Performance Analysis of SNR-Based Incremental Hybrid Decode-Amplify-Forward Cooperative Relaying Protocol

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***Abstract*—In this paper, we propose and analyze a new relaying scheme for the three-node cooperative relaying system, named as incremental hybrid decode-amplify-forward relaying (IHDAF), where the relay may choose to keep silent or transmit message in decode-and-forward (DF) or amplify-and-forward (AF) mode based on the qualities of the channels among the source, relay, and destination. Closed-form expressions of the outage probability and bit error rate (BER) of the proposed IHDAF protocol are derived. The optimal relationship of the two important signal-to-noise ratio (SNR) thresholds at the relay and destination to decide whether cooperation is necessary and the cooperative mode has been achieved. Moreover, the effects of the power allocation schemes, SNR thresholds, and relay locations on the outage probability and BER of the IHDAF protocol are studied. Theoretical analysis and simulation results show that the IHDAF relaying scheme outperforms the incremental-selective DF (ISDF), incremental DF (IDF), and cooperative STBC schemes, especially when the relay is close to the destination.**

***Index Terms*—Incremental HDAF relaying, outage probability, bit error rate, SNR threshold, power allocation.**

I. INTRODUCTION

As an efficient wireless transmission technique, cooperative relaying technology has been proposed to obtain spatial diversity by forming virtual antenna arrays without the need of employing multiple antennas at transmitters or receivers [1], [2]. It is particularly attractive for small-size and antenna-limited wireless devices. There exist two main advantages of the cooperative relaying technology: the low transmit radio frequency (RF) power requirement and the spatial diversity gain, as illustrated in [3], [4]. The spectral, energy, and economic efficiency of cooperative relaying cellular networks was studied in [5], [6], which demonstrated an inherent tradeoff between spectral and energy efficiency. Also in [5] the economic efficiency metric was proposed to obtain the maximum economic profitability while maintaining gains in both spectral and energy efficiency. In cooperative systems, when a node helps others to forward messages, it will serve as a relay and realize the cooperative relaying diversity, such as amplify-and-forward (AF) and decode-and-forward (DF) protocols [7], [8]. For the AF relaying scheme, a relay simply amplifies the signals received from the source and retransmits them to the destination without performing any signal regeneration, which may lead to the propagation of noise and interference. Different from the AF scheme, the DF relaying will first detect the received signals and then retransmit the recovered signals to the destination, which requires more signal processing capacity and may forward the detected signals by error.

To make the decision based on a certain received signal-to-noise ratio (SNR) threshold at the relay is a simple way to reduce error propagation for cooperative systems [9]. The SNR-based selection relaying scheme in multi-relay cooperative networks with distributed space-time coding was studied in [10]. It was demonstrated that the error propagation could be effectively mitigated by employing the appropriate thresholds at the relays. The apparent tradeoff between the creation of the required diversity branches to the destination and the minimization of the error propagation risk has motivated a lot of research on the threshold-based relaying [11], [12]. By minimizing the symbol error rate (SER) of the cooperative system, the authors in [13] obtained the maximum instantaneous scaled harmonic mean function of its source-to-relay and relay-to-destination channel gains to determine the two cases: "when to cooperate" and "whom to cooperate with". The frame error rate (FER) of the hybrid relay selection (HRS) scheme was analyzed in [14] for general wireless relay networks. The HRS scheme, which can adaptively choose AF and DF protocols based on the decoding results at the relay, is very effective to achieve robust performance in wireless relay networks. The SERs of the single-relay DF and AF cooperative techniques were derived

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and the optimum power allocation for the cooperation systems based on the SER performance analysis was determined in [15], [16].

According to its characteristics and flexibility, DF relaying can be further classified as fixed DF (FDF) relaying, where the relay just decodes and forwards its received messages, and adaptive DF (ADF) relaying also known as selective DF relaying, where the relay transmission happens only in the case that its recovered signals are correct. In comparison with the FDF scheme, the selective DF relaying decides whether it is necessary to forward the received signals by evaluating the quality of the received signals with a predefined metric such as a certain SNR threshold. The authors in [9], [17] studied the performance of the selective DF and proposed an SNR optimal threshold to minimize the average bit error rate (BER).

The authors in [18] analyzed the hybrid decode-amplify-forward (HDAF) protocol which combines the AF and ADF schemes together with hard decision at the relay. If a signal is corrupted, instead of remaining silent during the second-hop transmission as in the ADF scheme, the HDAF scheme will make the relay operate in the AF mode and hence improve the system performance. The performance of SNR-based HDAF relaying cooperative diversity networks was investigated in [19], considering the impacts of relay location and SNR threshold on the outage probability.

Incremental relaying technique was studied in [7] which can achieve significant spectral efficiency improvement over the fixed and selective DF relaying schemes by exploiting the limited feedback from the destination. The outage probability of the incremental relaying protocol was presented in [20], where the retransmitted signals were sent by the relays that can overhear the transmission in contrast with the conventional hybrid Automatic Repeat-reQuest (ARQ) scheme. The authors in [21] investigated the end-to-end performance of the uncoded incremental relaying cooperative diversity networks considering the DF and AF relaying over independent non-identical Rayleigh fading channels. It was shown that the system performance is highly dependent on the error threshold at the destination and the incremental relaying has achievable data rate and throughput comparable to those of the direct transmission, particularly at medium and high SNR regions. A hybrid decode-amplify-forward (HDAF) incremental relaying cooperative protocol using SNR-based relay selection was investigated in multi-relay cooperative system [22], where one of the relays exploiting HDAF technique was chosen to retransmit the signal once the destination could not receive the source's signal correctly. The outage probability analysis of the HDAF-based incremental relaying cooperative system was presented in [23]. Other preliminary performance analysis and proposed protocols for the incremental relaying can be found in [24], [25]. A relay scheme combining the incremental DF (IDF) with selective DF relaying strategies, named as incremental-selective DF (ISDF) relaying, was presented in [26]. Theoretical analysis and simulation results demonstrated that the ISDF relaying scheme outperforms the IDF relaying scheme for all the cases investigated in the paper.

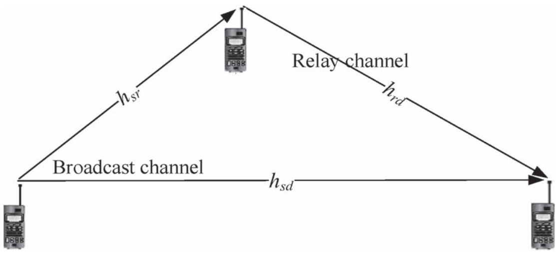

Fig. 1. A typical three-node half-duplex cooperative relaying system.

In this paper, we extend the research about the HDAF relaying strategy and take the incremental relaying scheme into consideration. The major contributions of this paper are summarized below.

1) A new relaying scheme termed as incremental HDAF (IHDAF) relaying is proposed, which combines the incremental relaying scheme with HDAF relaying protocol. The proposed IHDAF relaying scheme can greatly improve the system performance compared with the other two excellent relaying protocols, i.e., the ISDF relaying scheme and IDF relaying scheme.
2) Closed-form expressions of the outage probability and BER of the IHDAF relaying scheme are derived and presented over independent non-identical Rayleigh fading channels.
3) Based on the analysis of the BER performance, the optimal relationship of the SNR thresholds at the relay and the destination is obtained. The influence of the SNR thresholds and relay locations on the IHDAF system performance is also studied.
4) The effects of the power allocation schemes and relay locations on the outage probability of the IHDAF relaying scheme are investigated.

The rest of this paper is organized as follows. In Section II, the system model of the proposed IHDAF system is described. Then, closed-form expressions of the outage probability and BER of the proposed IHDAF system are derived in Section III. The optimal relationship of the SNR thresholds are also provided. In Section IV, simulation results are presented, which validate the theoretical analysis. We also demonstrate the better outage and BER performance of the proposed scheme compared with the existing IDF and ISDF schemes. Finally, Section V concludes the paper.

II. IHDAF RELAYING PROTOCOL

In this section, without loss of generality, we take the typical three-node half-duplex cooperative relaying system as an example system, which includes a source (*S*) node, a relay (*R*) node, and a destination (*D*) node as shown in Fig. 1. Using a novel cooperative multiple-input multiple-output (MIMO) channel modeling framework, a geometry-based stochastic model with high complexity was presented in [27]. To simplify the analysis of the IHDAF protocol in this paper, we only consider the Rayleigh fading channel model. The channel state information (CSI) is assumed to be available at the relay node and the destination node by using the training sequence. Additionally, we assume that each node is equipped with one omni-directional antenna.

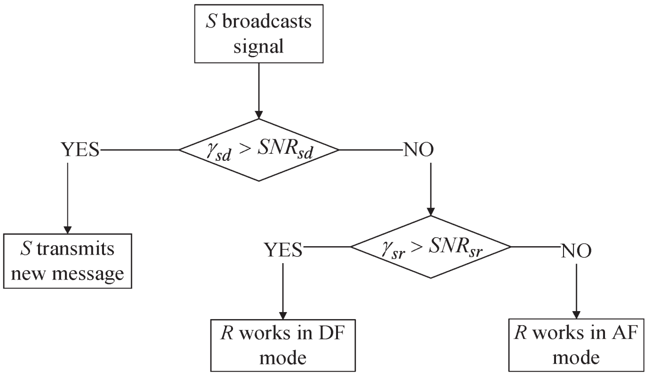

Fig. 2. Signal processing diagram of the IHDAF protocol.

The operation of the three-node half-duplex IHDAF cooperative relaying system is shown in Fig. 2. In the first phase, the source S broadcasts the signal to the relay R and the destination D simultaneously. Then, D will decide whether it can detect the message sent from the source correctly or not based on the SNR threshold (SNR_{sd}) at the destination. Here, SNR_{sd} is the minimum SNR for D to make correct detection without the help of the relay. If the instantaneous SNR of the $S-D$ link exceeds SNR_{sd}, R will keep silent and S will send a new message in the second phase. Otherwise, R will be required to forward the decoded signal to D. Before forwarding the received signal, R will evaluate the quality of the received signal in the proposed scheme on the basis of the SNR threshold (SNR_{sr}) at the relay and SNR_{sr} provides the minimum SNR for R to decode the received message from S successfully. Only when the instantaneous SNR of the $S-R$ link exceeds SNR_{sr}, R will decode and forward the received message. Otherwise, the relay will operate in the AF mode and try to improve the system performance due to the poor channel condition of the $S-R$ link, which is different from the ISDF relaying scheme. Then, in the second phase, R will forward the signal and D will combine the signals received in the two phases with maximal ratio combining (MRC) technique [28] and coherent detection. Since the HDAF relaying protocol is employed in the second phase, this scheme is termed as incremental HDAF relaying.

