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Research Article

A Comparative Study on the Performance of LLR- and SNR-Based Hybrid Relaying Schemes

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A comparative study on the theoretical bit error rate (BER) is presented for hybrid relaying schemes that toggle between adaptive decode-and-forward (ADF) and amplify-and-forward (AF) protocols, for a typical three-node wireless network. Toggling between the two forwarding protocols is based on the log-likelihood ratio (LLR) or the signal-to-noise ratio (SNR) of the received signal at the relay node. Closed-form expressions for the probability of error are presented, as well as the expressions of the proposed schemes' gains over classical ADF and AF protocols. Comparisons are carried out among the two schemes and other hybrid schemes found in the literature. Moreover, the impact of relay location on the probability of error is investigated.

1. Introduction

Since the early works of [1–5] on cooperative communications, the wireless communications community has come to realize the tremendous advantages that could be attained through the utilization of relay nodes in a wireless network, namely, gains in spatial diversity, improved cellular coverage, and the potential of increased capacity.

Relaying schemes are generally classified according to the forwarding protocol employed at the relay nodes. The two most common forwarding protocols are amplify-and-forward (AF) and decode-and-forward (DF). A relay node employing an AF protocol simply amplifies the received signal from the source node and forwards it to the destination node. No signal processing whatsoever is carried out at the relay node, thus significantly saving up on the cooperation overhead and reducing system complexity. Nevertheless, this forwarding protocol has the drawback of amplifying the noise as well. On the other hand, a relay node employing a DF protocol would decode the received signal from the source node, before encoding it once again and forwarding it to the destination node. Moreover, DF protocol is subclassified into (a) fixed decode-and-forward (FDF) protocol, whereby the relay node always forwards the received signal, thus allowing for errors occurring in the $S \rightarrow R$ link to propagate through the $R \rightarrow D$ link, ultimately leading to wrong decisions at D, and (b) adaptive decode-and-forward (ADF) protocol, whereby the received signal from S is only forwarded by R under the condition of probable correct decoding. Such a condition is usually checked through the satisfaction of a certain metric, for example, if the measured SNR is higher than a certain predefined threshold, denoted by η_{SNR}.

Hybrid relaying schemes that switch between AF and FDF protocols were tackled in [6–8]. In [6, 7], the authors provide simulations for a relaying system that allows R to toggle between FDF, AF, and no-send protocols by comparing either the measured SNR or the calculated LLR of the received signal at R with predefined thresholds. In [8], a closed-form expression is provided for the proposed relaying scheme, which allows R to perform soft decoding and then forwards the reliability information at the output of its decoder to D.

Hybrid relaying schemes that switch between AF and ADF protocols were tackled in [9–11]. In [9], a closed-form expression of the symbol-error-rate (SER), for M-PSK-modulated signals, is provided for the hybrid scheme. In their hybrid scheme, the authors allow R to toggle between ADF and AF protocols based on the mathematical calculation of the probability of the relay's ability to correctly decode the received signal from S. In reality, this is not very practical, so the authors of [10] choose to allow R to base its decision on the SNR of the received signal. In their proposed scheme, R employs DF protocol in case the SNR of the received signal exceeds η_{SNR}; otherwise it employs AF. A closed-form expression of the BER, only for BPSK-modulated signals, is provided in their work. The authors of [11] clarify that, for SNR-based hybrid relaying, it would be better for R to employ AF protocol if the SNR of the received signal from S exceeds η_{SNR}, otherwise R would employ ADF protocol. This is because $S \rightarrow R$ link is already in a "good state." A closed-form expression of the SER for MPSK-modulated signals is provided in their work.

In this paper, analysis of the performance of a hybrid relaying protocol that toggles between ADF and AF protocols, according to the quality of the received signal from S at R, is proposed. A comparative study between different metrics, LLR and SNR, is carried out. The contributions of this paper can be summarized in the following points: (a) a hybrid relaying protocol that employs either ADF or AF protocol, based on the LLR of the received signal from S at R, is proposed and (b) a hybrid relaying protocol that employs either ADF or AF protocol, based on the SNR of the received signal from S at R, is proposed. Note that the proposed approach distinguishes itself from other SNR-based approaches in the literature by employing ADF protocol instead of DF protocol. (c) The proposed protocols are analyzed by deriving the closed-form expressions for the BER BPSK-modulated signals. (d) The performance of the proposed protocols is compared with that of other hybrid protocols. (e) The proposed protocols' performance is demonstrated to outperform their counterparts, through several examples. (f) The effect of the S-R separation on the performance of the proposed protocols is analyzed. (g) The relaying gain of the proposed protocols over ADF and AF protocols is investigated. (h) For the high SNR regime, it is shown that the performance of the proposed protocols is identical to that of ADF protocol.

