BER PERFORMANCE ANALYSIS OF THE OPTIMUM ML RECEIVER FOR DECODE-AND-FORWARD COOPERATIVE PROTOCOL

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ABSTRACT

In this paper, the performance of optimum maximum-likelihood (ML) receiver is analyzed for the Decode-and-Forward (DF) cooperative communication protocol in wireless networks. A closed-form Bit-Error-Rate (BER) analysis is presented for the DF cooperative protocol with BPSK modulation and with ML detection at the destination. To further understand the result, we develop an approximation for the BER analysis in a special scenario. Simulation results are presented to validate both the closed-form BER expression and the approximation.

Index Terms— Cooperative communications, decode-and-forward protocol, optimum ML receiver, BER analysis.

1. INTRODUCTION

Cooperative communications in wireless networks has attracted considerable attentions in recent years [1]–[7] as it can substantially enhance the network performance, in which multiple users in a wireless network can help each other and cooperatively send information to destination. There are two fundamental user cooperation strategies [1]–[5]. Each relay user may simply amplify source user's signals and forward them to the destination, which results in an Amplify-and-Forward (AF) cooperative protocol, or the relay user may decode the received signals and forward the decoded information to the destination, which results in a Decode-and-Forward (DF) cooperative protocol.

Many works have been carried out on analyzing the performances of the DF cooperative protocol with coherent detection [1]–[6] and non-coherent detection [7]. Since the relay user may decode the received signal incorrectly, there may be error propagation from the relay to the destination. When the Maximum-Ratio-Combining (MRC) is used to combine the signal from the $Source \rightarrow Destination$ $(S \rightarrow D)$ link and the signal from the $Relay \rightarrow Destination$ $(R \rightarrow D)$ link, the performance of the MRC receiver may be severely degraded if the error propagation from the relay to the destination is not negligible. Fortunately, it has been shown in [6] that if an optimum maximum-likelihood (ML) receiver instead of the MRC receiver is deployed at the destination, the system performance can be significantly improved. A piecewise-linear (PL) approximation method was proposed in [6] to understand the optimum ML receiver and a performance upper bound was developed, but a closed-form analysis for the optimum ML receiver still remains open. In [7], based on the PL approximation method, the performance of a non-coherent DF cooperative protocol with an ML receiver was analyzed in case of the Binary-Frequency-Shift-Keying (BFSK) modulation.

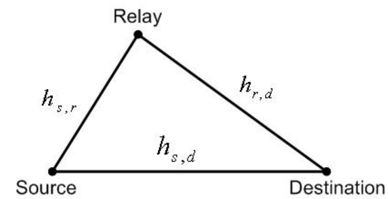

Fig. 1. A simplified cooperative communication model.

In this paper, we try to analyze the performance of the optimum ML receiver for the DF cooperative protocol with coherent detection. We provide a closed-form Bit-Error-Rate (BER) analysis for the optimum ML receiver with the Binary-Phase-Shift-Keying (BPSK) modulation. We also develop an approximation for the closed-form BER expression under a special scenario which helps us further understand the performance of the optimum ML receiver. Simulation results validate the closed-form expression and the approximation.

2. SYSTEM MODEL AND OPTIMUM ML RECEIVER

We consider a simplified cooperative communication system with one source, one relay and one destination as shown in Fig. 1. The system deploys the DF cooperative protocol to send information that can be specified in two phases. In Phase 1, the source transmits its information which is received by both the relay and the destination. The received signal at the relay and the destination $y_{s,r}$ and $y_{s,d}$ can be modeled as

$$y_{s,r} = \sqrt{P_1} h_{s,r} x + n_{s,r}, \quad (1)$$
$$y_{s,d} = \sqrt{P_1} h_{s,d} x + n_{s,d}, \quad (2)$$

where P_1 is the transmitted power by the source, $x \in \{1, -1\}$ is a BPSK information symbol, $n_{s,r}$ and $n_{s,d}$ represent the additive white noise at the relay and destination respectively. In (1) and (2), $h_{s,r}$ and $h_{s,d}$ are channel coefficients of the

