta_{s,d} \geq \alpha\ \beta_{s,r}\ \}$ denotes the direct-transmission event. This mode is denoted by the *direct-transmission* mode.

If $\frac{\beta_{s,d}}{\beta_{s,r}} < \alpha$, then the source employs the relay to transmit its information as in the conventional decode-and-forward cooperative protocol [5]. This mode is denoted by the *relay-cooperation* mode and can be described as follows. In the first phase the source broadcasts its symbol to the relay and the destination. The received symbols at the destination and the relay can be modeled as

$$\begin{aligned} y^{\phi^c}_{s,d} &= \sqrt{P_1}\, h_{s,d}\, x + \eta_{s,d}, \\ y^{\phi^c}_{s,r} &= \sqrt{P_1}\, h_{s,r}\, x + \eta_{s,r}, \end{aligned} \tag{2}$$

where P_1 is the source transmitted power, $\eta_{s,r}$ is an additive noise, and ϕ^c is the complement of the event ϕ. If the relay decodes the received symbol correctly, it re-transmits it in the second phase, otherwise, it remains idle. In the relay-cooperation mode the relay decides whether to forward the received information or not according to the quality of the received signal. For mathematical tractability we assume that the relay can tell whether the information is decoded correctly or not[2]. Thus, the received symbol at the destination is written as

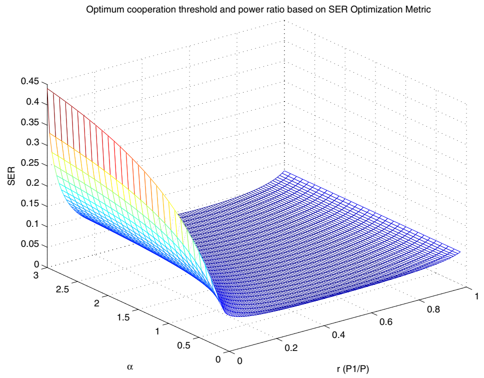

Fig. 2. Optimum cooperation threshold and power ratio based on SER optimization metric with QPSK modulation at SNR=10 dB and unity channel-variances, resulting in $\alpha_o = 1.49$ and $r_o = 0.614$.

$$y^{\phi^c}_{r,d} = \sqrt{\tilde{P}_2}\, h_{r,d}\, x + \eta_{r,d}, \tag{3}$$

where $\tilde{P}_2 = P_2$ if the relay decodes the symbol correctly, otherwise, $\tilde{P}_2 = 0$, and $\eta_{r,d}$ is an additive noise. Power is distributed between the source and the relay subject to the power constraint $P_1 + P_2 = P$.

The channel coefficients $h_{s,d}, h_{s,r}$, and $h_{r,d}$ are modeled as zero-mean complex Gaussian random variables with variances $\delta^2_{s,d}$, $\delta^2_{s,r}$, and $\delta^2_{r,d}$, respectively. The noise terms $\eta_{s,d}, \eta_{s,r}$, and $\eta_{r,d}$ are modeled as zero-mean, complex Gaussian random variables with equal variance N_0. We assume that the source sends its decision, whether to use the direct-transmission or the relay-cooperation mode, through a control channel to the destination and the relay. In addition, we assume that the channels vary slowly, so that the overhead resulting from the transmission of the source's decision is negligible. Considering this system model we derive closed-form expressions for both the transmission rate and the SER in the following section.

III. PERFORMANCE ANALYSIS

In this section we obtain the probability of the direct-transmission and the relay-cooperation modes. Then, we determine the transmission rate and the SER. Since $\beta_{i,j}$ is exponentially distributed with parameter $1/\delta^2_{i,j}$ [7], thus the probability of direct-transmission mode can be given by

$$Pr(\phi) = Pr(\beta_{s,d} \geq \alpha \beta_{s,r}) = \frac{\delta^2_{s,d}}{\delta^2_{s,d} + \alpha\ \delta^2_{s,r}}, \tag{4}$$

and the probability of relay-cooperation mode is

$$Pr(\phi^c) = 1 - Pr(\phi) = \frac{\alpha\ \delta^2_{s,r}}{\delta^2_{s,d} + \alpha\ \delta^2_{s,r}}. \tag{5}$$

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[2] Practically, this can be done at the relay by applying a simple SNR threshold on the received data. Although, it can lead to some error propagation, but for practical ranges of operating SNR the event of error propagation can be assumed negligible.