The rest of this paper is organized as follows. In Section 2, the system model is described. In Section 3, the proposed LLR- and SNR-based hybrid relaying schemes are outlined and the mathematics of the LLR calculation is laid out. In Section 4, the performance of the proposed schemes is analyzed by deriving closed-form expressions for the BER, and the performance gain over the ADF and AF relaying protocols is evaluated. In Section 5, numerical results are presented and interpreted. Comparisons to other hybrid relaying schemes, found in the literature, are also carried out. Finally, the conclusions are drawn in Section 6.

Throughout this paper, the following definitions and notations will be used. The source, relay, and destination nodes are denoted, respectively, by S, R, and D. Furthermore, the superscripts $(\cdot)^*$ and $(\cdot)^C$ denote the complex conjugate and the complementary event; $\mathrm{Re}[\cdot]$ and $E[\cdot]$ denote the real part and the statistical expectation, respectively.

2. System Model

A cooperative system comprising a single S, a single R, and a single D, as shown in Figure 1, is considered in this paper, where the direct communication is assisted by R. To avoid interference from simultaneous transmissions, R is assumed to operate in the half duplex mode and thus each transmission consists of two time slots, where each time slot spans a single frame interval. In the first time slot, S broadcasts its message signal, which is received by R and D. In the second time slot, if R employs ADF protocol, the received message from S is decoded and forwarded to D; otherwise if R employs AF protocol, the received message from S is forwarded with an amplifying factor G. In order to allow for equal power allocation between S and R, the choice for G is varied accordingly with each time slot. As in [9] and for a simpler analysis, orthogonal AF (OAF) protocol is considered (i.e., S remains silent during the second slot). Finally, D combines the transmissions from the two time slots, utilizing the maximal-ratio-combining (MRC) technique, thus maximizing the reliability. Furthermore, quasi-static fading is assumed, such that, for the duration of a single frame, the channel is assumed to be constant and only to change value independently for each subsequent new frame. During the first time slot, the received signals from S at R and D are given, respectively, by

$$\begin{aligned} y_{SR} &= h_{SR}x + n_{SR}, \\ y_{SD} &= h_{SD}x + n_{SD}, \end{aligned} \tag{1}$$

where x is the transmitted symbol from S. x is assumed to have an average energy per bit E_b and to belong to the constellation set of BPSK. During the second time slot and based on the employed relaying mode, whether ADF or AF, the received signals at D from R are given by

$$\begin{aligned} y_{RD}^{\mathrm{ADF}} &= h_{RD}x + n_{RD}, \\ y_{RD}^{\mathrm{AF}} &= h_{RD}Gy_{SR} + n_{RD}. \end{aligned} \tag{2}$$

In (1) and (2), the fading channel magnitudes, received signals, and additive white Gaussian noise (AWGN) with variance N_0 are, respectively, denoted by h_A, y_A, and n_A with $A \in \{SD, SR, RD\}$ and channel mean power Ω_A, where

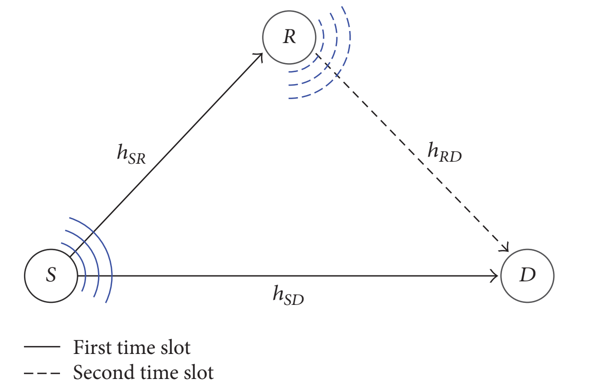

FIGURE 1: A simplified cooperative communication system model.

