

# BER-based relay selection strategy for cooperative communication

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**Abstract:** In this paper, a bit error ratio (BER)-based relay selection strategy is investigated under opportunistic relay selection. The challenging problem is to design the relay selection rule so that the relay is able to measure the performance of the cooperative system at the destination exactly with low computation costs. This paper derives a closed-form expression of the end-to-end bit error rate firstly. Then, an approximate BER expression based on the relationship between the instantaneous signal-to-noise ratio (SNR) of the relay-to-destination link and the probability of error propagation is derived. Finally, a simplified relay selection formula is proposed. Simulation results prove that the proposed relay selection rule can reflect the BER of each relay properly as well.

**Keywords:** cooperative communication, relay selection, demodulate-and-forward.

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## 1. Introduction

In the cooperative communication, the destination receives the signal not only through the source but also through relays. However, the number of relays participating in the cooperative communication in the literature is always constructive [1]. Therefore, an efficient relay selection strategy that provides no performance loss from the perspective of diversity multiplexing gain without increasing hardware complexity plays an indispensable role in the cooperative communication. Each relay estimates the channel quality of the source and the destination it communicates with, and selects the relay that provides the best performance at the destination. Relay selection strategies can be classified into two categories: partial relay selection (PRS) [2] where only the channel state information (CSI) of the source-to-relay (S-R) link is considered at each relay, and opportunistic relay selection (ORS) [3,4] where the CSI of both the S-R link and the relay-to-destination (R-D) link

is considered at each relay. Since the CSI of the S-R link cannot sufficiently represent the end-to-end (E2E) performance of the cooperative communication system, PRS is severely bounded compared with ORS [5].

The performance analysis of ORS has many results including outage probability and error probability [6–16]. Nikjah et al. [8] derived the exact outage probability and ergodic capacity of decode-and-forward (DF) ORS over Rayleigh fading channels. Soleimani-Nasab et al. [9] derived the probability density function (PDF) of the signal-to-noise ratio (SNR) of each link, and then derived the moment generation function (MGF) and the bit error ratio (BER) in the closed-form at high SNRs. Kundu et al. [10] derived the outage probability of the system and proposed three schemes. A predefined SNR threshold is set at relays to ensure the candidate relays are those for which only correctly decoded signals could be forwarded to the destination.

However, the above studies only focus on analyzing the outage probability and ergodic capacity of the system. Moreover, they also assume that each relay forwards correctly decoded signals to the destination. To consider a more practical scenario and further improve the performance, in [17–21], several BER-based relay selection strategies were proposed. Ikki et al. [17] derived the BER and output SNR at the destination. Tourki et al. [18] investigated the BER of an opportunistic relaying. Then they derived the PDF of the R-D link while considering the error propagation of the relay. Nagarajan et al. [19] derived the BER of threshold-based relay networks and obtained the optimum value of the relay-threshold. However, the closed-form solution of the threshold cannot be derived. Moreover, the performance analysis of previous research is quite complicated, which increases the computational complexity at the relay.

Recently, a few other selection strategies combining incremental relays were proposed [18,19,22–27]. For incre-

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mental relay selection, an SNR-based threshold is set at the destination for the direct link. When the instantaneous SNRs of the direct link are less than the thresholds, symbols received from the source and the best relay will be combined at the destination. However, for incremental relay selection strategies, the best relay selection strategy still depends on the traditional method, which can be further improved.

Motivated by recent works on the relay selection strategies, we propose a BER-based relay selection strategy. In the proposed strategy, the relay that can minimize the BER at the destination is selected. In order to analyze the performance, we firstly derive the BER expression of the system. Then, we derive the approximate BER expression based on the relation between the SNR of relay-to-destination link and the error propagation. Finally, a simplified closed-form relay selection formula is proposed, which is proportional to the BER. In the proposed strategy, relays only have the knowledge of SNR in terms of the S-R link and the R-D link by opportunistic relaying, and then the best relay will be determined without the knowledge of SNR in terms of the direct link.

The remainder of this paper is organized as follows. In Section 2, we introduce the system model. In Section 3, the closed-form expression of BER and the relay selection formula are derived. In Section 4, simulation results are obtained that validate the analysis of our proposal. Finally, conclusions are given in Section 5.