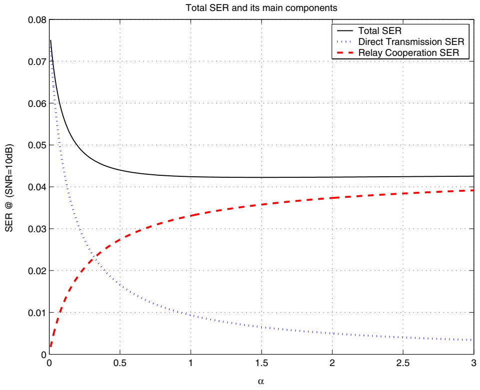

Fig. 3. Total SER and its two components with QPSK modulation at SNR=10 dB, $r_o = 0.614$, and unity channel-variances.

Since the data rate of the direct-transmission mode is 1 SPCU and that of the relay-cooperation mode is 1/2 SPCU, thus the average data rate can be written as

$$R = Pr(\phi) + \frac{1}{2}\, Pr(\phi^c) = \frac{2\,\delta_{s,d}^2 + \alpha\,\delta_{s,r}^2}{2\,\delta_{s,d}^2 + 2\,\alpha\,\delta_{s,r}^2}\,. \qquad (6)$$

If $\delta_{s,d}^2 \gg \delta_{s,r}^2$, then $R = 1$ SPCU, i.e. direct-transmission mode is always chosen. On the other hand, conventional cooperative protocol [5] will be dominant if $\delta_{s,d}^2 \ll \delta_{s,r}^2$, which results in $R = \frac{1}{2}$ SPCU.

The total probability of error can be written as

$$Pr(e) = Pr(e/\phi)\cdot Pr(\phi) + Pr(e/\phi^c)\cdot Pr(\phi^c)\ , \qquad (7)$$

where $Pr(e/\phi)\cdot Pr(\phi)$ represents the SER of the direct-transmission mode and $Pr(e/\phi^c)\cdot Pr(\phi^c)$ represents the relay-cooperation mode SER. For the direct-transmission mode the instantaneous signal-to-noise ratio (SNR) of the received signal is given by

$$\gamma^{\phi} = \frac{P\beta_{s,d}}{N_0}. \qquad (8)$$

Using M-PSK modulation the conditional direct-transmission SER can be written as given in [8] by

$$Pr(e/\phi, \beta_{s,d}) = \Psi(\gamma^{\phi})\ , \qquad (9)$$

where $\Psi(\gamma) = \frac{1}{\pi}\int_0^{\frac{(M-1)\pi}{M}} \exp(-\frac{b\,\gamma}{\sin^2\theta})\ d\theta$ and $b = \sin^2(\pi/M)$. By averaging (9) over $\beta_{s,d}$ we obtain the direct-transmission SER as

$$\begin{aligned} Pr(e/\phi)\ Pr(\phi) &= F_1\Big(1 + \frac{bP\delta_{s,d}^2}{N_0 \sin^2\theta}\Big) \\ &- F_1\Big(1 + \frac{\delta_{s,d}^2}{\alpha\delta_{s,r}^2} + \frac{bP\delta_{s,d}^2}{N_0\sin^2\theta}\Big), \end{aligned} \qquad (10)$$

where

$$F_1\Big(x(\theta)\Big) = \frac{1}{\pi}\int_0^{\frac{(M-1)\pi}{M}} \frac{1}{x(\theta)}d\theta. \qquad (11)$$

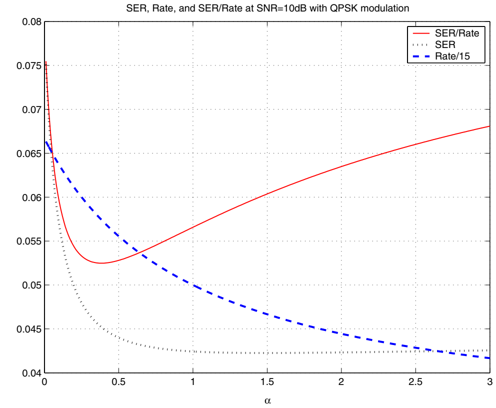

Fig. 4. SER, scaled version of the rate, and SER/rate with QPSK modulation at SNR=10 dB, $r_o = 0.614$, and unity channel-variances.