$h_A \sim \mathcal{CN}(0,\Omega_A)$ denotes the complex Gaussian random variable with zero-mean and variance Ω_A and $n_A \sim \mathcal{CN}(0,N_0)$ are statistically independent. For the AF mode, the amplifying factor G is chosen as [6]

$$G = \frac{1}{\sqrt{|h_{SR}|^2 + 1/\gamma_0}}, \quad (3)$$

where γ_0 is the SNR of the received signal at R.

3. Proposed HDAF Relaying Schemes and LLR Calculation

For the LLR-based HDAF and for each frame, the LLR value at R, Λ_{SR} is calculated and compared to a predetermined threshold, η_{LLR}. If Λ_{SR} exceeds η_{LLR}, R employs the ADF protocol; otherwise, it employs the AF protocol. That is,

$$\Lambda_{SR} \underset{\text{AF}}{\overset{\text{ADF}}{\gtrless}} \eta_{\text{LLR}}. \quad (4)$$

For BPSK, Λ_{SR} is calculated as [12]

$$\begin{aligned}\Lambda_{SR} &= \ln\left[\frac{P\{x_v \mid |h_{SR}|, y_{SR}\}}{P\{x_w \mid |h_{SR}|, y_{SR}\}}\right] \\ &= \ln\left[\frac{\text{Exp}\left[-\left|y_{SR} - |h_{SR}|^2\sqrt{E_b}\right|^2 / |h_{SR}|^2\sigma_{SR}^2\right]}{\text{Exp}\left[-\left|y_{SR} + |h_{SR}|^2\sqrt{E_b}\right|^2 / |h_{SR}|^2\sigma_{SR}^2\right]}\right] \\ &= \frac{4\sqrt{E_b}}{\sigma_{SR}^2}\text{Re}\{y_{SR}\},\end{aligned} \quad (5)$$

where x_v and x_w are any two different symbols from the BPSK constellation set, $\{+\sqrt{E_b}, -\sqrt{E_b}\}$.

For the SNR-based HDAF and for each frame, the measured SNR value at R, Γ_{SR} is compared to a predetermined threshold, η_{SNR}. If Γ_{SR} exceeds η_{SNR}, R employs the ADF protocol; otherwise, it employs the AF protocol. That is,

$$\Gamma_{SR} \underset{\text{AF}}{\overset{\text{ADF}}{\gtrless}} \eta_{\text{SNR}}. \quad (6)$$

For BPSK, Γ_{SR} is calculated as

$$\Gamma_{SR} = \frac{(d_{SR})^{-a}}{\sigma_{SR}^2}E_b, \quad (7)$$

where d_{SR} is the normalized distance between S and R, while a is the path-loss exponent.

4. Bit Error Probability and Relaying Gain

4.1. Bit Error Probability. The end-to-end BER of the relaying schemes described above are given by

$$\begin{aligned}P_{\text{SNR}}\{\mathcal{E}\} &= P_{\text{ADF}}\{\mathcal{E}\}P\{H_{\text{SNR}}\} \\ &\quad + P_{\text{AF}}\{\mathcal{E}\}(1 - P\{H_{\text{SNR}}\}),\end{aligned} \quad (8)$$

for the SNR-based scheme, and by

$$\begin{aligned}P_{\text{LLR}}\{\mathcal{E}\} &= P_{\text{ADF}}\{\mathcal{E}\}P\{H_{\text{LLR}}\} \\ &\quad + P_{\text{AF}}\{\mathcal{E}\}(1 - P\{H_{\text{LLR}}\}),\end{aligned} \quad (9)$$

for the LLR-based scheme. $P_{\text{ADF}}\{\mathcal{E}\}$ and $P_{\text{AF}}\{\mathcal{E}\}$ are the probabilities of error for the ADF and AF relaying protocols, respectively, and $P\{H_{\text{SNR}}\}$ is the probability that the measured Γ_{SR} at R exceeds the threshold η_{SNR}, while $P\{H_{\text{LLR}}\}$ is the probability that the calculated Λ_{SR} exceeds the threshold η_{LLR}. In [9, (17)], $P_{\text{ADF}}\{\mathcal{E}\}$ is approximated by

$$P_{\text{ADF}}\{\mathcal{E}\} = \frac{1}{\pi\Omega_{SD}\gamma_0^2 g^2}\left(\frac{\alpha}{\Omega_{RD}} + \frac{\beta^2}{\pi\Omega_{SR}}\right), \quad (10)$$