## 2. System model

In this paper, a dual-hop DF relay system, with a single source node  $S$ , a single destination node  $D$  and  $K$  relays are used, as depicted in Fig. 1. Each node is equipped with only one antenna. We assume that only one relay is selected to forward signals to the destination.

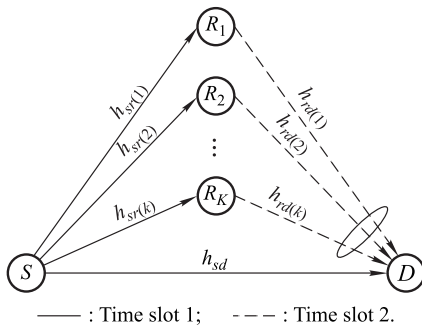


Fig. 1 System model of DF relay system with the best relay selection

The transmission is divided into two time slots. In the first time slot, the source broadcasts signals to both the destination and relays. Signals received at the destination and relays are expressed as follows:

$$r_{sd} = h_{sd}x_s + n_{sd} \quad (1)$$

$$r_{sr(k)} = h_{sr(k)}x_s + n_{sr(k)} \quad (2)$$

where  $x_s \in \{\pm 1\}$  is the symbol under the binary phase shift keying (BPSK) modulation;  $n_{sd}$  and  $n_{sr(k)}$  are complex additive white Gaussian noise (AWGN) signals with variances  $\sigma_{sd}^2$  and  $\sigma_{sr(k)}^2$  per dimension, respectively;  $h_{sd}$  and  $h_{sr(k)}$  are the coefficients of the channels between two nodes. We denote the coefficient as  $E\{|h_{ij}|^2\} = d_{ij}^{-\alpha}$ , where  $d_{ij}$  is the distance between the nodes  $i$  and  $j$ .  $\alpha$  is the path-loss exponent. Therefore, the instantaneous received SNR between the source and the destination can be expressed as  $\gamma_{sd} = |h_{sd}|^2/2\sigma_{sd}^2$ . The average SNR between the source and the destination can be expressed as  $\bar{\gamma}_{sd} = d_{sd}^{-\alpha}/2\sigma_{sd}^2$  [28].

In the second time slot, each relay measures the performance at the destination based on the instantaneous SNRs of the S-R link and the R-D link. Only the relay that can achieve the best performance at the destination will be selected as the best relay  $r_*$  to forward signals received from the source. The received signals at the destination can be expressed as follows:

$$r_{r_*d} = h_{r_*d}x_{r_*} + n_{r_*d} \quad (3)$$

where  $x_{r_*}$  is the decoded and remodulated symbol at the relay  $r_*$ .

In order to obtain the best relay  $r_*$  efficiently, we propose the following rule as the best relay selection strategy:

$$r_* = \arg \min_k \{P_e(\varepsilon_{d(k)})\} \approx$$

$$\arg \min_k \min \{\gamma_{sr(k)}, \gamma_{r(k)d} + \ln(1 + \bar{\gamma}_{sd})\} \quad (4)$$

where  $P_e(\varepsilon_{d(k)})$  is the BER at the destination when the  $k$ th relay is selected as the best relay to forward the received signals from the source.  $\min\{\gamma_{sr(k)}, \gamma_{r(k)d} + \ln(1 + \bar{\gamma}_{sd})\}$  is an effective method for measuring the BER at the destination proposed in this paper.

In the proposed strategy, the destination will combine both signals received from the source and the best relay by the maximum ratio combining (MRC).

Moreover, we assume that the relays are closed to each other. Therefore, the relays and the destination will receive the same average SNR  $\bar{\gamma}_{sr(k)}$  and  $\bar{\gamma}_{r(k)d}$ , respectively. By this way, we denote  $\bar{\gamma}_{sr} = \bar{\gamma}_{sr(k)}$  and  $\bar{\gamma}_{rd} = \bar{\gamma}_{r(k)d}$  for all relays.