In the following, the signal processing process of the IHDAF protocol is presented. In the first phase, the signals received at the destination and the relay can be denoted as

$$y_{sd} = \sqrt{P_S} h_{sd} x_s + n_d \tag{1}$$

$$y_{sr} = \sqrt{P_S} h_{sr} x_s + n_r \tag{2}$$

respectively, where h_{sd} and h_{sr} are the channel coefficients of the $S-D$ and $S-R$ links, respectively, x_s is the transmitted signal from the source S with unit average power, n_d and n_r are independently and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and variance N_0, and P_S is the transmission power of the source.

In the second phase, if the relay works in the DF mode, then the received signal at the destination can be given by

$$y_{rd} = \sqrt{P_R} h_{rd} x_r + n_{rd} \tag{3}$$

where h_{rd} is the channel coefficient of the $R-D$ link, x_r is the signal sent by the relay based on its decoding condition of x_s, and P_R is the transmission power of the relay. Similar to n_d in (1) and n_r in (2), the noise component n_{rd} is also assumed to be i.i.d. complex Gaussian random variable with zero mean and variance N_0. Additionally, we have $P = P_s + P_r$ with $P_s = \delta P$ and $P_r = (1-\delta)P$, where $\delta \in (0, 1]$ and $(1-\delta) \in [0, 1)$ denote the fractions of the total end-to-end transmission power P allocated to the source and relay, respectively. The system signal-to-noise ratio can be written as $\rho = SNR = P/N_0$.

If the relay operates in the AF mode during the second phase, the received signal at the destination can be expressed as

$$y_{rd} = \beta h_{rd} y_{sr} + n_{rd} \tag{4}$$

with the amplification coefficient $\beta = \frac{\sqrt{P_R}}{\sqrt{P_S |h_{sr}|^2 + N_0}}$.

According to the analysis above, the instantaneous SNRs of the $S-D$, $S-R$, and $R-D$ links can be expressed as $\gamma_{sd} = |h_{sd}|^2 P_S/N_0$, $\gamma_{sr} = |h_{sr}|^2 P_S/N_0$, and $\gamma_{rd} = |h_{rd}|^2 P_R/N_0$, respectively. Therefore, the link average SNRs are correspondingly equal to $\overline{\gamma}_{sd} = E(|h_{sd}|^2) P_S/N_0$, $\overline{\gamma}_{sr} = E(|h_{sr}|^2) P_S/N_0$, and $\overline{\gamma}_{rd} = E(|h_{rd}|^2) P_r/N_0$, respectively, where $E(\cdot)$ denotes the statistical average operator. All the channel coefficients here follow Rayleigh fading distribution. The probability density function (PDF) of γ_i ($i \in \{sd, sr, rd\}$) can be written as [29]

$$f_{\gamma_i}(\gamma) = \frac{1}{\overline{\gamma}_i} e^{-\frac{-\gamma}{\overline{\gamma}_i}}, \quad \text{for } \gamma \geq 0. \tag{5}$$

We can readily obtain that $P(\gamma_i > a) = \exp(-a/\overline{\gamma}_i)$. With the same method as in [21], we set $E(|h_{sd}|^2) = d_{sd}^{-\alpha}$, $E(|h_{sr}|^2) = d_{sr}^{-\alpha}$, and $E(|h_{rd}|^2) = d_{rd}^{-\alpha}$ to capture the effect of the path loss on the system error performance, where d_{ij} ($i \in \{s, r\}, j \in \{r, d\}$) is the distance between nodes i and j and $\alpha \in [3, 5]$ is the path loss factor.

III. PERFORMANCE ANALYSIS OF THE IHDAF RELAYING PROTOCOL

A. Outage Probability Analysis

In this subsection, our purpose is to derive the outage probability of the IHDAF relaying protocol. To guarantee the successful decoding at the terminal nodes, we assume that $SNR_{sd} > 2^R - 1$ and $SNR_{sr} > 2^{2R} - 1$, where R is the system information rate. With these assumptions, if the received SNR at D exceeds SNR_{sd} in the first phase, the direct transmission will not encounter the outage case. The system outage probability can be expressed as

$$\begin{aligned} P_{IHDAF}(outage) = P(\gamma_{sd} \leq SNR_{sd}) \big[& P(\gamma_{sr} > SNR_{sr}) \\ & P_{DF}(outage) + P(\gamma_{sr} \leq SNR_{sr}) P_{AF}(outage) \big] \end{aligned} \tag{6}$$

where $P_{AF}(outage)$ and $P_{DF}(outage)$ are the the outage probabilities in the case of AF and DF protocols, respectively. They can be further expressed as

$$P_{DF}(outage) = P(C_{DF} < R \mid \gamma_{sd} \leq SNR_{sd}, \gamma_{sr} > SNR_{sr}) \tag{7}$$

$$P_{AF}(outage) = P(C_{AF} < R \mid \gamma_{sd} \leq SNR_{sd}, \gamma_{sr} \leq SNR_{sr}) \tag{8}$$

respectively, where C_{DF} is the channel capacity when the relay employs the DF protocol and C_{AF} is the channel capacity when the relay works in the AF protocol. We can express C_{DF} and C_{AF} as

$$C_{DF} = \frac{1}{2}\log_2\left(1 + min(\gamma_{sr}, \gamma_{sd} + \gamma_{rd})\right) \tag{9}$$

$$C_{AF} = \frac{1}{2}\log_2\left(1 + \gamma_{sd} + \frac{\gamma_{sr}\gamma_{rd}}{\gamma_{sr} + \gamma_{rd} + 1}\right) \tag{10}$$

respectively.

To obtain the expressions of $P_{DF}(outage)$ and $P_{AF}(outage)$ is the key issue to obtain the final system outage probability. $P_{DF}(outage)$ can be expressed as

$$\begin{aligned} P_{DF}(outage) &= P\left(\gamma_{sd} + \gamma_{rd} < 2^{2R} - 1 | \gamma_{sd} \le SNR_{sd}\right) \\ &= \Omega_1. \end{aligned} \tag{11}$$

In the calculation of $P_{DF}(outage)$, we need to consider two conditions, $SNR_{sd} \le 2^{2R} - 1$ and $SNR_{sd} > 2^{2R} - 1$. Considering $SNR_{sd} \le 2^{2R} - 1$, we have

$$\begin{aligned} &P_{DF}(outage) = P\left(\gamma_{sd} + \gamma_{rd} < 2^{2R} - 1 | \gamma_{sd} \le SNR_{sd}\right) \\ &= \int_0^{SNR_{sd}} \int_0^{2^{2R}-1-x} f_{\gamma_{sd}}(x|\gamma_{sd} \le SNR_{sd}) f_{\gamma_{rd}}(y) dxdy \\ &= \begin{cases} 1 - \frac{\overline{\gamma}_{rd}}{\overline{\gamma}_{rd} - \overline{\gamma}_{sd}} \frac{e^{-(2^{2R}-1)/\overline{\gamma}_{rd}}}{1 - e^{-SNR_{sd}/\overline{\gamma}_{sd}}} \\ \times \left(1 - e^{-\left(\frac{1}{\overline{\gamma}_{sd}} - \frac{1}{\overline{\gamma}_{rd}}\right) SNR_{sd}}\right), & \frac{1}{\overline{\gamma}_{sd}} \ne \frac{1}{\overline{\gamma}_{rd}} \\ 1 - \frac{e^{-(2^{2R}-1)/\overline{\gamma}_{rd}}}{1 - e^{-SNR_{sd}/\overline{\gamma}_{sd}}} \frac{SNR_{sd}}{\overline{\gamma}_{sd}}, \frac{1}{\overline{\gamma}_{sd}} = \frac{1}{\overline{\gamma}_{rd}}. \end{cases} \end{aligned} \tag{12}$$

For $SNR_{sd} > 2^{2R} - 1$, $P_{DF}(outage)$ is derived as

$$\begin{aligned} &P_{DF}(outage) = P\left(\gamma_{sd} + \gamma_{rd} < 2^{2R} - 1 | \gamma_{sd} \le SNR_{sd}\right) \\ &= \int_0^{2^{2R}-1} \int_0^{2^{2R}-1-x} f_{\gamma_{sd}}(x|\gamma_{sd} \le SNR_{sd}) f_{\gamma_{rd}}(y) dxdy \\ &= \begin{cases} \left(1 - \frac{\overline{\gamma}_{rd} e^{-(2^{2R}-1)/\overline{\gamma}_{rd}} - \overline{\gamma}_{sd} e^{-(2^{2R}-1)/\overline{\gamma}_{sd}}}{\overline{\gamma}_{rd} - \overline{\gamma}_{sd}}\right) \\ \times \frac{1}{1 - e^{-SNR_{sd}/\overline{\gamma}_{sd}}}, & \frac{1}{\overline{\gamma}_{sd}} \ne \frac{1}{\overline{\gamma}_{rd}} \\ \left(1 - \frac{(2^{2R} - 1 + \overline{\gamma}_{sd}) e^{-(2^{2R}-1)/\overline{\gamma}_{sd}}}{\overline{\gamma}_{sd}}\right) \\ \times \frac{1}{1 - e^{-SNR_{sd}/\overline{\gamma}_{sd}}}, & \frac{1}{\overline{\gamma}_{sd}} = \frac{1}{\overline{\gamma}_{rd}}. \end{cases} \end{aligned} \tag{13}$$

With reference to [30] and [32], and considering the AF scheme with MRC technique, the overall received SNR at the destination can be written approximately by its upper bound as

$$\gamma_d^{AF} = \gamma_{sd} + \frac{\gamma_{sr}\gamma_{rd}}{\gamma_{sr} + \gamma_{rd} + 1} < \gamma_{AF} \tag{14}$$

where $\gamma_{AF} = \gamma_{sd} + \min(\gamma_{sr}, \gamma_{rd})$. As γ_{AF} is analytically more tractable than γ_d^{AF}, γ_{AF} will be used in the following derivation. Because $\gamma_{sr} \le SNR_{sr}$, we set $\gamma_{min} = min(\gamma_{sr}, \gamma_{rd})$ and express its cumulative distribution function (CDF) as

$$F_{\gamma_{min}}(x) = \begin{cases} 1 - e^{-(1/\overline{\gamma}_{sr} + 1/\overline{\gamma}_{rd})x}, & x < SNR_{sr} \\ 1, & x \ge SNR_{sr}. \end{cases} \tag{15}$$

The outage probability in the case of AF protocol can be further written as

$$\begin{aligned} P_{AF}(outage) &= P\left(\gamma_{sd} + \frac{\gamma_{sr}\gamma_{rd}}{\gamma_{sr} + \gamma_{rd} + 1} < 2^{2R} - 1 \mid \Psi_1, \Psi_2\right) \\ &> P\left(\gamma_{sd} + \min(\gamma_{sr}, \gamma_{rd}) < 2^{2R} - 1 \mid \Psi_1, \Psi_2\right) \\ &\doteq \Omega_2, \end{aligned} \tag{16}$$

where Ψ_1 and Ψ_2 denote the event of $\gamma_{sd} \le SNR_{sd}$ and $\gamma_{sr} \le SNR_{sr}$, respectively.