For the relay-cooperation mode maximum ratio combining (MRC) [9] is applied at the destination. The output of the MRC can be written as

$$y^{\phi^c} = \frac{\sqrt{P_1}h_{s,d}^*}{N_0}y_{s,d}^{\phi^c} + \frac{\sqrt{\tilde{P}_2}h_{r,d}^*}{N_0}y_{r,d}^{\phi^c}. \qquad (12)$$

The instantaneous SNR of the MRC output can be written as

$$\gamma^{\phi^c} = \frac{P_1\beta_{s,d} + \tilde{P}_2\beta_{r,d}}{N_0}. \qquad (13)$$

The conditional SER of the relay-cooperation mode is given in [5] by

$$\begin{aligned} Pr(e/\phi^c, \beta_{s,d}, \beta_{s,r}, \beta_{r,d}) &= \Psi(\gamma^{\phi^c})|_{\tilde{P}_2=0}\Psi(\frac{P_1\beta_{s,r}}{N_0}) \\ &+\Psi(\gamma^{\phi^c})|_{\tilde{P}_2=P_2}\big(1 - \Psi(\frac{P_1\beta_{s,r}}{N_0})\big)\ . \end{aligned} \qquad (14)$$

By averaging (14) over the exponentially distributed random variables $\beta_{s,d}, \beta_{s,r}$, and $\beta_{r,d}$ we get

$$\begin{aligned} Pr(e/\phi^c)Pr(\phi^c) &= F_2\Big(\frac{1}{\pi^2}, P_1, 0, \frac{(M-1)\pi}{M}, \frac{(M-1)\pi}{M}\Big) \\ &+ F_1\Big(\big(1 + \frac{\delta_{s,d}^2}{\alpha\delta_{s,r}^2} + \frac{bP_1\delta_{s,d}^2}{N_0\sin^2\theta}\big)\big(1 + \frac{bP_2\delta_{r,d}^2}{N_0\sin^2\theta}\big)\Big) \\ &- F_2\Big(\frac{1}{\pi^2}, P_1, P_2, \frac{(M-1)\pi}{M}, \frac{(M-1)\pi}{M}\Big), \end{aligned} \qquad (15)$$

where

$$F_2\big(C, P_1, P_2, \theta_1, \theta_2\big) = C\int_0^{\theta_1}\int_0^{\theta_2} \frac{1}{\big(1 + \frac{b\ P_1\delta_{s,r}^2}{N_0\sin^2\theta_2}\big)} \frac{d\theta_2\ d\theta_1}{\big(1 + \frac{\delta_{s,d}^2}{\alpha\delta_{s,r}^2} + \frac{b\ P_1\delta_{s,d}^2}{N_0}(\frac{1}{\sin^2\theta_1} + \frac{1}{\alpha\sin^2\theta_2})\big)\big(1 + \frac{b\ P_2\delta_{r,d}^2}{N_0\sin^2\theta_1}\big)}. \qquad (16)$$

Thus, the total SER expression for the M-PSK signalling is the summation of (10) and (15) as in (7).

Similarly, we provide the SER performance for M-QAM modulation ($M = 2^k$ with k even). The proof has been omitted

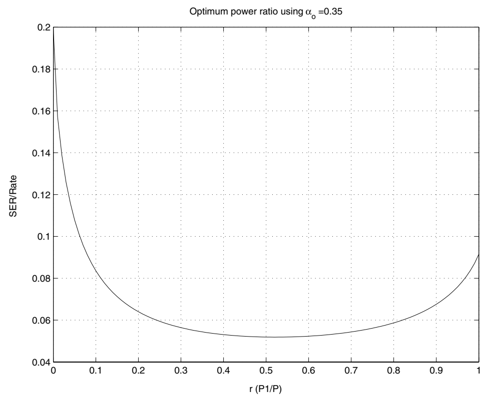

Fig. 5. Optimum power ratio of the SER/R-optimized scheme at $\alpha_o = 0.35$, SNR=10 dB, and unity channel-variances, resulting in $r_o = 0.52$.

for lack of space. The direct-transmission SER can be written as

$$Pr(e/\phi)Pr(\phi)|_{QAM} = F_3(1+\frac{bP\delta^2_{s,d}}{N_0\sin^2\theta}) - F_3(1+\frac{\delta^2_{s,d}}{\alpha\delta^2_{s,r}}+\frac{bP\delta^2_{s,d}}{N_0\sin^2\theta}), \quad (17)$$

where $b = \frac{3}{2(M-1)}$ and

$$F_3(x(\theta)) = \frac{4K}{\pi}\int_0^{\frac{\pi}{2}}\frac{1}{x(\theta)}d\theta - \frac{4K^2}{\pi}\int_0^{\frac{\pi}{4}}\frac{1}{x(\theta)}d\theta\ , \quad (18)$$