## 3. Performance analysis

The E2E BER of the proposed strategy can be expressed as follows:

$$P_e(\varepsilon_{d(k)}) = P_e(\varepsilon_{sr(k)})P_e(\varepsilon_{prop}) + (1 - P_e(\varepsilon_{sr(k)}))P_e(\varepsilon_{coop}) \quad (5)$$

where  $P_e(\varepsilon_{sr(k)})$  is the BER between the source and the  $k$ th relay which can be expressed as follows:

$$P_e(\varepsilon_{sr(k)}) = Q(\sqrt{2\gamma_{sr(k)}}) \quad (6)$$

where  $P_e(\varepsilon_{prop})$  is the conditional BER at the destination when the  $k$ th relay forwards error symbols, which can be expressed as follows:

$$P_e(\varepsilon_{coop}) = \exp\left(\frac{\gamma_{r(k)d}}{\bar{\gamma}_{sd}}\right) \left[ \exp\left(-\frac{\gamma_{r(k)d}}{\bar{\gamma}_{sd}}\right) Q(\sqrt{2\gamma_{r(k)d}}) - \sqrt{\frac{\bar{\gamma}_{sd}}{1+\bar{\gamma}_{sd}}} Q\left(\sqrt{2\gamma_{r(k)d} \frac{1+\bar{\gamma}_{sd}}{\bar{\gamma}_{sd}}}\right) \right] = Q(\sqrt{2\gamma_{r(k)d}}) - \exp\left(\frac{\gamma_{r(k)d}}{\bar{\gamma}_{sd}}\right) \sqrt{\frac{\bar{\gamma}_{sd}}{1+\bar{\gamma}_{sd}}} Q\left(\sqrt{2\gamma_{r(k)d} \frac{1+\bar{\gamma}_{sd}}{\bar{\gamma}_{sd}}}\right). \quad (7)$$

$P_e(\varepsilon_{coop})$  is the conditional BER at the destination when the  $k$ th relay forwards correct symbols, which can be expressed as follows:

$$P_e(\varepsilon_{prop}) \approx 1 - e^{-\frac{\gamma_{r(k)d}}{\bar{\gamma}_{sd}}}. \quad (8)$$

By substituting the result of (6), (7) and (8) into (5), the BER at the destination can be obtained by

$$P_e(\varepsilon_d) = P_e(\varepsilon_{sr(k)}) \left[ 1 - \exp\left(-\frac{\gamma_{r(k)d}}{\bar{\gamma}_{sd}}\right) \right] + (1 - P_e(\varepsilon_{sr(k)})) \left[ Q(\sqrt{2\gamma_{r(k)d}}) - \exp\left(\frac{\gamma_{r(k)d}}{\bar{\gamma}_{sd}}\right) \sqrt{\frac{\bar{\gamma}_{sd}}{1+\bar{\gamma}_{sd}}} Q\left(\sqrt{2\gamma_{r(k)d} \frac{1+\bar{\gamma}_{sd}}{\bar{\gamma}_{sd}}}\right) \right]. \quad (9)$$

However, due to the presence of exponential terms  $\exp(\cdot)$  and Q-function terms  $Q(\cdot)$  in expressions, the cost of hardware implementation in the system increases. Therefore, we reanalyze and derive the BER expression of the system, and then derive a simplified expression of the BER. Finally, we get a new simplified opportunistic relaying selection strategy.

Chiani et al. [29] proposed a simple approximation for the Q-function

$$Q(x) \approx \frac{1}{2} e^{-\frac{x^2}{2}}, \quad x \geq 0. \quad (10)$$

Therefore, by substituting the approximation relationship of the Q-function into (6), we will obtain an approximate expression as follows:

$$P_e(\varepsilon_{sr(k),appr}) = Q(\sqrt{2\gamma_{sr(k)}}) \approx \frac{1}{2} \exp(-\gamma_{sr(k)}). \quad (11)$$

Similarly, when the  $k$ th relay forwards error symbols, the BER at the destination can be approximated as follows:

$$P_e(\varepsilon_{coop,appr}) = \int_0^{+\infty} Q(\sqrt{2(\gamma_{sd} + \gamma_{r(k)d})}) \frac{1}{\bar{\gamma}_{sd}} e^{-\frac{\gamma_{sd}}{\bar{\gamma}_{sd}}} d\gamma_{sd} \approx \int_0^{+\infty} \frac{1}{2} \exp(\gamma_{sd} + \gamma_{r(k)d}) \frac{1}{\bar{\gamma}_{sd}} e^{-\frac{\gamma_{sd}}{\bar{\gamma}_{sd}}} d\gamma_{sd} = \frac{1}{2} \frac{e^{-\gamma_{r(k)d}}}{1 + \bar{\gamma}_{sd}}. \quad (12)$$