where

$$\begin{aligned}\alpha &= \frac{3\pi(M-1)}{8M} + \frac{\sin(2\pi/M)}{4} - \frac{\sin(4\pi/M)}{32}, \\ \beta &= \frac{\pi(M-1)}{2M} + \frac{\sin(2\pi/M)}{4M}, \\ g &= \sin^2\left(\frac{2\pi}{M}\right),\end{aligned} \quad (11)$$

where M is the modulation order, while $P_{\text{AF}}\{\mathcal{E}\}$ is given in [9, (21)] as

$$P_{\text{AF}}\{\mathcal{E}\} = \frac{3}{8\gamma_0^2 g^2}\left(\frac{1}{\Omega_{RD}} + \frac{1}{\Omega_{SR}}\right)\frac{1}{\Omega_{SD}}. \quad (12)$$

$P\{H_{\text{SNR}}\}$ is given in [13] as

$$P\{H_{\text{SNR}}\} = P\{\Lambda_{SR} > \eta_{\text{SNR}}\} = \text{Exp}\left[-\frac{\eta_{\text{SNR}}}{\sigma_{SR}^2}\right], \quad (13)$$

while $P\{H_{\text{LLR}}\}$ is given in [13] as

$$\begin{aligned}P\{H_{\text{LLR}}\} &= P\{\Lambda_{SR} > \eta_{\text{LLR}}\} \\ &= \frac{\text{Exp}\left[-\left(\sqrt{1+\gamma_{SR}^{-1}}+1\right)(\eta_{\text{LLR}}/2)\right]}{2\left(\gamma_{SR}+1+\sqrt{\gamma_{SR}^2+\gamma_{SR}}\right)} \\ &\quad + \frac{\text{Exp}\left[-\left(\sqrt{1+\gamma_{SR}^{-1}}-1\right)(\eta_{\text{LLR}}/2)\right]}{2\left(\gamma_{SR}+1-\sqrt{\gamma_{SR}^2+\gamma_{SR}}\right)}.\end{aligned} \quad (14)$$

By substituting (10), (12), and (13) in (8), $P_{\mathrm{SNR}}\{\mathscr{E}\}$ is obtained as

$$P_{\mathrm{SNR}}\{\mathscr{E}\} = \frac{1}{\pi\Omega_{SD}\gamma_0^2 g^2}\left(\frac{\alpha}{\Omega_{RD}} + \frac{\beta^2}{\pi\Omega_{SR}}\right) \cdot \mathrm{Exp}\left[-\frac{\eta_{\mathrm{SNR}}}{\sigma_{SR}^2}\right] + \frac{3}{8\gamma_0^2 g^2}\left(\frac{1}{\Omega_{RD}} + \frac{1}{\Omega_{SR}}\right) \cdot \frac{1}{\Omega_{SD}}\left(1 - \mathrm{Exp}\left[-\frac{\eta_{\mathrm{SNR}}}{\sigma_{SR}^2}\right]\right). \quad (15)$$

By substituting (10), (12), and (14) in (9), $P_{\mathrm{LLR}}\{\mathscr{E}\}$ is obtained as

$$\begin{aligned} P_{\mathrm{LLR}}\{\mathscr{E}\} = {} & \frac{1}{\pi\Omega_{SD}\gamma_0^2 g^2}\left(\frac{\alpha}{\Omega_{RD}} + \frac{\beta^2}{\pi\Omega_{SR}}\right) \cdot \left(\frac{\mathrm{Exp}\left[-\left(\sqrt{1+\gamma_{SR}^{-1}}+1\right)(\eta_{\mathrm{LLR}}/2)\right]}{2\left(\gamma_{SR}+1+\sqrt{\gamma_{SR}^2+\gamma_{SR}}\right)} + \frac{\mathrm{Exp}\left[-\left(\sqrt{1+\gamma_{SR}^{-1}}-1\right)(\eta_{\mathrm{LLR}}/2)\right]}{2\left(\gamma_{SR}+1-\sqrt{\gamma_{SR}^2+\gamma_{SR}}\right)}\right) \\ & + \frac{3}{8\gamma_0^2 g^2}\left(\frac{1}{\Omega_{RD}} + \frac{1}{\Omega_{SR}}\right)\frac{1}{\Omega_{SD}} \times \left(1 - \left(\frac{\mathrm{Exp}\left[-\left(\sqrt{1+\gamma_{SR}^{-1}}+1\right)(\eta_{\mathrm{LLR}}/2)\right]}{2\left(\gamma_{SR}+1+\sqrt{\gamma_{SR}^2+\gamma_{SR}}\right)} + \frac{\mathrm{Exp}\left[-\left(\sqrt{1+\gamma_{SR}^{-1}}-1\right)(\eta_{\mathrm{LLR}}/2)\right]}{2\left(\gamma_{SR}+1-\sqrt{\gamma_{SR}^2+\gamma_{SR}}\right)}\right)\right). \end{aligned} \quad (16)$$