$Source \rightarrow Relay$ ($S \rightarrow R$) and $S \rightarrow D$ links respectively. Then in Phase 2, the relay decodes the received signal and forwards the decoded information $\tilde{x}$ to the destination. Note that the decoded information $\tilde{x}$ may be incorrect. The signal received by the destination $y_{r,d}$ can be modeled as

$$y_{r,d} = \sqrt{P_2} h_{r,d} \tilde{x} + n_{r,d}, \tag{3}$$

where P_2 is the transmitted power by the relay, $n_{r,d}$ represents the additive white noise at the destination. In (3), $h_{r,d}$ represents the channel coefficient of the $R \rightarrow D$ link. The channel coefficients $h_{s,r}$, $h_{s,d}$ and $h_{r,d}$ are modeled as independent, zero-mean real Gaussian random variables with variances $\delta_{s,r}^2$, $\delta_{s,d}^2$ and $\delta_{r,d}^2$ respectively. The noise $n_{s,r}$, $n_{s,d}$ and $n_{r,d}$ are modeled as zero-mean real Gaussian random variables with variance σ^2.

The optimum ML receiver at the destination for the DF cooperative protocol is [6]

$$\frac{P(x=1|y_{s,d}, y_{r,d})}{P(x=-1|y_{s,d}, y_{r,d})} \underset{-1}{\overset{1}{\gtrless}} 1. \tag{4}$$

Note that the probability of decoding in error at the relay is

$$\epsilon = Q\left(\frac{\sqrt{P_1}|h_{s,r}|}{\sigma}\right), \tag{5}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{t^2}{2}dt}$. Assume that the source sends out the symbol $x = 1$, the instantaneous error probability at the destination can be developed as

$$P_b^h = P\left(\frac{2\sqrt{P_1} y_{s,d} h_{s,d}}{\sigma^2} < \ln\left(\frac{\epsilon + (1-\epsilon)e^{-\frac{2\sqrt{P_2} y_{r,d} h_{r,d}}{\sigma^2}}}{(1-\epsilon) + \epsilon e^{-\frac{2\sqrt{P_2} y_{r,d} h_{r,d}}{\sigma^2}}}\right)\right). \tag{6}$$

It is very challenging to calculate the overall system BER using (6) directly. We try to develop a closed-form error probability based on the tight PL approximation [6, 7]. Specifically, the PL approximation simplifies the function $f(t) = \ln \frac{\epsilon+(1-\epsilon)e^t}{(1-\epsilon)+\epsilon e^t}$ as

$$f_{PL}(t) = \begin{cases} -T, & t \leq -T; \\ t, & -T < t < T; \\ T, & t \geq T, \end{cases} \tag{7}$$

where $T = \ln \frac{1-\epsilon}{\epsilon}$.

3. PERFORMANCE ANALYSIS

In this section, we first develop an instantaneous error probability for the optimum ML receiver based on the tight PL approximation in (7). Then by averaging it over all the fading channels, we can get a closed-form BER expression for the optimum ML receiver. Finally, we approximate the closed-form error probability in a special scenario.

3.1. Closed-Form Analysis

Based on the tight PL approximation (7), we can decompose the error probability expression (6) as

$$\begin{aligned} P_b^h \simeq P_{b,PL}^h &= P(X<-T)P(Y<-T) \\ &+ P(X<T)P(Y>T) + P(X<Y, -T<Y<T), \end{aligned} \tag{8}$$

where $X = \frac{2\sqrt{P_1} y_{s,d} h_{s,d}}{\sigma^2}$ and $Y = -\frac{2\sqrt{P_2} y_{r,d} h_{r,d}}{\sigma^2}$. According to (2), X is a real Gaussian random variable with mean $\frac{2P_1 h_{s,d}^2}{\sigma^2}$ and variance $\frac{4P_1 h_{s,d}^2}{\sigma^2}$. From (3) and (5), the pdf of Y, denoted as $f_Y(y)$, can be given by

$$\frac{\sigma}{\sqrt{8\pi P_2 h_{r,d}^2}} \left((1-\epsilon) e^{-\frac{(y\sigma^2 + 2P_2 h_{r,d}^2)^2}{8P_2 h_{r,d}^2 \sigma^2}} + \epsilon\, e^{-\frac{(y\sigma^2 - 2P_2 h_{r,d}^2)^2}{8P_2 h_{r,d}^2 \sigma^2}}\right). \tag{9}$$