Moreover, when the channel gain of the S-R link increases to some extent, there exists

$$1 - P_e(\varepsilon_{sr(k)}) \approx 1. \quad (13)$$

Therefore, the approximate BER at the destination can be expressed as follows:

$$P_e(\varepsilon_{d(k),appr}) \approx P_e(\varepsilon_{sr(k),appr}) P_e(\varepsilon_{prop}) + P_e(\varepsilon_{coop,appr}) = \frac{1}{2} e^{-\gamma_{sr(k)}} (1 - e^{-\frac{\gamma_{r(k)d}}{\bar{\gamma}_{sd}}}) + \frac{1}{2} \frac{e^{-\gamma_{r(k)d}}}{1 + \bar{\gamma}_{sd}}. \quad (14)$$

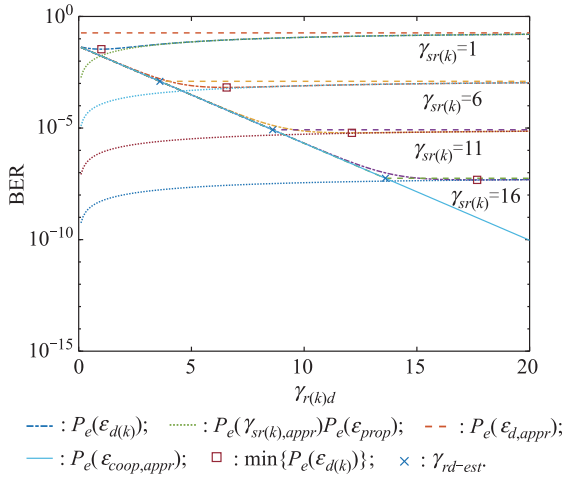
Although (14) is significantly simplified compared with (9), there still exists exponential terms. Therefore, we propose a method for further simplification in combination with the characteristics of the cooperative communication system.

According to whether the relay correctly detects the received symbol, the BER can be expressed as a piecewise function as follows:

$$P_e(\varepsilon_{d(k),appr}) = \begin{cases} \frac{1}{2} e^{-\gamma_{sr}} (1 - e^{-\frac{\gamma_{r(k)d}}{\bar{\gamma}_{sd}}}), & x_{r(k)} \neq x_s \\ \frac{1}{2} \frac{e^{-\gamma_{r(k)d}}}{1 + \bar{\gamma}_{sd}}, & x_{r(k)} = x_s \end{cases}. \quad (15)$$

Further, considering a cooperative communication system with the instantaneous SNR of the S-D link is 10 dB, we set the instantaneous SNR of the S-R link as 1, 6, 11 and 16, respectively. By this way, we can plot the BER as a function of the  $\gamma_{r(k)d}$  under different  $\gamma_{sr(k)}$  in Fig. 2. Firstly, it shows that the value of the BER decreases when the value of  $\gamma_{r(k)d}$  increases. In addition, there are obvious differences between  $P_e(\varepsilon_{d,appr})$  and  $P_e(\varepsilon_d)$  when the value of  $\gamma_{sr}$  is relatively small, and  $P_e(\varepsilon_{d,appr})$  matches well with  $P_e(\varepsilon_d)$  when the value of  $\gamma_{sr}$  is relatively large. Secondly,  $P_e(\varepsilon_{d,appr})$  and  $P_e(\varepsilon_{coop,appr})$  are closely approximated when the value of  $\gamma_{rd}$  is relatively small.  $P_e(\varepsilon_{d,appr})$  and  $P_e(\varepsilon_{sr,appr})P_e(\varepsilon_{prop})$  are closely approximated when the value of  $\gamma_{rd}$  is relatively large. Meanwhile, there exists a common intersection point  $\gamma_{rd-est}$  for two curves, and the value of  $\gamma_{rd-est}$  increases with the increase of  $\gamma_{sr}$ . This can be explained by the fact that the BER is determined by the channel quality of the

R-D link when the value of  $\gamma_{rd}$  is smaller than the value of  $\gamma_{sr}$ . When the value of  $\gamma_{rd}$  is greater than the value of  $\gamma_{sr}$ , the error propagation caused by the relay will directly affect the performance of the system, especially when the value of  $\gamma_{rd}$  is large enough,  $P_e(\varepsilon_{prop}) \approx 1$ . Thirdly, the BER firstly decreases and then increases when  $\gamma_{rd}$  increases in Fig. 2, and the corresponding  $\gamma_{rd}$  approaches  $\gamma_{sr}$  when the system obtains the optimal performance. This illustrates that the system can achieve the best performance when the quality of the S-R link is similar to that of the R-D link.