in which $K = 1 - \frac{1}{\sqrt{M}}$. The relay-cooperation SER can be written as

$$Pr(e/\phi^c)Pr(\phi^c)|_{QAM} = F_4(P_1,0) - F_4(P_1,P_2) + F_3\big((1+\frac{\delta^2_{s,d}}{\alpha\delta^2_{s,r}}+\frac{bP_1\delta^2_{s,d}}{N_0\sin^2\theta})(1+\frac{bP_2\delta^2_{r,d}}{N_0\sin^2\theta})\big), \quad (19)$$

where

$$\begin{aligned} F_4(P_1,P_2) &= F_2\big((\frac{4K}{\pi})^2, P_1, P_2, \frac{\pi}{2}, \frac{\pi}{2}\big) \\ &- F_2\big(K(\frac{4K}{\pi})^2, P_1, P_2, \frac{\pi}{2}, \frac{\pi}{4}\big) \\ &- F_2\big(K(\frac{4K}{\pi})^2, P_1, P_2, \frac{\pi}{4}, \frac{\pi}{2}\big) \\ &+ F_2\big((\frac{4K^2}{\pi})^2, P_1, P_2, \frac{\pi}{4}, \frac{\pi}{4}\big). \quad (20) \end{aligned}$$

The total SER expression for the M-QAM signalling is the summation of (17) and (19) as in (7). It is obvious that both the SER and transmission rate depend on the choice of α, P_1, and P_2. In the next section we determine the optimum choices for these parameters to maximize the overall system performance.

IV. JOINT OPTIMIZATION OF COOPERATION THRESHOLD AND POWER ALLOCATION

In this section we obtain the optimum cooperation threshold α and the optimum power ratio $r = P_1/P$ according to two optimization criteria. The first criterion is based on minimizing the SER only, while the second takes the transmission rate also into consideration, and minimizes the ratio between the SER and the transmission rate. In addition, we present the simulation results in this section.

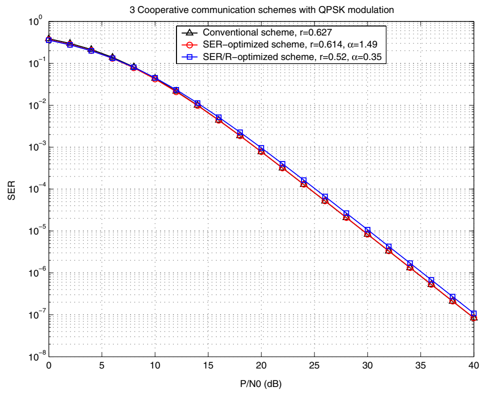

Fig. 6. SER performance of the SER/R-optimized, SER-optimized, and conventional schemes with QPSK modulation and at unity channel-variances case.

A. SER Optimization Criterion

In this subsection we use the SER as an optimization metric to get the optimum values for the cooperation threshold α_o and the power ratio r_o that minimize the SER. The optimum values are determined through exhaustive search using the obtained SER closed-form expression.

In Fig. 2 the SER, at SNR=10 dB and using a unity channel-variances case $\delta^2_{s,d} = \delta^2_{s,r} = \delta^2_{r,d} = 1$ with QPSK Modulation, is plotted versus both α and r. The minimum value of SER turns out to be at $\alpha_o = 1.49$ and $r_o = 0.614$, giving a transmission rate equal to $R_0 = 0.7008$ SPCU. In Fig. 3 the total SER and its two components (10) and (15) are plotted versus α with the same conditions as in Fig. 2. It is shown that the direct-transmission SER decreases, while the relay-cooperation SER increases, as α increases. Moreover, it can be observed that the SER is not highly sensitive to the variations in α. This result was the main motivation to search for a better metric for optimum α_o and r_o, as will be presented in the next subsection.

B. Joint SER with Transmission Rate Optimization Criterion

In this subsection we apply an optimization metric, which takes the SER and the transmission rate into consideration. In Fig. 4 the SER and a scaled version of the transmission rate are shown. It is clear that the transmission rate is more sensitive to the variations in α than the SER. As we see, SER is almost constant for $\alpha \geq 0.5$, while the transmission rate decreases dramatically as α increases. Thus, a more reasonable optimization metric should be found which takes into consideration not only the SER but also the transmission rate. A simple and intuitive optimization metric is the ratio between the SER and the transmission rate, or SER/R.