4.2. Relaying Gain over ADF and AF Protocols. In this subsection, we investigate the performance gains of the proposed hybrid relaying protocol over ADF and AF protocols. Employing the adapted concept of relaying gain G_B^A (in dB), introduced in [9], with $A \in$ {LLR-based HDAF, SNR-based HDAF} and $B \in$ {ADF, AF} and finding the gain in BER performance of the proposed HDAF schemes in comparison to ADF and AF protocols, we have

$$G_B^A = \frac{10}{2} \times \log_{10}\left[\lim_{\gamma_0\to\infty}\frac{P_B\{\mathscr{E}\}}{P_A\{\mathscr{E}\}}\right]. \quad (17)$$

The use of the limit operation in (17) signifies that the computed gain is obtained for the high SNR regime. Substituting (10) and (16) in (17) and carrying out some elementary operations, the gain of the proposed LLR-based HDAF over ADF protocol can be expressed as

$$\begin{aligned} G_{\mathrm{ADF}}^{\mathrm{LLR}} = 5\log_{10}\Bigg[8\chi\Bigg(&4\chi\left(\frac{\mathrm{Exp}\left[-(1/2)(-1+\xi)\eta_{\mathrm{LLR}}\right]}{1+\gamma_{SR}-\delta} + \frac{\mathrm{Exp}\left[-(1/2)(1+\xi)\eta_{\mathrm{LLR}}\right]}{1+\gamma_{SR}+\delta}\right) \\ &+ 3\pi\varphi\left(\frac{1-\mathrm{Exp}\left[-(1/2)(1+\xi)\eta_{\mathrm{LLR}}\right]}{2(1+\gamma_{SR}+\delta)} + \frac{\mathrm{Exp}\left[-(1/2)(-1+\xi)\eta_{\mathrm{LLR}}\right]}{-2(1+\gamma_{SR}-\delta)}\right)\Bigg)^{-1}\Bigg], \end{aligned} \quad (18)$$

where $\chi = (\alpha/\gamma_{RD} + \beta^2/\pi\gamma_{SR})$, $\delta = \sqrt{\gamma_{SR}(1+\gamma_{SR})}$, $\varphi = (1/\gamma_{RD} + 1/\gamma_{SR})$, and $\xi = \sqrt{1+1/\gamma_{SR}}$.

Substituting (12) and (16) in (17) and carrying out some elementary operations, the gain of the proposed LLR-based HDAF over AF protocol can be expressed as

$$\begin{aligned} G_{\mathrm{AF}}^{\mathrm{LLR}} = 5\log_{10}\Bigg[3\varphi\Bigg(&\frac{4}{\pi}\chi\left(\frac{\mathrm{Exp}\left[-(1/2)(-1+\xi)\eta_{\mathrm{LLR}}\right]}{1+\gamma_{SR}-\delta} + \frac{\mathrm{Exp}\left[-(1/2)(1+\xi)\eta_{\mathrm{LLR}}\right]}{1+\gamma_{SR}+\delta}\right) \\ &+ 3\varphi\left(\frac{1-\mathrm{Exp}\left[-(1/2)(1+\xi)\eta_{\mathrm{LLR}}\right]}{2(1+\gamma_{SR}+\delta)} + \frac{\mathrm{Exp}\left[-(1/2)(-1+\xi)\eta_{\mathrm{LLR}}\right]}{-2(1+\gamma_{SR}-\delta)}\right)\Bigg)^{-1}\Bigg]. \end{aligned} \quad (19)$$