**Fig. 2** Theoretical BER with respect to  $\gamma_{r(k)d}$  under different  $\gamma_{sr(k)}$

According to the analyses above, we denote the corresponding SNR for the intersection point of  $P_e(\varepsilon_{sr,appr})P_e(\varepsilon_{prop})$  and  $P_e(\varepsilon_{coop,appr})$  as  $T_{rd}$ . Then (15) can be expressed as follows:

$$P_e(\varepsilon_{d(k),appr}) = \begin{cases} \frac{1}{2} e^{-\gamma_{sr(k)}} (1 - e^{-\frac{\gamma_{r(k)d}}{\bar{\gamma}_{sd}}}), & \gamma_{r(k)d} > T_{rd} \\ \frac{1}{2} \frac{e^{-\gamma_{r(k)d}}}{1 + \bar{\gamma}_{sd}}, & \gamma_{r(k)d} \leq T_{rd} \end{cases}. \quad (16)$$

The intersection point  $T_{rd}$  can be obtained by

$$\frac{1}{2} \frac{1}{1 + \bar{\gamma}_{sd}} e^{-T_{rd}} = \frac{1}{2} e^{-\gamma_{sr(k)}} (1 - e^{-T_{rd}/\bar{\gamma}_{sd}}). \quad (17)$$

Applying natural logarithms to both sides of (17), we obtain

$$-T_{rd} - \ln(1 + \bar{\gamma}_{sd}) = -\gamma_{sr} + Z \quad (18)$$

where we denote

$$Z = \ln \left( 1 - \exp \left( -\frac{\gamma_{r(k)d}}{\bar{\gamma}_{sd}} \right) \right), \quad Z < 0. \quad (19)$$

Due to the Rayleigh fading channel [30], the PDF of  $Z$  can be derived as

$$f_z(z) = \frac{\bar{\gamma}_{sd}}{\bar{\gamma}_{rd}} (1 - e^z)^{\bar{\gamma}_{sd}/\bar{\gamma}_{rd}} \frac{1}{1 - e^z} e^z, \quad z < 0. \quad (20)$$

We denote the mean of  $Z$  as  $C$ . Especially, the PDF of  $Z$  can be further simplified as the exponential distribution when  $\bar{\gamma}_{sd} = \bar{\gamma}_{rd}$ . Therefore, the intersection point  $T_{rd}$  can be obtained by

$$T_{rd} = \gamma_{sr} - C - \ln(1 + \bar{\gamma}_{sd}). \quad (21)$$

By substituting the result of (21) into (16), the BER expression can be further simplified as follows:

$$\ln P_e(\varepsilon_{d,appr}) \propto \begin{cases} -\gamma_{rd} - \ln(1 + \bar{\gamma}_{sd}), & -\gamma_{sr} + C \leq -\gamma_{rd} - \ln(1 + \bar{\gamma}_{sd}) \\ -\gamma_{rd} + C, & -\gamma_{sr} + C > -\gamma_{rd} - \ln(1 + \bar{\gamma}_{sd}) \end{cases}. \quad (22)$$

Finally, we obtain the rule of the relay selection as follows:

$$\gamma_T = \max\{-\gamma_{sr} + C, -\gamma_{rd} - \ln(1 + \bar{\gamma}_{sd})\} = \min\{\gamma_{sr} - C, \gamma_{rd} + \ln(1 + \bar{\gamma}_{sd})\}. \quad (23)$$

Moreover, when the SNRs of the S-D link and the R-D link are large enough, (23) can be further simplified as follows:

$$\gamma_T = \min\{\gamma_{sr}, \gamma_{rd} + \ln(1 + \bar{\gamma}_{sd})\}. \quad (24)$$

We can clearly see that the proposed rule of the relay selection in (24) can estimate the performance of the destination node without increasing the computational burden of the relay. As described in (4) and (24), only the relay with the minimum BER, which is equivalent to the minimum  $\gamma_T$ , can be selected as the best relay and forwards signals to the destination.