According to [31], we can get the expression of $P(\gamma_{\min} < 2^{2R} - 1 \mid \Psi_2)$ and derive its PDF as

$$\begin{aligned} &f_{\gamma_{\min}}(x \mid \Psi_2) \\ &= \frac{\partial}{\partial\gamma}\left[\frac{\Pr\left(\min(\gamma_{sr}, \gamma_{rd}) \le x, \Psi_2\right)}{\Pr(\Psi_2)}\right] \\ &= \begin{cases} \frac{\mu\exp(-\mu x) - \exp\left(-\frac{SNR_{sr}}{\overline{\gamma}_{sr}}\right)\frac{1}{\overline{\gamma}_{rd}}\exp\left(-\frac{x}{\overline{\gamma}_{rd}}\right)}{1 - \exp\left(-\frac{SNR_{sr}}{\overline{\gamma}_{sr}}\right)}, & x \le SNR_{sr} \\ 0, & x > SNR_{sr} \end{cases} \end{aligned} \tag{17}$$

where $\mu = 1/\overline{\gamma}_{sr} + 1/\overline{\gamma}_{rd}$.

For the calculation of $P(\gamma_{sd} + \gamma_{min} < 2^{2R} - 1 \mid \Psi_1, \Psi_2)$, we should also consider two cases, $SNR_{sd} \le 2^{2R} - 1$ and $SNR_{sd} > 2^{2R} - 1$. When $SNR_{sd} \le 2^{2R} - 1$, we can obtain

$$\begin{aligned} &P\left(\gamma_{sd} + \gamma_{min} < 2^{2R} - 1 \mid \Psi_1, \Psi_2\right) \\ &= \int_0^{SNR_{sd}} \int_0^{2^{2R}-1-x} f_{\gamma_{sd}}(x \mid \Psi_1) f_{\gamma_{min}}(y \mid \Psi_2) dxdy \\ &= I_1 - \frac{1}{1 - \exp\left(-\frac{SNR_{sr}}{\overline{\gamma}_{sr}}\right)} \frac{1}{1 - \exp\left(-\frac{SNR_{sd}}{\overline{\gamma}_{sd}}\right)} (I_2 - I_3) \end{aligned} \tag{18}$$

where

$$I_1 = \int_0^{SNR_{sd}} f_{\gamma_{sd}}(x \mid \Psi_1) dx = 1 \tag{19}$$

$$\begin{aligned} I_2 &= \int_0^{SNR_{sd}} f_{\gamma_{sd}}(x \mid \Psi_1) \exp\left(-\mu(2^{2R} - 1 - x)\right) dx \\ &= \begin{cases} \frac{\exp(-(2^{2R}-1)\mu)}{\overline{\gamma}_{sd}} \frac{1 - \exp\left(-\left(\frac{1}{\overline{\gamma}_{sd}} - \mu\right) SNR_{sd}\right)}{\frac{1}{\overline{\gamma}_{sd}} - \mu}, & \frac{1}{\overline{\gamma}_{sd}} \ne \mu \\ \frac{\exp(-(2^{2R}-1)\mu) SNR_{sd}}{\overline{\gamma}_{sd}}, & \frac{1}{\overline{\gamma}_{sd}} = \mu \end{cases} \end{aligned} \tag{20}$$

$$I_3 = \begin{cases} \exp\left(-\frac{SNR_{sr}}{\overline{\gamma}_{sr}}\right) \exp\left(-\frac{2^{2R}-1}{\overline{\gamma}_{rd}}\right) \\ \times \frac{\overline{\gamma}_{rd}\left(1 - \exp\left(-\left(\frac{1}{\overline{\gamma}_{sd}} - \frac{1}{\overline{\gamma}_{rd}}\right) SNR_{sd}\right)\right)}{\overline{\gamma}_{rd} - \overline{\gamma}_{sd}}, \overline{\gamma}_{sd} \ne \overline{\gamma}_{rd} \\ \exp\left(-\frac{SNR_{sr}}{\overline{\gamma}_{sr}}\right) \exp\left(-\frac{2^{2R}-1}{\overline{\gamma}_{rd}}\right) \frac{SNR_{sd}}{\overline{\gamma}_{sd}}, \overline{\gamma}_{sd} = \overline{\gamma}_{rd}. \end{cases} \tag{21}$$

Considering the outage case and $SNR_{sd} > 2^{2R} - 1$, the upper limit SNR_{sd} of the integral in terms of x in (18) can be replaced by $2^{2R} - 1$. Hence, the expressions of I_1, I_2, and I_3 above can be rewritten as

$$I_1 = \int_0^{2^{2R}-1} f_{\gamma_{sd}}(x \mid \Psi_1) dx = \frac{1 - \exp\left(-\frac{2^{2R}-1}{\overline{\gamma}_{sd}}\right)}{1 - \exp\left(-\frac{SNR_{sd}}{\overline{\gamma}_{sd}}\right)} \tag{22}$$

$$\begin{aligned} I_2 &= \int_0^{2^{2R}-1} f_{\gamma_{sd}}(x \mid \Psi_1) \exp\left(-\mu(2^{2R} - 1 - x)\right) dx \\ &= \begin{cases} \frac{\exp\left(-(2^{2R}-1)\mu\right)}{\overline{\gamma}_{sd}} \frac{1-\exp\left(-\left(\frac{1}{\overline{\gamma}_{sd}}-\mu\right)(2^{2R}-1)\right)}{\frac{1}{\overline{\gamma}_{sd}}-\mu}, & \frac{1}{\overline{\gamma}_{sd}} \neq \mu \\ \frac{\exp\left(-(2^{2R}-1)\mu\right)(2^{2R}-1)}{\overline{\gamma}_{sd}}, & \frac{1}{\overline{\gamma}_{sd}} = \mu \end{cases} \end{aligned} \tag{23}$$

$$I_3 = \begin{cases} \exp\left(-\frac{SNR_{sr}}{\overline{\gamma}_{sr}}\right) \exp\left(-\frac{2^{2R}-1}{\overline{\gamma}_{rd}}\right) \\ \times \frac{\overline{\gamma}_{rd}\left(1-\exp\left(-\left(\frac{1}{\overline{\gamma}_{sd}}-\frac{1}{\overline{\gamma}_{rd}}\right)(2^{2R}-1)\right)\right)}{\overline{\gamma}_{rd}-\overline{\gamma}_{sd}}, & \overline{\gamma}_{sd} \neq \overline{\gamma}_{rd} \\ \exp\left(-\frac{SNR_{sr}}{\overline{\gamma}_{sr}}\right) \exp\left(-\frac{2^{2R}-1}{\overline{\gamma}_{rd}}\right) \frac{2^{2R}-1}{\overline{\gamma}_{sd}}, & \overline{\gamma}_{sd} = \overline{\gamma}_{rd}. \end{cases} \tag{24}$$

Substituting I_1, I_2, and I_3 into (18) and (16), the expression of $P_{AF}(outage)$ can be achieved. Based on (5), we have $P(\gamma_{sr} \leq SNR_{sd}) = 1 - \exp(-\frac{SNR_{sd}}{\overline{\gamma}_{sd}})$, $P(\gamma_{sr} \leq SNR_{sr}) = 1 - \exp(-\frac{SNR_{sr}}{\overline{\gamma}_{sr}})$, and $P(\gamma_{sr} > SNR_{sr}) = \exp(-\frac{SNR_{sr}}{\overline{\gamma}_{sr}})$. Then, substituting $P_{DF}(outage)$ obtained in (12) and $P_{AF}(outage)$ obtained in (16) into (6), the closed-form expression for the outage probability of the IHDAF relaying cooperative system can be finally obtained over Rayleigh fading channels and it can be expressed as

$$\begin{aligned} P_{outage} &\doteq \left(1 - \exp\left(-\frac{SNR_{sd}}{\overline{\gamma}_{sd}}\right)\right) \exp\left(-\frac{SNR_{sr}}{\overline{\gamma}_{sr}}\right) \Omega_1 \\ &+ \left(1 - \exp\left(-\frac{SNR_{sd}}{\overline{\gamma}_{sd}}\right)\right) \left(1 - \exp\left(-\frac{SNR_{sr}}{\overline{\gamma}_{sr}}\right)\right) \Omega_2. \end{aligned} \tag{25}$$

According to the definition and the derivation of the diversity order in [34], [35], we have *Lemma* 1.

Lemma 1: The diversity order for the IHDAF protocol is obtained as

$$D = \begin{cases} 1, & \gamma_{sd} > SNR_{sd} \\ 2, & \gamma_{sd} \leq SNR_{sd}. \end{cases} \tag{26}$$

Proof: The proof is given in Appendix A. ■

It is shown that the IHDAF scheme can achieve the full diversity order of 2 if $\gamma_{sd} \leq SNR_{sd}$ is satisfied, which means that the cooperative transmission is taken into consideration. If $\gamma_{sd} > SNR_{sd}$, the IHDAF scheme only has the diversity order of 1, which means that only the direct transmission works, whereas it can save the channels and improve the spectral efficiency with the application of incremental relaying.