Under the same simulation setup used to generate Fig. 2 the optimum values using the SER/R optimization metric are $\alpha_o = 0.35$ and $r_o = 0.52$, giving a transmission rate equal to $R_0 =$

Parameter	SER/R Metric	SER Metric	Conventional
α_o	0.35	1.49	-
r_o	0.52	0.614	0.627
R	0.8704	0.7008	0.5
$Pr(\phi)$	0.7407	0.4016	0

TABLE I

Results of the two optimization metrics for unity channel-variances case.

0.8704 SPCU. Fig. 5 depicts the SER/R curve versus the power ratio r, using the optimum cooperation threshold $\alpha_o = 0.35$. It is clear that the optimum power ratio is $r_o = 0.52$. Fig. 6 depicts the performance of three transmission schemes. We see that the conventional cooperative communication scheme with optimum power allocation $r_o = 0.627$ [5] has the same SER performance as that of the SER-optimized proposed scheme with $\alpha_o = 1.49$ and $r_o = 0.614$. Moreover, the SER/Rate-optimized one gives approximately the same SER performance as the other two schemes. This is due to the low sensitivity of the SER performance with the choice of α, as depicted in Fig. 4. For simplicity, we used the optimum cooperation threshold and the optimum power ratio, obtained at SNR=10 dB, for the whole SNR range.

In Table I the optimum values for both α and r are tabulated for the SER/R-optimized, the SER-optimized, and the conventional schemes. In the SER-optimized scheme $\alpha_o = 1.49$ which makes sense, because it is intuitive to relay the information most of the time in order to minimize the SER; this is achieved when $\alpha > 1$. In other words, the SER-optimized scheme tends to operate like the conventional cooperative protocol. Moreover, the optimum power ratio in the SER-optimized is 0.614 which is so close to that of conventional scheme 0.627 [5]. As for the SER/R-optimized scheme $\alpha_o = 0.35$ which causes a great improvement in the transmission rate to be $R_o = 0.8704$ SPCU. Finally, the probability of choosing the direct transmission (4) is also given in Table I.

C. Simulation Results

In this subsection we present some computer simulations to illustrate the previous theoretical analysis. We consider the unity channel-variances case where $\delta^2_{s,d} = \delta^2_{s,r} = \delta^2_{r,d} = 1$ and consider unity noise-variance $N_0 = 1$ as well. For fair comparison the SER performance curves are plotted as a function of P/N_0. Fig. 7 compares both the theoretical (7) and the simulated SER performances of the SER/R-optimized scheme. QPSK signalling is used in this comparison. The optimum values for the cooperation threshold and power ratio are $\alpha_o = 0.35$ and $r_o = 0.52$, respectively, as in Table I. The transmission rate resulting from the simulations is 0.87037 SPCU. Fig. 7 depicts that the theoretical SER performance is matching with the simulation curve.

V. CONCLUSION

In this paper we have proposed a new decode-and-forward cooperative scheme, based on utilizing the partial CSI available at the source. The main idea is that the source chooses whether to send its information to its destination through direct transmission only, or to employ a relay in forwarding the information to the destination, as in the conventional cooperative protocols. The proposed scheme improves the transmission rate, as we have shown that the transmission rate can be increased from 0.5 to 0.87 SPCU. Moreover, we have proposed two optimization metrics to search for the optimum choice of both the cooperation threshold and the power ratio. First, we have considered minimizing the SER only as the optimization metric and we have shown that the transmission rate can be increased to 0.7 SPCU. It was clear that using the SER-optimized metric degrades the transmission rate. Thus, in the second optimization metric we have considered minimizing the ratio between the SER and the transmission rate and we have shown that the transmission rate can be increased to 0.87 SPCU. Closed-form expressions for both the transmission rate and the SER were used in the optimization. Finally, simulation results have been presented to verify the obtained analytical results.

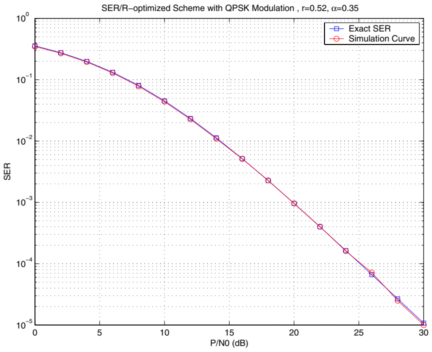

Fig. 7. Performance of SER/R-optimized scheme with QPSK modulation at $\alpha_o = 0.35$, $r_o = 0.52$, and unity channel-variances.

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