## 4. Simulation results

In this section, we evaluate the performance of our proposed scheme.

In Fig. 3, we consider the scenario  $d_{sd} = d_{sr} = d_{rd} = 1$ . We observe that the proposed relay selection strategy achieves better performance than the traditional relay selection. The simulation results based on (24) approximate to that of the relay selection strategy based on the minimum BER. It illustrates that the proposed approximation formula can effectively reflect the E2E BER at the destination.

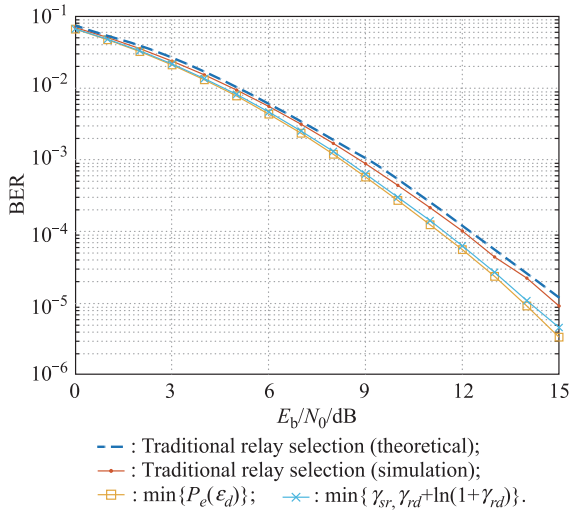


Fig. 3 E2E BER performance for the case  $d_{sd} = d_{sr} = d_{rd} = 1$ ,  $N_r = 4$

Next, as depicted in Fig. 4, we compare the E2E BER performance for different relays under  $d_{sd} = d_{sr} = 0.5$ ,  $d_{rd} = 1$ . We observe that the proposed scheme can achieve a better performance than the traditional relay selection under different relays. Moreover, with the increase of the number of the relays, the system can achieve a better performance.

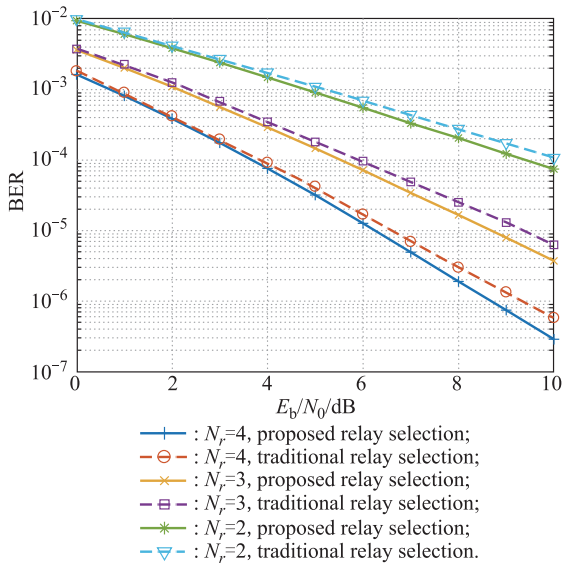


Fig. 4 E2E BER performance for the case  $d_{sd} = d_{sr} = 0.5$ ,  $d_{rd} = 1$

Finally, the simulation results of the proposed scheme under the scenario  $d_{sd} = 1$ ,  $d_{sr} = 1 - d_{rd}$  at  $\bar{\gamma}_{sd} = 10$  dB is shown in Fig. 5. With the increase of  $d_{sr}$ , the performance of the proposed strategy firstly decreases and then increases. When  $d_{sr} = 0.4$ , the proposed strategy achieves the best performance. Moreover, the proposed strategy also achieves a better performance than both the traditional re-

lay selection and the SNR-based relay selection [18]. However, when the location of the relay is closed to the source or the destination, the performance improvement by the proposed strategy is less significant. This can be attributed to the fact that, when relays are closed to the source or the destination, the impact of the noise of the R-D link and the error propagation will be more pronounced, respectively. In this case, an effective improvement of the system performance cannot be obtained by improving the relay selection method only. Otherwise, when relays are far away from the source and the destination, the noise of the R-D link and the error propagation will influence the performance of the system simultaneously. In this case, through the effective relay selection method, the performance of the system will be significantly improved.