B. BER Performance Analysis

In this subsection, we aim to derive the BER of the IHDAF relaying protocol, which can be expressed as

$$\begin{aligned} P_{IHDAF}(e) &= (1-\Pr(\gamma_{sd} \leq SNR_{sd}))\, P_{direct}(e) \\ &+ \Pr(\gamma_{sd} \leq SNR_{sd}) \Pr(\gamma_{sr} > SNR_{sr}) P_{DF}(e) \\ &+ \Pr(\gamma_{sd} \leq SNR_{sd})\, (1-\Pr(\gamma_{sr} > SNR_{sr}))\, P_{AF}(e) \end{aligned} \tag{27}$$

where $P_{direct}(e)$ is the error probability when the destination decides that the relay has no need to forward the received information from the source, $P_{DF}(e)$ is the probability that an error occurs after the destination combines the signals from the source and the relay in the DF mode, while $P_{AF}(e)$ is the error probability at destination when the relay is required to forward the signal in the AF mode.

The error probabilities with BPSK modulation over a point-to-point link conditioned on the instantaneous link SNR (γ) and average link SNR ($\overline{\gamma}$) are given by [36]

$$P(e \mid \gamma) = Q(\sqrt{2\gamma}) \tag{28}$$

$$P(e \mid \overline{\gamma}) = \frac{1}{2}\left(1 - \sqrt{\overline{\gamma}/(1+\overline{\gamma})}\right) \tag{29}$$

respectively, where the Q function is defined as $Q(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-t^2/2}\, dt$.

If the instantaneous SNR of the $S - D$ link, γ_{sd}, exceeds the threshold value SNR_{sd}, the destination will perform the detection only based on the direct transmission from the source. The corresponding error probability can be expressed as

$$P_{direct}(e) = \int_0^\infty P(e \mid \gamma) f_{\gamma_{sd}}(\gamma \mid \gamma_{sd} > SNR_{sd})\, d\gamma \tag{30}$$

where

$$\begin{aligned} f_{\gamma_{sd}}(\gamma \vert \gamma_{sd} > SNR_{sd}) &= \frac{\partial}{\partial \gamma}\left[\frac{\Pr(SNR_{sd} < \gamma_{sd} \leq \gamma)}{\Pr(\gamma_{sd} > SNR_{sd})}\right] \\ &= \begin{cases} \frac{e^{SNR_{sd}/\overline{\gamma}_{sd}} e^{-\gamma/\overline{\gamma}_{sd}}}{\overline{\gamma}_{sd}}, & \gamma > SNR_{sd} \\ 0, & \gamma \leq SNR_{sd}. \end{cases} \end{aligned} \tag{31}$$

Substituting (31) into (30) and making the partial integration, the error probability of the direction transmission can be calculated as

$$\begin{aligned} P_{direct}(e) &= Q\left(\sqrt{2SNR_{sd}}\right) - e^{SNR_{sd}/\overline{\gamma}_{sd}} \sqrt{\frac{\overline{\gamma}_{sd}}{\overline{\gamma}_{sd}+1}} \\ &\times Q\left(\sqrt{\frac{2SNR_{sd}(1+\overline{\gamma}_{sd})}{\overline{\gamma}_{sd}}}\right). \end{aligned} \tag{32}$$

When the instantaneous SNR of the $S - D$ link, γ_{sd}, is no larger than SNR_{sd} and the instantaneous SNR of the $S - R$ link, γ_{sr}, exceeds SNR_{sr}, the relay will work in the DF mode. Then, the destination will combine the signals from both the source and relay and make the decision. In this case, the error probability can be formulated as

$$P_{DF}(e) = P_R(e) P_{prop}(e) + (1-P_R(e))\, P_{coop}(e) = \Theta_1 \tag{33}$$

where $P_R(e)$ is the detection error probability of the relay, which depends on the threshold SNR_{sr}, and $P_{prop}(e)$ denotes the probability of error propagation event, which is referred to the case that an error occurs after the destination combines the signal from the source and the incorrectly detected signal from the relay. The error probability of the cooperative case is denoted by $P_{coop}(e)$, which is referred to the event that an error occurs after the destination combines the signal from the source and the correctly detected signal from the relay.

Using the same method as we calculate (32), the error probability of the relay is obtained as

$$\begin{aligned} P_R(e) &= \int_0^\infty P(e \mid \gamma) f_{\gamma_{sr}}(\gamma \mid \gamma_{sr} > SNR_{sr})\, d\gamma \\ &= Q\left(\sqrt{2SNR_{sr}}\right) \\ &\quad - e^{\frac{SNR_{sr}}{\overline{\gamma}_{sr}}} \sqrt{\frac{\overline{\gamma}_{sr}}{1+\overline{\gamma}_{sr}}}\, Q\left(\sqrt{\frac{2SNR_{sr}(1+\overline{\gamma}_{sr})}{\overline{\gamma}_{sr}}}\right). \end{aligned} \tag{34}$$

There still exists a decision error for the relay to transmit an erroneous signal to the destination, even when the relay measures the quality of the received signal before forwarding it. Such error propagation can be avoided by appropriately choosing SNR_{sr} at the relay. When the relay makes an incorrect detection and forwards an erroneous signal to the destination, the error propagation probability can be derived and approximated as (as shown in Appendix II of [33])

$$\begin{aligned} P_{prop}(e) &\approx \int_0^\infty \int_{\gamma_1}^\infty f_{\gamma_{sd}}(\gamma_1 | \gamma_{sd} \le SNR_{sd}) f_{\gamma_{rd}}(\gamma_2) d\gamma_1 d\gamma_2 \\ &= \frac{\overline{\gamma}_{rd}}{\overline{\gamma}_{sd} + \overline{\gamma}_{rd}} \frac{1 - e^{-SNR_{sd}(1/\overline{\gamma}_{sd} + 1/\overline{\gamma}_{rd})}}{1 - e^{-SNR_{sd}/\overline{\gamma}_{sd}}}. \end{aligned} \tag{35}$$

When the relay decodes correctly, an error may also occur after the destination combines the signals from the source and relay. This error probability can be written as [29]

$$P_{coop}(e) = \int_0^\infty Q\left(\sqrt{2\gamma}\right) f_{\gamma_t}(\gamma \mid \gamma_{sd} \le SNR_{sd})\, d\gamma \tag{36}$$

where $\gamma_t = \gamma_{sd} + \gamma_{rd}$ is the total instantaneous SNR of the output of the MRC combiner at the destination.

Proposition 1: The error probability of the cooperative case $P_{coop}(e)$ can be calculated under two conditions, $\overline{\gamma}_{sd} \neq \overline{\gamma}_{rd}$ and $\overline{\gamma}_{sd} = \overline{\gamma}_{rd}$. With $\overline{\gamma}_{sd} \neq \overline{\gamma}_{rd}$, we have

$$\begin{aligned} P_{coop}(e) &= \frac{1}{(\overline{\gamma}_{rd} - \overline{\gamma}_{sd})(1 - e^{-SNR_{sd}/\overline{\gamma}_{sd}})} \Bigg(\frac{\overline{\gamma}_{sd}}{2} \sqrt{\frac{\overline{\gamma}_{sd}}{1+\overline{\gamma}_{sd}}} \\ &\quad - \frac{\overline{\gamma}_{rd}}{2} \sqrt{\frac{\overline{\gamma}_{rd}}{1+\overline{\gamma}_{rd}}} - \overline{\gamma}_{sd} \sqrt{\frac{\overline{\gamma}_{sd}}{1+\overline{\gamma}_{sd}}} Q(\sqrt{2a}) \\ &\quad + (\overline{\gamma}_{sd} - \overline{\gamma}_{rd}) Q(\sqrt{2SNR_{sd}}) e^{-SNR_{sd}/\overline{\gamma}_{sd}} - \frac{\overline{\gamma}_{sd} - \overline{\gamma}_{rd}}{2} \\ &\quad + \overline{\gamma}_{rd} \sqrt{\frac{\overline{\gamma}_{rd}}{1+\overline{\gamma}_{rd}}} Q(\sqrt{2b}) e^{-SNR_{sd}(1/\overline{\gamma}_{sd} - 1/\overline{\gamma}_{rd})} \Bigg) \end{aligned} \tag{37}$$

where $a = SNR_{sd}(1+\overline{\gamma}_{sd})/\overline{\gamma}_{sd}$, and $b = SNR_{sd}(1+\overline{\gamma}_{rd})/\overline{\gamma}_{rd}$.

When $\overline{\gamma}_{sd} = \overline{\gamma}_{rd}$, we get

$$\begin{aligned} P_{coop}(e) &= A\left(-\overline{\gamma}_{sd} SNR_{sd} e^{-\frac{SNR_{sd}}{\overline{\gamma}_{sd}}} - \overline{\gamma}_{sd}^2 e^{-fracSBR_{sd}\overline{\gamma}_{sd}} \right) \\ &\quad \times Q(\sqrt{2SNR_{sd}}) + \frac{A\overline{\gamma}_{sd}^2}{2} + A\Bigg(\frac{\overline{\gamma}_{sd}^2 \sqrt{SNR_{sd}}}{2\sqrt{\pi}(1+\overline{\gamma}_{sd})} e^{-\frac{(1+\overline{\gamma}_{sd})SNR_{sd}}{\overline{\gamma}_{sd}}} \\ &\quad - \frac{\overline{\gamma}_{sd}^{\frac{5}{2}}}{2(1+\overline{\gamma}_{sd})^{\frac{3}{2}}} \left(\frac{1}{2} - Q(\sqrt{2a}) \right) \Bigg) + A\left(\overline{\gamma}_{sd} \sqrt{\frac{\overline{\gamma}_{sd}}{1+\overline{\gamma}_{sd}}} \left(Q(\sqrt{2a}) - \frac{1}{2} \right) \right) \\ &\quad + ASNR_{sd} \left(B - \overline{\gamma}_{sd} \sqrt{\frac{\overline{\gamma}_{sd}}{1+\overline{\gamma}_{sd}}} Q(\sqrt{2a}) \right) \end{aligned} \tag{38}$$

where $A = 1/(\overline{\gamma}_{sd}^2(1 - e^{-\frac{SNR_{sd}}{\overline{\gamma}_{sd}}}))$ and $B = \overline{\gamma}_{sd} e^{-\frac{SNR_{sd}}{\overline{\gamma}_{sd}}} Q(\sqrt{2SNR_{sd}})$.