Substituting (10) and (15) in (17) and carrying out some elementary operations, the gain of the proposed SNR-based HDAF over ADF protocol can be expressed as

$$G_{\mathrm{ADF}}^{\mathrm{SNR}} = 5\log_{10}\left[\frac{1}{\mathrm{Exp}\left[-\eta_{\mathrm{SNR}}\right] + 3\left(1-\mathrm{Exp}\left[-\eta_{\mathrm{SNR}}\right]\right)}\right]. \quad (20)$$

Finally, substituting (12) and (15) in (17) and carrying out some elementary operations, the gain of the proposed SNR-based HDAF over AF protocol can be expressed as

$$G_{\mathrm{AF}}^{\mathrm{SNR}} = 5\log_{10}\left[\frac{1}{1-(2/3)\,\mathrm{Exp}\left[-\eta_{\mathrm{SNR}}\right]}\right]. \quad (21)$$

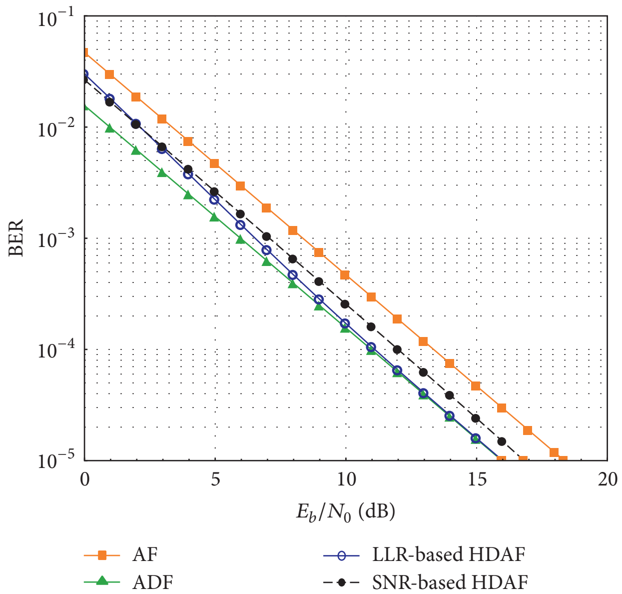

Figure 2: BER of the proposed hybrid relaying schemes and AF and ADF protocols for a symmetric cooperative system, where $d_{SR} = d_{RD} = 0.5$.

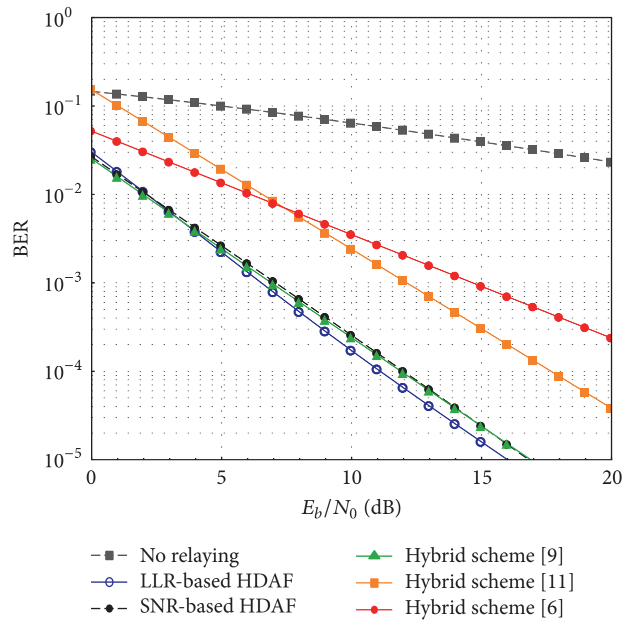

Figure 3: BER of the proposed hybrid relaying scheme and various others for a symmetric cooperative system, where $d_{SR} = d_{RD} = 0.5$.

5. Numerical Results

In this section, the performance of the proposed relaying scheme is evaluated numerically. The performance is measured in terms of BER curves. It is then compared with different relaying schemes, namely, the hybrid relaying schemes presented in [6, 9, 11].

Figure 2 shows the BER plotted against the SNR for the proposed LLR- and SNR-based HDAF schemes and AF and ADF protocols. As expected, performance of the proposed schemes is lower-bounded by that of AF protocol and upper-bounded by that of ADF protocol. With increasing SNR, the LLR-based scheme shows better error performance than AF protocol, over the SNR-based scheme. This is attributed to the higher sensitivity of the LLR-based scheme over the SNR-based scheme.