Thus, the error probability (8) can be evaluated as

$$P_{b,PL}^h = I_1 + I_2 + I_3, \tag{10}$$

where

$$\begin{aligned} I_1 &= \int_{-\infty}^{-T} f_X(x)dx \int_{-\infty}^{-T} f_Y(y)dy, \\ I_2 &= \int_{-\infty}^{T} f_X(x)dx \int_{T}^{\infty} f_Y(y)dy, \\ I_3 &= (1-\epsilon)Q_0(1) + \epsilon Q_0(-1), \end{aligned}$$

in which $f_X(x)$ and $f_Y(y)$ are the pdfs of X and Y respectively, and

$$\begin{aligned} Q_0(t) = & \frac{\sigma^2}{8\pi\sqrt{P_1 P_2 h_{s,d}^2 h_{r,d}^2}} \\ & \times \int_{-T}^{T}\int_{-\infty}^{y} e^{-\frac{(x\sigma^2 - 2P_1 h_{s,d}^2)^2}{8P_1 h_{s,d}^2 \sigma^2}} e^{-\frac{(y\sigma^2 + 2tP_2 h_{r,d}^2)^2}{8P_2 h_{r,d}^2 \sigma^2}} dxdy. \end{aligned}$$

We average $P_{b,PL}^h$ over the fading channels $h_{s,r}$, $h_{s,d}$ and $h_{r,d}$ to find the error probability of the optimum receiver as

$$P_{b,PL} = \frac{\iiint (I_1 + I_2 + I_3) e^{-\frac{1}{2}\left(\frac{h_{s,r}^2}{\delta_{s,r}^2} + \frac{h_{r,d}^2}{\delta_{r,d}^2} + \frac{h_{s,d}^2}{\delta_{s,d}^2}\right)} dh_{s,r} dh_{r,d} dh_{s,d}}{\sqrt{8\pi^3 \delta_{s,r}^2 \delta_{r,d}^2 \delta_{s,d}^2}}. \tag{11}$$

To calculate the above average error probability, we need the following two lemmas.

Lemma 1 *For any constants $\alpha > 0$ and $\beta > 0$, we have*

$$\int_{-\infty}^{\infty} \frac{1}{|t|} e^{-\alpha\frac{1}{t^2} - \beta t^2} dt = 4e^{-2\sqrt{\alpha\beta}} \int_0^\infty \frac{e^{-t^2}}{\sqrt{t^2 + 4\sqrt{\alpha\beta}}} dt. \tag{12}$$

Lemma 2 *For any constant $\gamma > 1$, we have*

$$\begin{aligned} &\int_0^\infty \int_{-\infty}^{y} \frac{e^{\frac{x-|x|\gamma}{2}}}{\sqrt{t^2 + |x|\gamma}} e^{-t^2} dxdt \\ &= \begin{cases} \int_0^{\pi/2} g(1) e^{\frac{y(1+\gamma)}{2\sin^2\theta}} d\theta, & y \leq 0; \\ \int_0^{\pi/2} g(1)d\theta + \int_0^{\pi/2} g(-1)(1 - e^{-\frac{y(\gamma-1)}{2\sin^2\theta}}) d\theta, & y > 0, \end{cases} \end{aligned}$$

where $g(v) = \frac{2}{\sqrt{\gamma(\gamma+v)(2+\frac{\gamma+v}{\gamma}\mathrm{ctg}^2\theta)}}$.

The proofs of Lemmas 1 and 2 follow from a series of changing variables and representing the Q-function as $Q(x) = \frac{1}{\pi}\int_0^{\pi/2} e^{-\frac{x^2}{2\sin^2\theta}}d\theta$. Due to the space limitation, the details are not included. With the two lemmas, we are ready to develop a simplified calculation of the averaging error probability over the fading channels. We have the following results.

Theorem 1 *Averaging I_3 over the channels, we have*

$$\begin{aligned} P_{b,I_3}^{h_{s,r}} &\triangleq \frac{1}{2\pi\sqrt{\delta_{s,d}^2\delta_{r,d}^2}}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I_3 e^{-\frac{h_{s,d}^2}{2\delta_{s,d}^2}} e^{-\frac{h_{r,d}^2}{2\delta_{r,d}^2}} dh_{s,d}dh_{r,d} \\ &= C_1[F_1(-1,1) - F_1(1,-1) + F_2(1)] \\ &\quad + C_2[F_1(1,1) - F_1(-1,-1) + F_2(-1)], \end{aligned} \tag{13}$$

where $C_1 = \frac{4(1-\epsilon)\sigma^2}{\pi^2\sqrt{\delta_{s,d}^2\delta_{r,d}^2 P_1P_2\beta_0\beta_0'}}$, $C_2 = \frac{4\epsilon\sigma^2}{\pi^2\sqrt{\delta_{s,d}^2\delta_{r,d}^2 P_1P_2\beta_0\beta_0'}}$ *and*