Proof: The proof is given in Appendix B. ■

When the instantaneous SNR of the $S - R$ link is less than SNR_{sr}, instead of remaining silent during the second phase in the ISDF scheme, R will employ AF relaying scheme in the IHDAF scheme to improve the system performance. In this case, the error probability can be given by

$$\begin{aligned} P_{AF}(e) &= \int_0^\infty P(e \mid \gamma) f_{\gamma_{AF}}\left(\gamma \mid \Psi_1', \Psi_2'\right) d\gamma \\ &= \int_0^\infty Q(\sqrt{2\gamma}) f_{\gamma_{AF}}\left(\gamma \mid \Psi_1', \Psi_2'\right) d\gamma = \Theta_2 \end{aligned} \tag{39}$$

where Ψ_1' and Ψ_2' denote the event of $\gamma_{sd} \le SNR_{sd}$ and $\gamma_{sr} \le SNR_{sr}$, respectively.

Proposition 2: The error probability $P_{AF}(e)$ in (39) can be divided into the positive and negative parts as

$$P_{AF}(e) = P_{AF-P}(e) - P_{AF-N}(e) \tag{40}$$

where

$$\begin{aligned} &P_{AF-P}(e) \\ &= \frac{\mu}{A_0\left(\mu - 1/\overline{\gamma}_{sd}\right)\overline{\gamma}_{sd}} \Big(e^{(\mu - 1/\overline{\gamma}_{sd})SNR_{sd}} H_2(SNR_{sd}, 1/\mu)/\mu \\ &\quad + \overline{\gamma}_{sd} H_1(SNR_{sd}, \overline{\gamma}_{sd}) - H_1(SNR_{sr}, 1/\mu)/\mu \\ &\quad - e^{-(\mu - 1/\overline{\gamma}_{sd})SNR_{sr}} \overline{\gamma}_{sd} H_2(SNR_{sr}, \overline{\gamma}_{sd}) \Big) \end{aligned} \tag{41}$$

and

$$\begin{aligned} &P_{AF-N}(e) \\ &= \frac{e^{-SNR_{sr}/\overline{\gamma}_{sr}}}{A_0(\overline{\gamma}_{sd} - \overline{\gamma}_{rd})} \Big(\overline{\gamma}_{sd} H_1(SNR_{sd}, \overline{\gamma}_{sd}) - \overline{\gamma}_{rd} H_1(SNR_{sr}, \overline{\gamma}_{rd}) \\ &\quad + e^{(1/\overline{\gamma}_{rd} - 1/\overline{\gamma}_{sd})SNR_{sd}} \overline{\gamma}_{rd} H_2\left(SNR_{sd}, \overline{\gamma}_{rd}\right) \\ &\quad - e^{-(1/\overline{\gamma}_{rd} - 1/\overline{\gamma}_{sd})SNR_{sr}} \overline{\gamma}_{sd} H_2(SNR_{sr}, \overline{\gamma}_{sd}) \Big) \end{aligned} \tag{42}$$

with $A_0 = (1 - e^{-SNR_{sd}/\overline{\gamma}_{sd}})(1 - e^{-SNR_{sr}/\overline{\gamma}_{sr}})$, $\mu = 1/\overline{\gamma}_{sr} + 1/\overline{\gamma}_{rd}$, $H_1(x, y) = \frac{1}{2} - \frac{Q(\sqrt{2x})}{e^{x/y}} - \frac{1}{2}\sqrt{\frac{y}{1+y}} + \sqrt{\frac{y}{1+y}}Q(\sqrt{\frac{2x(1+y)}{y}})$, and $H_2(x, y) = \frac{Q(\sqrt{2x})}{e^{x/y}} - \sqrt{\frac{y}{1+y}}Q(\sqrt{\frac{2x(1+y)}{y}})$.

Proof: The proof is given in Appendix C. ■

Substituting the obtained results of (32), (33), and (39) into (27), the closed-form expression of the error probability of the IHDAF relaying cooperative system over Rayleigh fading channels can be obtained and it is written as

$$\begin{aligned} P_{IHDAF} \doteq & \exp\left(-\frac{SNR_{sd}}{\overline{\gamma}_{sd}}\right) Q(\sqrt{2SNR_{sd}}) \\ & - \sqrt{\frac{\overline{\gamma}_{sd}}{\overline{\gamma}_{sd}+1}} Q\left(\sqrt{\frac{2SNR_{sd}(1+\overline{\gamma}_{sd})}{\overline{\gamma}_{sd}}}\right) \\ & + \left(1 - \exp\left(-\frac{SNR_{sd}}{\overline{\gamma}_{sd}}\right)\right) \exp\left(-\frac{SNR_{sr}}{\overline{\gamma}_{sr}}\right) \Theta_1 \\ & + \left(1 - \exp\left(-\frac{SNR_{sd}}{\overline{\gamma}_{sd}}\right)\right)\left(1 - \exp\left(-\frac{SNR_{sr}}{\overline{\gamma}_{sr}}\right)\right) \Theta_2. \end{aligned} \tag{43}$$

C. Optimal Relationship of the Two Key Thresholds

From the complex BER expression of the IHDAF protocol, it is difficult to obtain the optimum values of the two SNR thresholds, SNR_{sd} and SNR_{sr}. However, we can get the optimal relationship between SNR_{sd} and SNR_{sr} by setting the partial derivative of $P_{IHDAF}(e)$ in (27) with respect to SNR_{sd} as zero, i.e.,

$$\begin{aligned} & \frac{\partial P_{IHDAF}(e)}{\partial SNR_{sd}} \\ & = \frac{\partial\left(\Pr(\gamma_{sd} \le SNR_{sd})(1 - \Pr(\gamma_{sr} > SNR_{sr}))\, P_{AF}(e)\right)}{\partial SNR_{sd}} \\ & \quad + \frac{\partial\left(\Pr(\gamma_{sd} \le SNR_{sd})\Pr(\gamma_{sr} > SNR_{sr}) P_{DF}(e)\right)}{\partial SNR_{sd}} \\ & \quad + \frac{\partial\left((1 - \Pr(\gamma_{sd} \le SNR_{sd}))\, P_{direct}(e)\right)}{\partial SNR_{sd}} \\ & = 0. \end{aligned} \tag{44}$$

The optimal relationship of SNR_{sd} and SNR_{sr} can be obtained by solving (44) and we have

$$\int_{SNR_{sr}}^{\infty} Q\left(\sqrt{2\gamma}\right) e^{-\gamma/\overline{\gamma}_{sr}}\, d\gamma = M\left(SNR_{sd}\right) \tag{45}$$

where

$$\begin{aligned} & M(SNR_{sd}) \\ & = \overline{\gamma}_{sr} \frac{Q\left(\sqrt{2SNR_{sd}}\right) - e^{\mu SNR_{sd}} H_2\left(SNR_{sd}, 1/\mu\right)}{e^{-SNR_{sd}/\overline{\gamma}_{rd}} - e^{SNR_{sd}/\overline{\gamma}_{rd}} H_2(SNR_{sd}, \overline{\gamma}_{rd})}. \end{aligned} \tag{46}$$

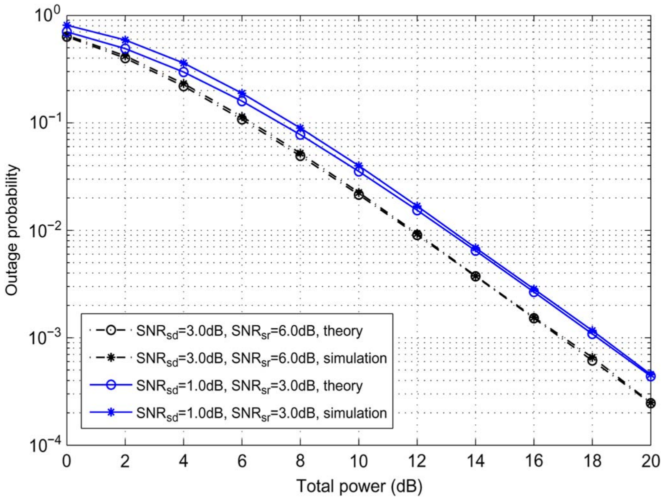

Fig. 3. Theoretical and simulation results of the outage probability of the IHDAF protocol with $d_{sr} = d_{rd} = 0.5$ and equal power allocation.

As the expressions of the two sides in (45) are both monotonically decreasing functions, there exists a one-to-one relationship between SNR_{sr} and SNR_{sd}. Therefore, given SNR_{sr}, we can use (45) to get the corresponding optimal SNR_{sd} in different cases, and vice versa.

IV. NUMERICAL RESULTS AND ANALYSIS

In this section, computer simulations are performed to illustrate and verify the above theoretical analysis. A typical topology structure that the relay is located on a straight line between the source and the destination is applied. In the simulations, the distance between the source and destination is normalized to be 1.0 (i.e., $d_{sd} = 1.0$) and the pass loss factor is $\alpha = 3.0$. In addition, the values of the thresholds SNR_{sd} and SNR_{sr} follow the optimal relationship as expressed in (45) for the IHDAF protocol.

The theoretical and simulation results of the outage probability of the proposed IHDAF scheme are shown in Fig. 3. It can be seen that the simulation and analytical results match well with each other with the increase of SNR, which verifies the correctness of both the theoretical derivations and simulations. However, for the low power case (i.e., $SNR_{sd} = 1.0, SNR_{sr} = 3.0$), the simulation and theoretical results are not matching very well. This phenomenon happens due to the ideal theoretical analysis and the SNR approximation in (14). Compared with the case of using smaller threshold values ($SNR_{sd} = 1.0$ and $SNR_{sr} = 3.0$), the IHDAF relaying scheme can get better outage performance or smaller outage probability using larger threshold values ($SNR_{sd} = 3.0$ and $SNR_{sr} = 6.0$). Also, we find that it is hard to present the relationship between the two SNR thresholds and get the optimal SNR thresholds only through the analysis of the outage probability. With the analysis of the BER performance, the above issue can be solved.