BER performance is also plotted against the SNR, for the proposed scheme against other hybrid schemes [6, 9, 11] for a symmetric relay positioning, with $d_{SR} = d_{RD} = 0.5$ in Figure 3. The proposed LLR-based HDAF scheme outperforms all the others, including the SNR-based one. For an asymmetric relay positioning, BER performance is plotted against the SNR, in Figures 4 and 5, for $d_{SR} = 0.2$ and $d_{SR} = 0.8$, respectively. In Figure 4, as the relay is positioned close to S, the proposed LLR-based HDAF scheme outperforms all the other hybrid schemes, followed closely by the SNR-based one. This is because as d_{SR} decreases, the probability of R correctly detecting the signal from S and thus employing ADF protocol increases, which results in an overall improved system performance. In Figure 5, as the relay is positioned close to D, only the hybrid scheme of [9] outperforms the proposed LLR- and SNR-based schemes. This is easily justified as follows: since the hybrid scheme of [9] is dependent on the correct detection of the received symbol at R, then, as d_{SR} increases, the probability of correct detection decreases and thus R is only active as an AF relay node. This in turn yields better BER performance, since AF protocol always provides better performance as d_{SR} increases.

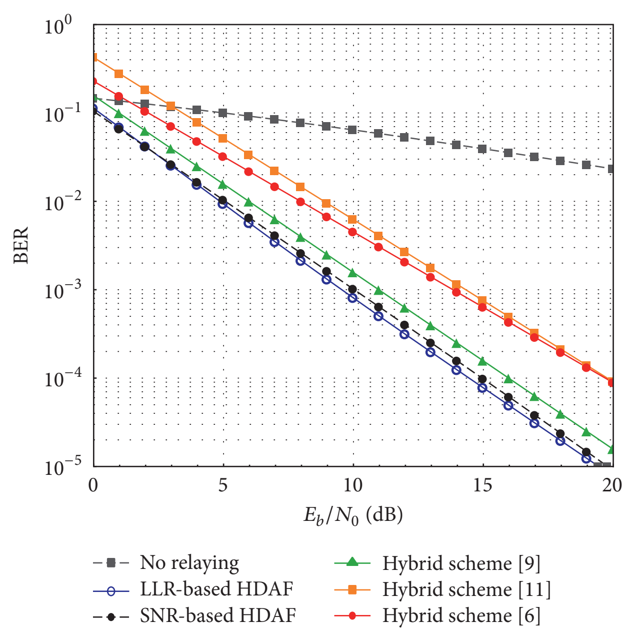

Figure 4: BER of the proposed hybrid relaying scheme and various others for an asymmetric cooperative system, where $d_{SR} = 0.2$ and $d_{RD} = 0.8$.

Tables 1 and 2 give the required SNR values, in dB, to reach a BER of 10^{-3} and 10^{-4}, respectively, by each of the proposed hybrid relaying schemes. It is observed that, in both cases, the LLR-based HDAF performs better than the SNR-based

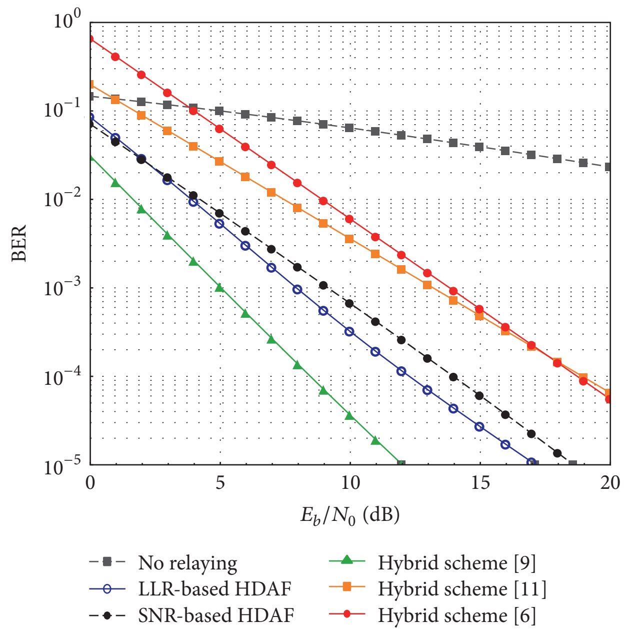

FIGURE 5: BER of the proposed hybrid relaying scheme and various others for an asymmetric cooperative system, where $d_{SR} = 0.8$ and $d_{RD} = 0.2$.