$$\begin{aligned} F_1(u,v) &= \int_0^{\frac{\pi}{2}}\int_0^{\frac{\pi}{2}} \frac{1 - e^{-\frac{T(\beta_0'+u+\frac{\beta_0+v}{\sin^2\theta})}{2\sin^2\theta'}}}{\sqrt{(\beta_0+v)(2+\frac{\beta_0+v}{\beta_0}\text{ctg}^2\theta)}} \\ &\times \frac{1}{\sqrt{(\beta_0+u+\frac{\beta_0+v}{\sin^2\theta})(2+\frac{\beta_0'+u+\frac{\beta_0+v}{\sin^2\theta}}{\beta_0'}\text{ctg}^2\theta')}} d\theta d\theta', \\ F_2(u) &= \left(\frac{A}{\sqrt{\beta_0+1}} + \frac{B}{\sqrt{\beta_0-1}}\right)\int_0^{\frac{\pi}{2}} \frac{1 - e^{-\frac{T(\beta_0'+u)}{2\sin^2\theta'}}}{\sqrt{(\beta_0'+u)(2+\frac{\beta_0'+u}{\beta_0'}\text{ctg}^2\theta')}} d\theta', \end{aligned} \tag{14}$$

in which $A = \int_0^{\frac{\pi}{2}} \frac{1}{\sqrt{2+\frac{\beta_0+1}{\beta_0}\text{ctg}^2\theta}}d\theta$, $B = \int_0^{\frac{\pi}{2}} \frac{1}{\sqrt{2+\frac{\beta_0-1}{\beta_0}\text{ctg}^2\theta}}d\theta$, $\beta_0 = \sqrt{1+\frac{\sigma^2}{P_1\delta_{s,d}^2}}$ and $\beta_0' = \sqrt{1+\frac{\sigma^2}{P_2\delta_{r,d}^2}}$.

Proof : Due to space limitation, we sketch only the calculation of averaging the channels $h_{s,d}$ and $h_{r,d}$ on $Q_0(1)$. Averaging on $Q_0(-1)$ takes a similar procedure. First, we reform the integration of $h_{s,d}$ on $Q_0(1)$, i.e., $I_{Q_0(1)}^{h_{s,d}}$, as follows

$$\begin{aligned} I_{Q_0(1)}^{h_{s,d}} &= \frac{1}{\sqrt{2\pi\delta_{s,d}^2}}\int_{-\infty}^{\infty}\int_{-\infty}^{y} \frac{1}{|h|} e^{-\frac{(x\sigma^2-2P_1h^2)^2}{8P_1h^2\sigma^2}} e^{-\frac{h^2}{2\delta_{s,d}^2}} dxdh \\ &= \frac{1}{\sqrt{2\pi\delta_{s,d}^2}}\int_{-\infty}^{y} e^{\frac{x}{2}}\left[\int_{-\infty}^{\infty}\frac{1}{|h|}e^{-\frac{\alpha}{h^2}-\beta h^2}dh\right]dx, \end{aligned} \tag{15}$$

where $\alpha = \frac{x^2\sigma^2}{8P_1}$ and $\beta = \frac{P_1}{2\sigma^2} + \frac{1}{2\delta_{s,d}^2}$. By Lemma 1, substituting α and β into (12), we have

$$I_{Q_0(1)}^{h_{s,d}} = \frac{4}{\sqrt{2\pi\delta_{s,d}^2}}\int_0^{\infty}\int_{-\infty}^{y} \frac{e^{\frac{x-|x|\beta_0}{2}}}{\sqrt{h^2+|x|\beta_0}} e^{-h^2} dxdh. \tag{16}$$

According to Lemma 2, (16) can be further shown as

$$\begin{cases} \frac{4}{\sqrt{2\pi\delta_{s,d}^2}}\int_0^{\pi/2} g(1) e^{\frac{y(1+\beta_0)}{2\sin^2\theta}}d\theta, & y \le 0; \\ \frac{4}{\sqrt{2\pi\delta_{s,d}^2}}\Big(\int_0^{\pi/2} g(1)d\theta \\ \quad + \int_0^{\pi/2} g(-1)(1-e^{-\frac{y(\beta_0-1)}{2\sin^2\theta}})d\theta\Big), & y > 0. \end{cases} \tag{17}$$