Fig. 4 shows the outage probabilities of the IHDAF, ISDF, and IDF protocols when the relay moves away from the source to the destination. In the simulations, the system total power is set to be 20 dB, the two SNR thresholds are set as

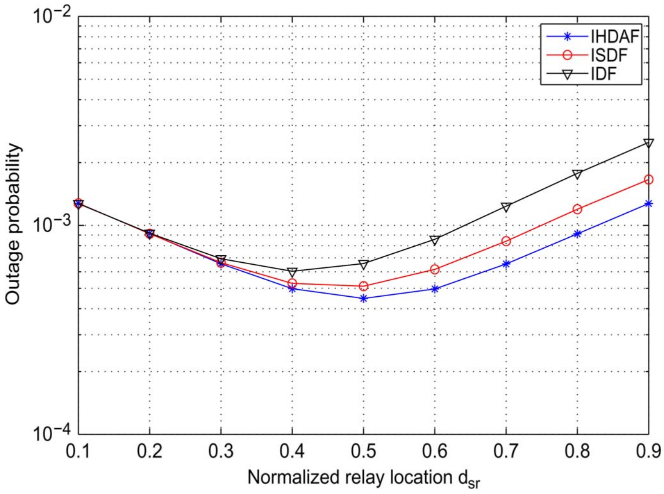

Fig. 4. Outage probabilities of the three protocols considering different normalized relay locations d_{sr} ($SNR_{sd} = 3.0$, $SNR_{sr} = 6.0$, and equal power allocation).

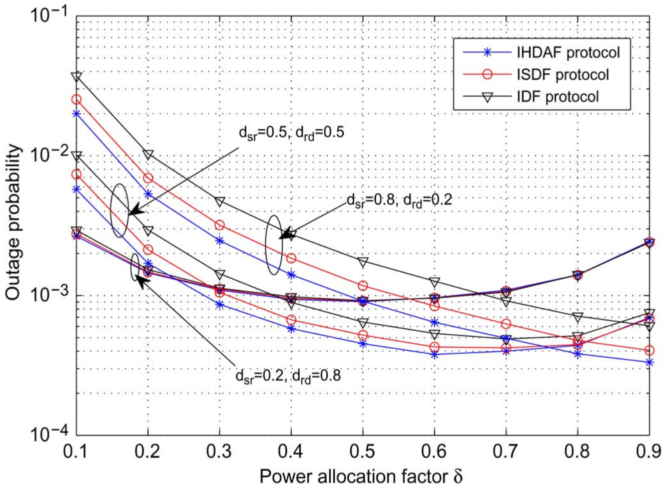

Fig. 5. Outage probabilities of the three relaying protocols under different power allocation factors and relay locations ($SNR_{sd} = 3.0$, $SNR_{sr} = 6.0$).

$SNR_{sd} = 3.0$ (4.771 dB) and $SNR_{sr} = 6.0$ (7.782dB), and the power allocation factor is set to be 0.5. From this figure, it is easy to see that the variation trends of the outage probability for the three protocols are similar. The three protocols have almost the same outage performance when $d_{sr} < 0.3$. The IHDAF protocol can have lower outage probability than the ISDF and IDF protocols when $d_{sr} > 0.3$ and this advantage becomes more significant with the increase of d_{sr}. It is also found that the optimal distances d_{sr} corresponding to the lowest outage probabilities for the three protocols are different. The IHDAF, ISDF, and IDF protocols can have the optimal outage performance with the distances from the source to the destination d_{sr} to be 0.5, 0.4, and $0.4 \sim 0.5$, respectively. The optimal distance is also influenced by the SNR thresholds and the power allocation schemes. The results of Fig. 4 can be understood through the evaluation of the decoding conditions at the relay. If the relay is close to the source, then the quality of the received signals at the relay is good enough for the correct decoding. Hence, the IHDAF protocol can only achieve marginal advantage with the application of AF scheme in the second phase. On the contrary, if the relay is close to the destination, then the quality of the signals obtained by the relay is not so good and the advantages for the IHDAF protocol to select the AF scheme in the second phase will be significant.

Fig. 5 illustrates the outage probabilities of the IHDAF, ISDF, and IDF relaying schemes with different power allocation factors δ when the relay locates in different positions with $d_{sr} = 0.2$, $d_{sr} = 0.5$, and $d_{sr} = 0.8$. We also set the two SNR thresholds as $SNR_{sd} = 3.0$ (4.771 dB) and $SNR_{sr} = 6.0$ (7.782 dB). In addition, the total power of the system is set to be 20 dB. From Fig. 5, it shows that the three protocols result in almost identical performance when the relay is close to the source ($d_{sr} = 0.2$). This phenomenon can be explained as follows. When the channel condition of the source-to-relay link is very good, the probability that the relay correctly decodes the signals from the source is high. In this case, the IHDAF can only achieve very limited gains in comparison with the ISDF and IDF protocols. Also, the system outage probability will achieve the minimum when the power is equally allocated to the source and relay. If the relay is in the middle of the system ($d_{sr} = 0.5$), the IHDAF relaying scheme outperforms the other two schemes significantly at low power allocation factor region ($\delta \leq 0.6$), while it performs almost the same as the ISDF relaying scheme in high power allocation factor region ($\delta > 0.6$). The reason is that the SNR of the source-to-relay link will be always larger than SNR_{sr} in high power allocation factor region. The HDAF scheme in the second phase can be approximated as the DF scheme. Furthermore, the performance will be better if the source is allocated more power ($\delta > 0.5$) than the relay. When the relay is close to the destination ($d_{sr} = 0.8$), the IHDAF relaying scheme achieves the best performance compared with the other two schemes over the whole region. In addition, it can be observed that the outage probability gets smaller with the increase of the power allocation factor. This can also be explained as follows. As the channel condition of the relay-to-destination link is very good, the quality of the source-to-relay link will determine the system performance.

To examine the effect of the SNR threshold SNR_{sr} on the system BER performance of the IHDAF relaying scheme, we simulate the error probability curves as the function of the total SNR of the system for different SNR_{sr} and the corresponding optimal SNR_{sd}. Fig. 6 depicts the error probabilities with $SNR_{sr} = 0.5$ (−3.0103 dB), 1.0 (0 dB), 4.0 (7.7815 dB), and 8.0 (9.0309 dB) (the corresponding value of SNR_{sd} can be obtained by substituting the value of SNR_{sr} into (58)) in the conditions of $d_{sr} = d_{rd} = 0.5$ and equal power allocation. From Fig. 6, it is clear that the simulation results match well with the theoretical results, which also validates the derivation result in (20). Besides, the BER performance of the IHDAF relaying scheme does not always improve the system performance with the increase of SNR_{sr}. The error propagation probability will be smaller when SNR_{sr} is becoming larger. When SNR_{sr} exceeds 4.0 (6.0201 dB), the IHDAF relaying scheme has almost the same BER performance no matter of the SNR_{sr} values. To show the effects of the two SNR thresholds, SNR_{sr} and SNR_{sr}, on the system performance, we also provide the comparison of

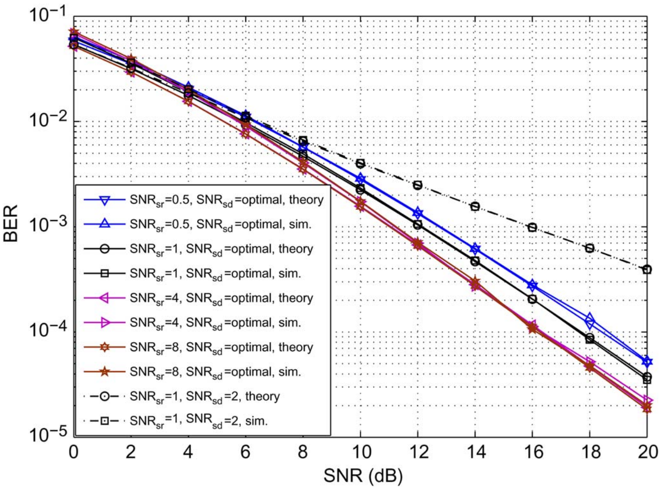

Fig. 6. Theoretical and simulation results of the BER performance with different SNR_{sr} and the corresponding optimal SNR_{sd} for the IHDAF protocol ($d_{sr} = d_{rd} = 0.5$ and equal power allocation).

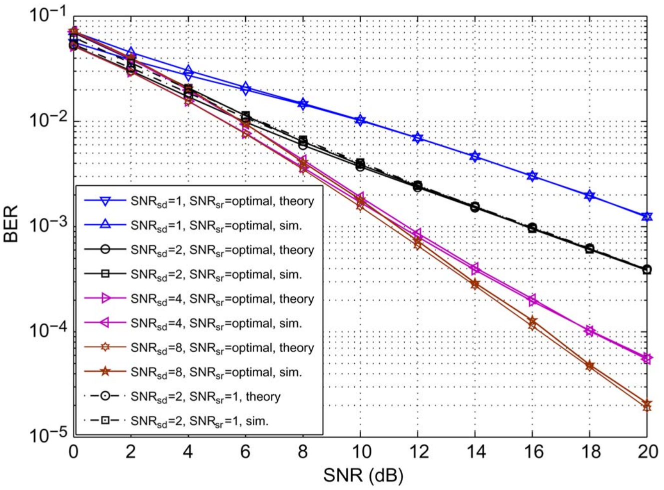

Fig. 7. Theoretical and simulation results of the BER performance with different SNR_{sd} and the corresponding optimal SNR_{sr} for the IHDAF protocol ($d_{sr} = d_{rd} = 0.5$ and equal power allocation).