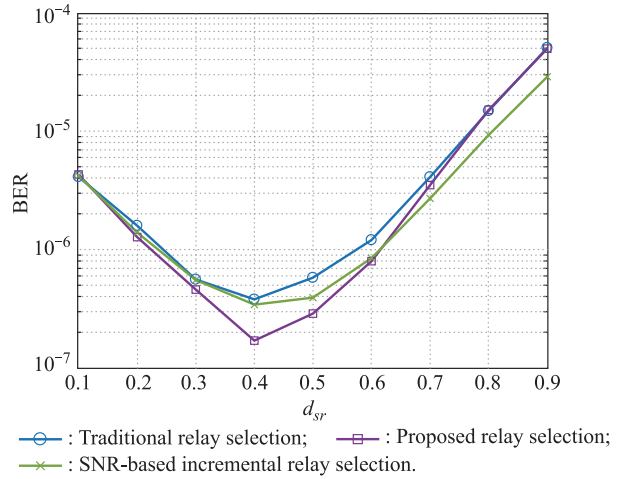


Fig. 5 E2E BER performance for the case  $d_{sd} = 1$ ,  $d_{sr} = 1 - d_{rd}$  at  $\bar{\gamma}_{sd} = 10$  dB,  $N_r = 4$

### 5. Conclusions

In this paper, we propose a BER-based relay selection strategy for the cooperative communication system. A relay selection rule is applied at each relay to measure the reliability of the source-relay-destination link. Only the relay that can minimize the BER at the destination is selected as the best relay. In order to simplify the relay selection strategy, we derive the E2E BER expression of the system firstly. By analyzing the relationship between the SNR of the relay-to-destination link and the probability of error propagation, we derive the approximate BER expression. Finally, a simplified closed-form relay selection formula is proposed. Simulation results show that the performance of the proposed relay selection strategy is closed to the theoretical relay selection strategy and it clearly outperforms other relay selection strategies.