Similarly, integrating $I_{Q_0(1)}^{h_{s,d}}$ over the channel $h_{r,d}$, we have

$$\frac{1}{\sqrt{2\pi\delta_{r,d}^2}}\int_{-\infty}^{\infty}\int_{-T}^{T} \frac{I_{Q_0(1)}^{h_{s,d}}}{|h_{r,d}|} e^{-\frac{(y\sigma^2+2P_2h_{r,d}^2)^2}{8P_2h_{r,d}^2\sigma^2}} e^{-\frac{h_{r,d}^2}{2\delta_{r,d}^2}} dydh_{r,d}. \tag{18}$$

Substituting the result (17) into (18) and going through the same procedure as shown above, i.e., using Lemma 1 and Lemma 2 again, we have the result in Theorem 1.

Theorem 2 *Averaging I_1 and I_2 over the channels, we have*

$$\begin{aligned} P_{b,I_1}^{h_{s,r}} &\triangleq \frac{1}{2\pi\sqrt{\delta_{s,d}^2\delta_{r,d}^2}}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I_1 e^{-\frac{h_{s,d}^2}{2\delta_{s,d}^2}} e^{-\frac{h_{r,d}^2}{2\delta_{r,d}^2}} dh_{s,d}dh_{r,d} \\ &= C_1F_3(\beta_0,1)F_3(\beta_0',-1) + C_2F_3(\beta_0,1)F_3(\beta_0',1) \end{aligned} \tag{19}$$

$$\begin{aligned} P_{b,I_2}^{h_{s,r}} &\triangleq \frac{1}{2\pi\sqrt{\delta_{s,d}^2\delta_{r,d}^2}}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I_2 e^{-\frac{h_{s,d}^2}{2\delta_{s,d}^2}} e^{-\frac{h_{r,d}^2}{2\delta_{r,d}^2}} dh_{s,d}dh_{r,d} \\ &= AC_1F_3(\beta_0',1) + AC_2F_3(\beta_0',-1) \\ &\quad + BC_1F_3(\beta_0',1) + BC_2F_3(\beta_0',-1), \end{aligned} \tag{20}$$

where $C_1, C_2, A, B, \beta_0, \beta_0'$ are specified in Theorem 1, and

$$F_3(u,v) = \int_0^{\frac{\pi}{2}} \frac{e^{-\frac{T(u+v)}{2\sin^2\theta}}}{\sqrt{(u+v)(2+\frac{u+v}{u}\text{ctg}^2\theta)}}d\theta. \tag{21}$$

The proof of Theorem 2 follows a similar procedure as that for Theorem 1 in which we use Lemma 1 and Lemma 2 repeatedly to find the result.

3.2. BER Approximation

In the following, we try to approximate the closed-form BER expression in order to further understand the performance of the optimum ML receiver. We consider a special scenario that the relay is close to the source which implies that the variance of the $S \to R$ link $\delta_{s,r}^2$ is much larger than that of the $S \to D$ and $R \to D$ links. We consider an equal power strategy, i.e., $P_1 = P_2 = P$, and assume that the $S \to D$ and $R \to D$ channels have the same channel statistics, i.e., $\delta_{s,d}^2 = \delta_{r,d}^2 \triangleq \delta^2$. When the transmitted power P is high enough, the decoding error at the relay $\epsilon \to 0$, then the first two terms I_1 and I_2 in (10) can be approximated as

$$I_1 + I_2 \to Q_1\left(\frac{\sqrt{P_1}|h_{s,d}|}{\sigma}\right) \tag{22}$$

where $Q_1(t) = Q\left(\frac{T}{2t} + t\right)$. Thus, averaging over the fading channels, we have

$$\frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} Q_1\left(\frac{\sqrt{P_1}|h_{s,d}|}{\sigma}\right) e^{-\frac{h_{s,d}^2}{2\delta^2}} e^{-\frac{h_{s,r}^2}{2\delta_{s,r}^2}} dh_{s,d}dh_{s,r}}{2\pi\sqrt{\delta^2\delta_{s,r}^2}} \to \frac{\sigma^2}{\pi^2 P\delta_{s,r}\delta}. \tag{23}$$