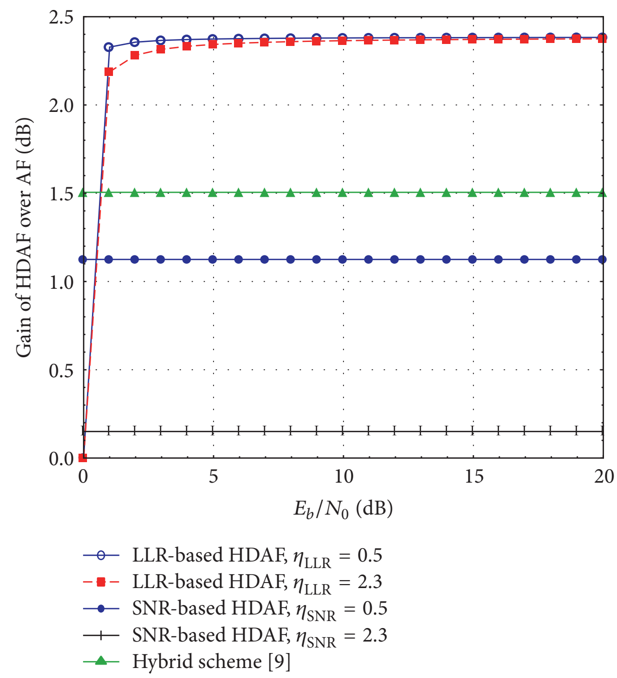

FIGURE 6: Gain of the proposed hybrid relaying schemes and that of the HDAF in [9] over AF protocol for a symmetric cooperative system, where $d_{SR} = 0.5$.

TABLE 1: A comparison of SNR values at BER of 10^{-3} for the proposed hybrid relaying schemes, at various d_{SR}.

d_{SR}	0.2	0.5	0.8
SNR values [dB] for LLR-based HDAF	9.5	6.4	7.9
SNR values [dB] for SNR-based HDAF	10	7	9

TABLE 2: A comparison of SNR values at BER of 10^{-4} for the proposed hybrid relaying schemes, at various d_{SR}.

d_{SR}	0.2	0.5	0.8
SNR values [dB] for LLR-based HDAF	14.3	11	12.1
SNR values [dB] for SNR-based HDAF	14.8	12	13.9

HDAF. Furthermore, it is clear that, for both schemes, the least power is required when R is located at the mid-distance between S and D (i.e., $d_{SR} = 0.5$).

Finally, Figure 6 shows the gain of several hybrid schemes over AF protocol, namely, the proposed LLR- and SNR-based schemes and that of [9]. It is clear that proposed LLR-based HDAF exhibits increasing gains with increasing SNR and these gains saturate at SNR ≅ 2.4 dB, irrespective of the value of η_{LLR}. It is noted, however, that as the value of η_{LLR} increases (from 0.5 to 2.3) the gain saturates at a slower rate. On the other hand, the proposed SNR-based scheme and the hybrid scheme of [9] introduce constant gains irrespective of the SNR value. Figure 6 also shows that the proposed SNR-based scheme provides gains of 0.15 dB and 1.1 dB for η_{SNR} values of 2.3 and 0.5, respectively, while the hybrid scheme of [9] provides a 1.5 dB gain over AF protocol.

6. Conclusions and Future Works

In this paper, we derived closed-form expressions for two hybrid relaying schemes for cooperative wireless networks whereby toggling between the ADF and the AF forwarding protocols is based on LLR- and SNR-based thresholds. We have shown that the proposed LLR-based scheme outperforms all existing ones, except for the case of R being very close to D, where only the hybrid scheme of [9] proved to be better. The proposed SNR-based hybrid scheme is unlike other SNR-based hybrid schemes found in the literature in that it toggles between ADF and AF protocols, while others toggle between FDF and AF protocols. Finally, the BER gain expressions of both proposed schemes over ADF and AF protocols have been derived.

Future works could include investigating the optimum LLR and SNR thresholds to be used. Also, BER expressions for higher order modulations could be derived for the proposed schemes.

Competing Interests

The authors declare no competing interests.

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