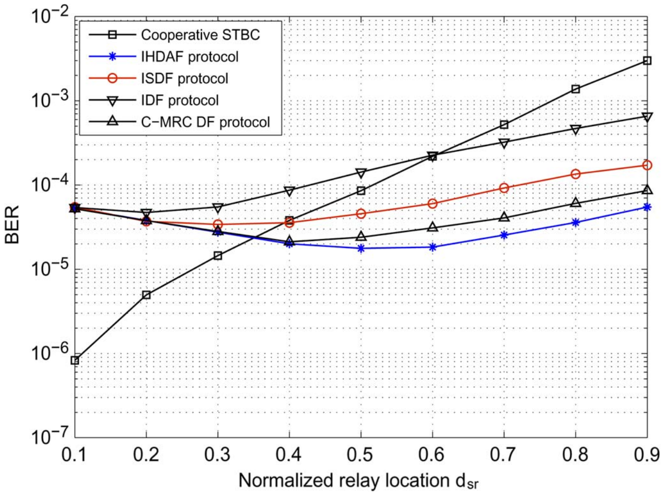

Fig. 8. BER performance of the cooperative STBC scheme and three relaying protocols with different normalized relay locations d_{sr} ($SNR_{sr} = 6.0$, optimal SNR_{sd}, and equal power allocation).

the two scenarios with ($SNR_{sr} = 1$ and $SNR_{sd} = optimal$) and ($SNR_{sr} = 1$ and $SNR_{sd} = 2$). With the optimal SNR_{sd}, there are about 4.0 dB gains compared with the case of $SNR_{sd} = 2$ when $BER = 10^{-3}$. It is obvious that the BER performance can be improved significantly with the optimal selection of SNR_{sr} and SNR_{sd}.

In Fig. 7, we provide the BER performance of the IHDAF protocol against the total SNR for different SNR_{sd} and the corresponding optimal SNR_{sr}. Here, we used $SNR_{sd} = 1.0, 2.0, 4.0$, and 8.0, $d_{sr} = d_{rd} = 0.5$, and equal power allocation. Considering the optimal relationship between SNR_{sr} and SNR_{sr}, the BER performance of the IHDAF protocol can be improved with the increase of SNR_{sd}. Similar to Fig. 6, the performance improvement becomes not significant when $SNR_{sd} > 4.0$. For different SNR_{sd} and its corresponding optimal SNR_{sr}, it is found that the IHDAF protocol with $SNR_{sd} = 8$ can obtain about 0.4 dB and 4.8 dB gains compared with the ones with $SNR_{sd} = 4$ and $SNR_{sd} = 2$, respectively. For the two scenarios with ($SNR_{sd} = 2$ and $SNR_{sr} = optimal$) and ($SNR_{sd} = 2$ and $SNR_{sr} = 1$), they achieve almost the same BER performance since $SNR_{sr} = 1$ in the latter case is very close to the optimal value of SNR_{sr} in the former case. Fig. 7 also verifies the correctness of our theoretical results and simulation results and shows the importance of the selection of the two SNR thresholds.

In Fig. 8, we study the impact of the relay locations on the system BER performance for the three incremental relaying protocols, the C-MRC based DF scheme [32], and also the cooperative distributed STBC scheme [37] considering the system total power to be 20 dB, the two SNR thresholds to be $SNR_{sr} = 6.0$ and the corresponding optimal SNR_{sd}, and the power allocation factor to be 0.5. It is obvious that the variation trends of the BER performance for the three incremental protocols and the C-MRC based DF protocol are similar and the IHDAF scheme is almost the best one within the four protocols. When $d_{sr} < 0.2$, the difference in BER performance of the three incremental protocols is very limited. For the C-MRC based DF scheme, its BER performance is very close to that of IHDAF scheme with $d_{sr} < 0.4$ and it suffers some performance loss compared with IHDAF scheme when $d_{sr} > 0.4$, since the error probability for the relay to detect the signals from the source will rise up with the increase of d_{sr}. The cooperative STBC scheme can get the best performance when $d_{sr} < 0.35$ among all the schemes, but its performance degrades quickly with the increase of d_{sr}, which can be explained by the way to make the STBC structure and realize the coding gain. When $d_{sr} > 0.4$, the IHDAF protocol will achieve the best BER performance among all the schemes. It is also noticed that the optimal distances d_{sr} to achieve the best BER performance of the protocols are different. The optimal relay locations d_{sr} are approximately 0.5, 0.3, 0.2, and 0.4 for the IHDAF, ISDF, IDF, and C-MRC DF protocols, respectively. The simulation results of Fig. 8 can also be explained as we did for Fig. 4.

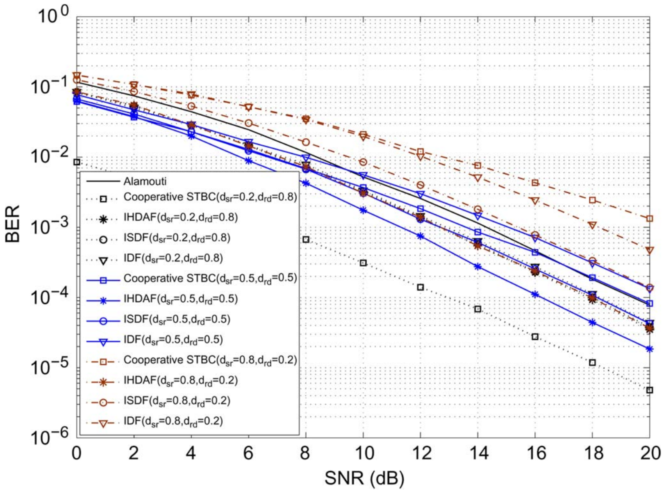

Fig. 9. BER performance of the Alamouti scheme, cooperative STBC scheme, and three relaying protocols with $SNR_{sr} = 6.0$ and optimal SNR_{sd}, equal power allocation, and different relay locations ($d_{sr} = 0.2$, $d_{sr} = 0.5$, and $d_{sr} = 0.8$, respectively).

To make a fair comparison with the other protocols, the thresholds SNR_{sr} of the IHDAF, ISDF, IDF protocols are set to be 6.0 and the optimal corresponding thresholds SNR_{sd} can be obtained. In the simulation, we also consider the other two coded schemes, Alamouti scheme and cooperative STBC scheme. Fig. 9 shows the BER performance of the five schemes with different relay locations with $d_{sr} = 0.2$, $d_{sr} = 0.5$, and $d_{sr} = 0.8$, respectively. Equal power allocation scheme is considered here. It demonstrates that the cooperative STBC scheme can get the best performance with smaller d_{sr}, but with the increase of the d_{sr}, the IHDAF relaying scheme achieves the best performance among all the schemes due to the employment of AF mode and the increase of correct decoding probability of R, which can be also observed from Fig. 8. For the IHDAF protocol, the relay location does not make much influence on the system BER performance. But for the other schemes, the BER performance is significantly affected by the relay position.

V. CONCLUSION

In this paper, we have proposed and investigated the IHDAF relaying scheme. With the consideration of the relay position and the power allocation strategy, we have derived the accurate outage probability and the BER of the IHDAF scheme. The analysis and simulation results have shown that the selection of the appropriate SNR thresholds can improve the system performance to some extent. Also, the IHDAF scheme outperforms the ISDF, IDF, and cooperative STBC significantly in terms of BER performance when the relay gets close to the destination.

APPENDIX A
PROOF OF LEMMA 1

Based on the definition of the diversity order, we have

$$D = -\lim_{SNR\to\infty} \frac{\log P_{outage}}{\log SNR} = 1. \tag{47}$$

Equivalently, a scheme achieving diversity order D has an outage probability that behaves as $P_{outage} \propto SNR^{-D}$ at high effective SNR.

For the derivation of the diversity order of IHDAF scheme, we should consider the following three cases, $\gamma_{sd} > SNR_{sd}$, $\gamma_{sd} \le SNR_{sd}$ with $\gamma_{sr} > SNR_{sr}$, and $\gamma_{sd} \le SNR_{sd}$ with $\gamma_{sr} < SNR_{sr}$. Considering $\gamma_{sd} > SNR_{sd}$, it means that only the direct transmission will be considered. For the other two cases, either DF or AF protocol will be employed besides direct transmission.

If $\gamma_{sd} > SNR_{sd}$, we have the channel capacity as

$$C_{DT} = \log_2(1+\gamma_{sd}) = \log_2\left(1+|h_{sd}|^2 P_S/N_0\right) \tag{48}$$

Defining $\xi_{DT} = P_S/N_0$ with ξ_{DT} large enough, we have

$$\begin{aligned} P_{outage} &= P(C_{DT} < R) = P\left(|h_{sd}|^2 < \frac{2^R-1}{\xi_{DT}}\right) \\ &= \int_0^{\frac{2^R-1}{\xi_{DT}}} e^{-x}dx = 1-\exp\left(-\frac{2^R-1}{\xi_{DT}}\right) \approx \left(\frac{2^R-1}{\xi_{DT}}\right)^1 \end{aligned} \tag{49}$$

which demonstrates that the IHDAF scheme in the target SNR region takes only direct transmission and extracts only first-order diversity in the effective SNR.

If $\gamma_{sd} \le SNR_{sd}$ and $\gamma_{sr} > SNR_{sr}$, the channel capacity can be expressed as (9). After MRC, the total instantaneous SNR in this case can be obtained as $\gamma_d^{DF} = \gamma_{sd} + \gamma_{rd}$ and we have

$$\begin{aligned} C_{DF} &= \frac{1}{2}\log_2(1+\gamma_d^{DF}) \\ &= \frac{1}{2}\log_2\left(1+|h_{sd}|^2 P_S/N_0 + |h_{rd}|^2 P_R/N_0\right). \end{aligned} \tag{50}$$

Defining $\xi_{DF} = \min(P_S/N_0, P_R/N_0)$, it is easy to verify that the outage probability at transmission rate R can be upper-bounded for large ξ_{DF} as

$$\begin{aligned} P_{outage} &= P(C_{DF} < R) = P\left(|h_{sd}|^2 + |h_{rd}|^2 \le \frac{2^{2R}-1}{\xi_{DF}}\right) \\ &= 1-\exp -\frac{2^{2R}-1}{\xi_{DF}}\left(1+\frac{2^{2R}-1}{\xi_{DF}}\right) \approx \left(\frac{2^{2R}-1}{\xi_{DF}}\right)^2 \end{aligned} \tag{51}$$

which demonstrates that the proposed scheme in the target SNR region employs DF protocol and acheives second-order diversity in the effective SNR ξ_{DF}.