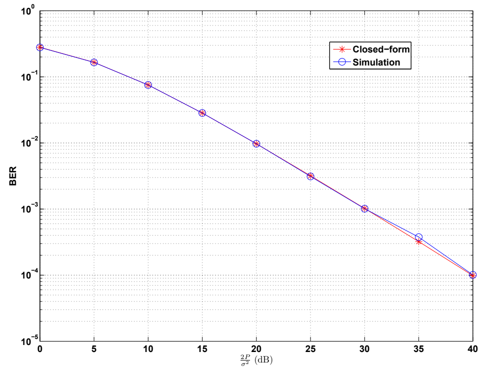

Fig. 2. Comparison of the BER simulation results and the closed-form expression for the optimum ML receiver. Assume that $\delta_{s,r}^2 = \delta_{s,d}^2 = \delta_{r,d}^2 = 1$.

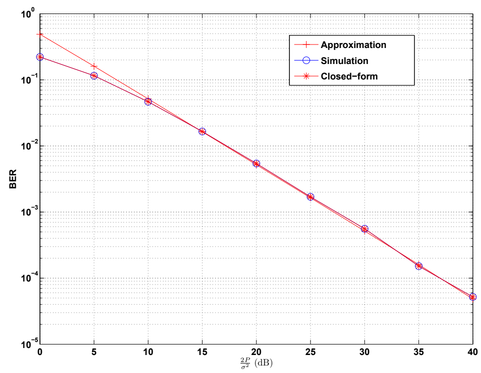

Fig. 3. Comparison of the BER approximation with simulation results for the optimum ML receiver. Assume that $\delta_{s,r}^2 = 100$ and $\delta_{s,d}^2 = \delta_{r,d}^2 = 1$.

Note that when the transmitted power P is high enough, the two constants $\beta_0 \to 1$ and $\beta_0' \to 1$. Thus, we have

$$\frac{\int_{-\infty}^{\infty} P_{b,I_3}^{h_{s,r}} e^{-\frac{h_{s,r}^2}{2\delta_{s,r}^2}} dh_{s,r}}{\sqrt{2\pi\delta_{s,r}^2}} \to \frac{\sigma^2}{\pi^2\delta^2 P}\left(\frac{\pi\sigma}{2\sqrt{P}} + D_0 - 2\sqrt{2}D_1\right), \quad (24)$$

where $D_0 = \int_0^{\frac{\pi}{2}}\int_0^{\frac{\pi}{2}}\left(\frac{\sin^3\theta\sin\theta'}{\sqrt{\sin^2\theta\sin^2\theta' + \cos^2\theta'}} + 1\right)d\theta d\theta'$ is a constant, and $D_1 = \int_0^{\frac{\pi}{2}} \frac{P\sqrt{a}\ln(\sqrt{1+\frac{a}{2P}} + \sqrt{\frac{a}{2P}})}{2Pa + a^2} d\theta$ in which we denote $a = \frac{\sigma^2}{2\delta^2\sin^2\theta}$ for simplicity.

Therefore, the closed-form BER expression can be simplified as the sum of (23) and (24). Note that the BER approximation decreases with respect to P which is expected for a system with two independent channel links of each with a real Gaussian distribution.

4. SIMULATION RESULTS

We compare first the simulation result of the optimum ML receiver with a numerical result based on the obtained closed-form BER expression. We assume that the fading channels have the same variance ($\delta_{s,r}^2 = \delta_{s,d}^2 = \delta_{r,d}^2 = 1$) and the variance of the additive white noise is one, i.e., $\sigma^2 = 1$. From the simulation results in Fig. 2, we can see that the curve based on the closed-form BER expression matches closely with the simulation curve in all range of the considered SNR which validates the theoretical analysis.

We also compare the BER approximation with simulation results in the special case that the relay is close to the source ($\delta_{s,r}^2 = 100$ and $\delta_{s,d}^2 = \delta_{r,d}^2 = 1$). From Fig. 3, we observe that the BER approximation is loose at low SNR, but tight at high SNR. It merges with the simulation curve at a system BER performance of 10^{-2}. We can also see that the numerical result based on the closed-form BER expression matches again with the simulation result in this case.

5. CONCLUSION

In this paper, we present a closed-form BER analysis for the optimum ML receiver for a coherent DF cooperative protocol with BPSK modulation. We also develop a BER approximation in a special case that the relay is close to the source to further illuminate the system performance. Note that we consider only BPSK modulation in the paper for simplicity. A natural future research is to extend the analysis to other modulation schemes such as PSK and QAM modulation.

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