### References

[1] BLETSAS A, SHIN H, WIN M Z, et al. Cooperative diversity

- with opportunistic relaying. Proc. of the IEEE Wireless Communications and Networking Conference, 2006: 1034–1039.
- [2] KRIKIDIS I, THOMPSON J, MCLAUGHLIN S, et al. Amplify-and-forward with partial relay selection. IEEE Communications Letters, 2018, 12(4): 235–237.
  - [3] BLETSAS A, KHISTI A, REED D P, et al. A simple cooperative diversity method based on network path selection. Journal on Selected Areas in Communications, 2006, 24(3): 659–672.
  - [4] BLETSAS A, SHIN H, WIN M Z. Cooperative communications with outage-optimal opportunistic relaying. IEEE Trans. on Wireless Communications, 2007, 6(9): 3450–3460.
  - [5] KIM J, LEE I. Outage analysis of partial relay selection schemes with feedback delay and channel estimation errors in nonidentical Rayleigh fading channels. International Journal of Antennas and Propagation, 2017, 15: 1–9.
  - [6] KIM Y G, BEAULIEU N C. SEP of decode-and-forward cooperative systems with relay selection in nakagami-m fading channels. IEEE Trans. on Vehicular Technology, 2015, 64(5): 1882–1894.
  - [7] IKKI S S, UYSAL M. Performance analysis of incremental-relay-selection decode-and-forward technique. Proc. of the IEEE Conference on Global Telecommunications, 2009: 1935–1940.
  - [8] NIKJAH R, BEAULIEU N C. Exact closed-form expressions for the outage probability and ergodic capacity of decode-and-forward opportunistic relaying. Proc. of the Global Telecommunications Conference, 2009. DOI:10.1109/GLOCOM.2009.5425888.
  - [9] SOLEIMANI-NASAB E, KALANTARI A, ARDEBILIPOUR M, et al. Performance analysis of multi-antenna DF relay networks over Nakagami-m fading channels. IEEE Communications Letters, 2011, 15(12): 1372–1374.
  - [10] KUNDU C, NGATCHED T M, DOBRE O A, et al. Relay selection to improve secrecy in cooperative threshold decode-and-forward relaying. Proc. of the IEEE Global Communications Conference, 2016. DOI:10.1109/GLOCOM.2016.7842212.
  - [11] LI C, CHEN Z, WANG Y, et al. Outage analysis of the full-duplex decode-and-forward two-way relay system. IEEE Trans. on Vehicular Technology, 2017, 66(5): 4073–4086.
  - [12] ZHANG Y, GE J. Joint antenna-and-relay selection in MIMO decode-and-forward relaying networks over Nakagami-m fading channels. IEEE Signal Processing Letters, 2017, 24(4): 456–460.
  - [13] DENG D, FAN L, LEI X, et al. Joint user and relay selection for cooperative NOMA networks. IEEE Access, 2017, 5: 20220–20227.
  - [14] YANG Z, DING Z, WU Y, et al. Novel relay selection strategies for cooperative NOMA. IEEE Trans. on Vehicular Technology, 2017, 66(11): 10114–10123.
  - [15] PURI P, GARG P. Relay selection strategy for parallel relayed FSO systems. Proc. of the 28th IEEE Annual International Symposium on Personal, Indoor, and Mobile Radio Communications, 2017. DOI:10.1109/PIMRC.2017.8292251.
  - [16] LIU F, WANG S, LIU Y, et al. Outage analysis of full-duplex two-way DF relaying with joint source and relay selection. Proc. of the 29th IEEE Annual International Symposium on Personal, Indoor and Mobile Radio Communications, 2018. DOI:10.1109/PIMRC.2018.8580955.
  - [17] IKKI S S, AHMED M H. Exact error probability and channel capacity of the best-relay cooperative-diversity networks. IEEE Signal Processing Letters, 2009, 16(12): 1051–1054.
  - [18] TOURKI K, YANG H, ALOUINI M, et al. Error-rate performance analysis of opportunistic regenerative relaying. Proc. of the 22nd IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 2011: 1516–1520.
  - [19] NAGARAJAN V, BALASARASWATHI M. Threshold-based selection combining for relay networks. Computers & Electrical Engineering, 2017: 129–139.
  - [20] LOU Y, YU Q, CHENG J, et al. Weighted selection combining for differential decode-and-forward cooperative networks. IEEE Signal Processing Letters, 2017, 24(8): 1242–1246.
  - [21] KAYA H, OZTURK E. Performance analysis of distributed turbo coded scheme with two ordered best relays. IET Communications, 2015, 9(5): 638–648.
  - [22] HAKIM H, BOUJEMAA H, AJIB W, et al. BEP and throughput analysis of incremental selective relaying in DS-CDMA systems. Proc. of the Vehicular Technology Conference, 2012. DOI:10.1109/VTCFall.2012.6399088.
  - [23] BASTAMI A H, OLFAT A. Optimal incremental relaying in cooperative diversity systems. IET Communications, 2013, 7(2): 152–168.
  - [24] BASTAMI A H, OLFAT A. BER-constrained incremental relaying with relay selection in cooperative wireless networks. Wireless Personal Communications, 2013, 72(1): 121–136.
  - [25] TOURKI K, YANG H, ALOUINI M, et al. Error-rate performance analysis of incremental decode-and-forward opportunistic relaying. IEEE Trans. on Communications, 2011, 59(6): 1519–1524.
  - [26] OZDEMIR O. Exact BER performance analysis of incremental relaying over Rayleigh fading channels. Proc. of the International Conference on Ubiquitous and Future Networks, 2016: 273–276.
  - [27] HAGHIGHAT J, HAJINEZHAD S, ESLAMI M, et al. Incremental relaying for time-varying fading channels with thresholds at relay and destination. IEEE Trans. on Communications, 2018, 66(5): 1871–1882.
  - [28] PROAKIS J G. Digital communications. 5th ed. New York: McGraw-Hill, 2007.
  - [29] CHIARI M, DARDARI D, SIMON M K, et al. New exponential bounds and approximations for the computation of error probability in fading channels. IEEE Trans. on Wireless Communications, 2003, 2(4): 840–845.
  - [30] PAPOULIS A, HOFFMAN J G. Probability, random variables, and stochastic processes. 4th ed. New York: McGraw-Hill, 2002.

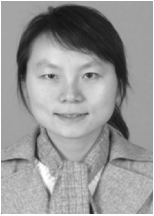
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