If $\gamma_{sd} \le SNR_{sd}$ and $\gamma_{sr} < SNR_{sr}$, the channel capacity can be expressed as (10). We can rewrite it as

$$C_{AF} = \frac{1}{2}\log_2\left(1+|h_{sd}|^2 P_S/N_0 + \frac{|h_{sr}|^2 P_S/N_0}{1+\beta^2|h_{rd}|^2}\beta^2|h_{rd}|^2\right). \tag{52}$$

The outage probability in this case can be upper-bounded as

$$
\begin{aligned}
P_{outage} &= P(C_{AF} < R) = P\left(|h_{sd}|^2 + |h_{rd}|^2 \le \frac{2^{2R}-1}{\xi_{AF}}\right)\\
&= 1 - \exp - \frac{2^{2R}-1}{\xi_{AF}}\left(1 + \frac{2^{2R}-1}{\xi_{AF}}\right) \approx \left(\frac{2^{2R}-1}{\xi_{AF}}\right)^2
\end{aligned}
\tag{53}
$$

with $\xi_{AF} = \min(P_S/N_0, P_R/N_0 \frac{\beta^2|h_{rd}|^2}{1+\beta^2|h_{rd}|^2})$. It is ready to know that the full diversity order can be obtained by the proposed scheme in the effective SNR ξ_{AF}.

Hence, the diversity order for the proposed IHDAF scheme can be finally expressed as (26).

APPENDIX B
PROOF OF PROPOSITION 1

The expression of $f_{\gamma_t}(\gamma \mid \gamma_{sd} \le SNR_{sd})$ within the integration part of (36) can be obtained as

$$
\begin{aligned}
&f_{\gamma_t}(\gamma|\gamma_{sd} \le SNR_{sd})\\
&\quad = \int_0^{\gamma} f_{\gamma_{sd}}(\gamma - x|\gamma_{sd} \le SNR_{sd}) f_{\gamma_{rd}}(x|\gamma_{sd} \le SNR_{sd})\, dx\\
&\quad = \int_0^{\gamma} f_{\gamma_{sd}}(\gamma - x|\gamma_{sd} \le SNR_{sd}) f_{\gamma_{rd}}(x)\, dx\\
&\quad = \begin{cases} \frac{\int_0^{\gamma} f_{\gamma_{sd}}(\gamma - x) f_{\gamma_{rd}}(x)\, dx}{P(\gamma_{sd} \le SNR_{sd})}, & \gamma \le SNR_{sd}\\ \frac{\int_{\gamma - SNR_{sd}}^{\gamma} f_{\gamma_{sd}}(\gamma - x) f_{\gamma_{rd}}(x)\, dx}{P(\gamma_{sd} \le SNR_{sd})}, & \gamma > SNR_{sd}. \end{cases}
\end{aligned}
\tag{54}
$$

The computation of $f_{\gamma_t}(\gamma \mid \gamma_{sd} \le SNR_{sd})$ should consider two cases, i.e., $\overline{\gamma}_{sd} \ne \overline{\gamma}_{rd}$ and $\overline{\gamma}_{sd} = \overline{\gamma}_{rd}$. When $\overline{\gamma}_{sd} \ne \overline{\gamma}_{rd}$, we can have

$$
\begin{aligned}
&f_{\gamma_t}(\gamma|\gamma_{sd} \le SNR_{sd})\\
&\quad = \begin{cases} \frac{e^{-\gamma/\overline{\gamma}_{rd}} - e^{-\gamma/\overline{\gamma}_{sd}}}{(\overline{\gamma}_{rd} - \overline{\gamma}_{sd})(1 - e^{-SNR_{sd}/\overline{\gamma}_{sd}})}, & \gamma \le SNR_{sd}\\ \frac{1 - e^{-SNR_{sd}(1/\overline{\gamma}_{sd} - 1/\overline{\gamma}_{rd})}}{(\overline{\gamma}_{rd} - \overline{\gamma}_{sd})(1 - e^{-SNR_{sd}/\overline{\gamma}_{sd}})} e^{-\gamma/\overline{\gamma}_{rd}}, & \gamma > SNR_{sd}. \end{cases}
\end{aligned}
\tag{55}
$$

Then, by substituting (55) into (36), we can achieve the expression of P_{coop} with $\overline{\gamma}_{sd} \ne \overline{\gamma}_{rd}$ in (37).

When $\overline{\gamma}_{sd} = \overline{\gamma}_{rd}$, $f_{\gamma_t}(\gamma \mid \gamma_{sd} \le SNR_{sd})$ can be expressed as

$$
f_{\gamma_t}(\gamma|\gamma_{sd} \le SNR_{sd}) = \begin{cases} \frac{\frac{1}{\overline{\gamma}_{sd}^2} \gamma e^{-\gamma/\overline{\gamma}_{sd}}}{1 - e^{-SNR_{sd}/\overline{\gamma}_{sd}}}, & \gamma \le SNR_{sd}\\ \frac{\frac{1}{\overline{\gamma}_{sd}^2} SNR_{sd} e^{-\gamma/\overline{\gamma}_{sd}}}{1 - e^{-SNR_{sd}/\overline{\gamma}_{sd}}}, & \gamma > SNR_{sd}. \end{cases}
\tag{56}
$$

With the same method above, the expression of P_{coop} with $\overline{\gamma}_{sd} = \overline{\gamma}_{rd}$ can be obtained in (38).

APPENDIX C
PROOF OF PROPOSITION 2

According to (14), the overall received SNR at the destination in the case of AF mode can be approximated by its upper bound as $\gamma_{AF} = \gamma_{sd} + \min(\gamma_{sr}, \gamma_{rd}) = \gamma_{sd} + \gamma_{\min}$ in (14), where γ_{sd}, γ_{sr}, and γ_{rd} are independent of each other. The conditional PDF $f_{\gamma_{AF}}(\gamma \mid \Psi_1'\Psi_2')$ in (39) can be calculated as

$$
f_{\gamma_{AF}}\left(\gamma \mid \Psi_1', \Psi_2'\right) = \int_0^{\gamma} f_{\gamma_{sd}}\left(\gamma - x \mid \Psi_1'\right) f_{\gamma_{\min}}\left(x \mid \Psi_2'\right) dx
\tag{57}
$$

where

$$
\begin{aligned}
f_{\gamma_{sd}}\left(\gamma - x \mid \Psi_1'\right) &= \frac{\partial}{\partial x}\left[\frac{\Pr\left(\gamma_{sd} \le \gamma - x, \Psi_1'\right)}{\Pr\left(\Psi_1'\right)}\right]\\
&= \begin{cases} \frac{e^{-(\gamma - x)/\overline{\gamma}_{sd}}}{\overline{\gamma}_{sd}(1 - e^{-SNR_{sd}/\overline{\gamma}_{sd}})}, & \gamma - x \le SNR_{sd}\\ 0, & \gamma - x > SNR_{sd} \end{cases}
\end{aligned}
\tag{58}
$$

$$
\begin{aligned}
f_{\gamma_{\min}}\left(x \mid \Psi_2'\right) &= \frac{\partial}{\partial x}\left[\frac{\Pr\left(\min(\gamma_{sr}, \gamma_{rd}) \le x, \Psi_2'\right)}{\Pr\left(\Psi_2'\right)}\right]\\
&= \begin{cases} \frac{\mu e^{-\mu x} - e^{-SNR_{sr}/\overline{\gamma}_{sr}} \frac{1}{\overline{\gamma}_{rd}} e^{-x/\overline{\gamma}_{rd}}}{1 - e^{-SNR_{sr}/\overline{\gamma}_{sr}}}, & x \le SNR_{sr}\\ 0, & x > SNR_{sr} \end{cases}
\end{aligned}
\tag{59}
$$

and $\mu = 1/\overline{\gamma}_{sr} + 1/\overline{\gamma}_{rd}$.

To make the BER expressions simpler, we assume that (60), shown at the bottom of the page, and $g(x)$ will not be zero only if $\gamma - x \le SNR_{sd}$ and $x \le SNR_{sr}$.

Without loss of generality, we set $SNR_{sd} \le SNR_{sr}$ so that $P_{AF}(e)$ can be expressed as

$$
\begin{aligned}
P_{AF}(e) &= \int_0^{SNR_{sd}} Q\left(\sqrt{2\gamma}\right) I_1(\gamma) d\gamma\\
&\quad + \int_{SNR_{sd}}^{SNR_{sr}} Q\left(\sqrt{2\gamma}\right) I_2(\gamma) d\gamma + \int_{SNR_{sr}}^{\infty} Q\left(\sqrt{2\gamma}\right) I_3(\gamma) d\gamma
\end{aligned}
\tag{61}
$$

where $I_1 = \int_0^{\gamma} g(x)\ dx$, $I_2 = \int_{\gamma - SNR_{sd}}^{\gamma} g(x)\ dx$, and $I_3 = \int_{\gamma - SNR_{sd}}^{SNR_{sr}} g(x)\, dx$.

Substituting (60) into (61), we can get a new expression of $P_{AF}(e)$, which can be divided into the positive and negative parts as $P_{AF}(e) = P_{AF-P}(e) - P_{AF-N}(e)$ with $P_{AF-P}(e)$ in (41) and $P_{AF-N}(e)$ in (42).

$$
\begin{aligned}
g(x) &= \frac{e^{-(\gamma - x)/\overline{\gamma}_{sd}}}{\overline{\gamma}_{sd}(1 - e^{-SNR_{sd}/\overline{\gamma}_{sd}})} \frac{\mu e^{-\mu x} - e^{-(SNR_{sr}/\overline{\gamma}_{sr} + x/\overline{\gamma}_{rd})}/\overline{\gamma}_{rd}}{(1 - e^{-SNR_{sr}/\overline{\gamma}_{sr}})}\\
&= \frac{\mu e^{-\left(\gamma/\overline{\gamma}_{sd} + (\mu - 1/\overline{\gamma}_{sd})x\right)} - e^{-\left(SNR_{sr}/\overline{\gamma}_{sr} + \gamma/\overline{\gamma}_{sd} + (x/\overline{\gamma}_{rd} - x/\overline{\gamma}_{sd})\right)}/\overline{\gamma}_{rd}}{\overline{\gamma}_{sd}(1 - e^{-SNR_{sd}/\overline{\gamma}_{sd}})(1 - e^{-SNR_{sr}/\overline{\gamma}_{sr}})}
\end{aligned}
\tag{60}
$$

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