Performance Analysis of Hybrid Cooperation in Asymmetric Fading Channels

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Abstract —In this paper, symbol-error-rate (SER) performance analysis is provided for hybrid cooperation (HC) system in an asymmetric fading environment where the source-to-relay and the relay-to-destination channels experience independent Rayleigh/Rician and Rician/Rayleigh fading, respectively, while the direct channel link between the source and the destination is subject to Rayleigh fading. Unlike most existing relaying protocols which use amplify-and-forward (AF) or decode-and-forward (DF) protocol separately, the HC system takes advantage of both AF and DF protocols simultaneously. Based on the theoretical analysis, analytical expressions for the moment generating function (MGF) of the end-to-end signal-to-noise ratio (SNR) are derived and used to evaluate the SER performance of the HC system with M -ary phase shift keying (M -PSK) modulation. Numerical and simulation results are presented to verify the theoretical analysis, where we also illustrate the impact of the Rician factors on system performance.

Index Terms—Wireless network, hybrid cooperation, symbol-error-rate (SER)

I. INTRODUCTION

The technologies of using cooperative relays in wireless networks have gained tremendous research interests recently because of the advantages of increasing the capacity and coverage and reducing the outage probability and symbol-error-rate (SER) [1]. Among the most popular relaying protocols are amplify-and-forward (AF) and decode-and-forward (DF). Compared to DF which requires full decoding and re-encoding of the received signals at the relay before forwarding to the destination, AF requires lower implementation complexity in digital signal processing at the relay since the relay in AF mode simply scales and retransmits the noisy version of the analog signal waveform received from the source to the destination and it has the advantage of operating at all channel fading conditions including when the source-to-relay channel experiences outage. Though no decoding and re-encoding are performed at the relay, the noise is also amplified in AF mode. Further, since the signals of the source might experience impairments due to the error-prone channel of the source-to-relay link, DF may lead to severe performance degradation if the relay wrongly decodes the received signals. But when the source-to-relay channel has a good quality and the signals can be decoded correctly at the relay, DF promises a higher gain since it regenerates and passes on a clean set of signals. Recently, a new signal forwarding strategy called hybrid cooperation (HC) was proposed which combines the merits of both AF and DF [2]. In this scheme, the relay can switch between AF and DF according to whether it can decode correctly or not. Until now, several works have studied the performance of AF and DF relay systems using performance measures such as the average SER [3]-[5] and the outage probability [6]. In [2], the outage probability and bit error rate (BER) performance of a multi-relay HC system were investigated over independent and non-identical distribution flat Rayleigh fading channel where the potential gain of the HC scheme over the AF and DF schemes were also analyzed. While in [7], the frame error rate (FER) performance of a multiple relay HC system in Rayleigh fading channels was investigated. However, most of these studies assume symmetric fading channels. While in many practical scenarios, different channel links in relay networks may experience asymmetric fading conditions. For example, a base station (BS)-to-relay link may experience Rician fading because of a strong line-of-sight (LoS) component, whereas the relay-to-mobile link may undergo Rayleigh fading. Recently, there is an increased research interests on the performance analysis of relay networks under asymmetric fading scenarios [8]-[10]. In this situation, channel links associated in the relay network are subject to different fading distributions. In [8] and [9], the end-to-end performance of a dual-hop AF relaying system in Rayleigh/Rice fading channels had been investigated. In [10], the outage probability and SER performance of a dual-hop AF relaying system were analyzed in mixed Rician and Nakagami-*m* fading channels. However, to the best of our knowledge, there is no published literature studying the performance of the HC system over asymmetric fading channels.

In this paper, the SER performance of a dual-hop HC system in an asymmetric fading environment is investigated. We assume that the source-to-relay and

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relay-to-destination channels experience Rayleigh or Rician fading, while the source-to-destination channel is subject to Rayleigh fading. We derive analytical expressions for the moment generating function (MGF) of the end-to-end signal-to-noise ratio (SNR) and then the SER of the HC system with *M*-ary phase shift keying (*M*-PSK) modulation is derived. Finally, numerical and simulation results are presented.

II. SYSTEM MODEL

We consider the specific cooperative system given in Fig. 1 which consists of a source node S, a destination node D and a half-duplex relay node R .

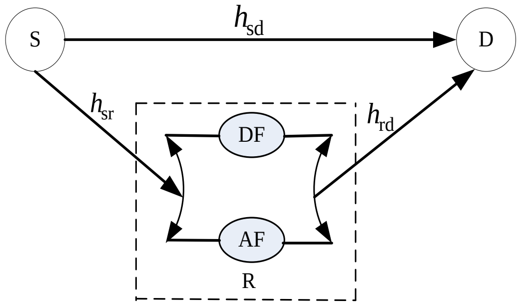

Fig. 1. System model

The source communicates with the destination both directly and through the relay in two time slots. The first time slot is the transmission of a signal from S to both D and R . In the second time slot, R forwards the signal received in the first time slot to D. Specifically, R may decode the received signal and forward it (corresponding to the DF mode), or simply amplify and retransmit it (corresponding to the AF mode) to D under a power constraint and this can be implemented by using the cyclic redundancy check (CRC) codes. Finally, D combines the signals received from both stages using a maximum-ratio-combining (MRC) scheme to make a best estimation of the original signal. The instantaneous end-to-end SNR, γ_{eq}, at the destination is given as[11]

$$\gamma_{\text{eq}} = \begin{cases} \gamma_{\text{sd}} + \gamma_{\text{rd}} & \text{DF mode} \\ \gamma_{\text{sd}} + \gamma_{\text{sr}}\gamma_{\text{rd}} \big/ \left(\gamma_{\text{sr}} + \gamma_{\text{rd}} + 1\right) & \text{AF mode} \end{cases} \quad (1)$$

In (1), $\gamma_{\text{sd}} = |h_{\text{sd}}|^2 P_{\text{S}} \big/ N_0$, $\gamma_{\text{sr}} = |h_{\text{sr}}|^2 P_{\text{S}} \big/ N_0$ and $\gamma_{\text{rd}} = |h_{\text{rd}}|^2 P_{\text{R}} \big/ N_0$ are the per hop SNRs where P_{S} and P_{R} are the transmit power of S and R, respectively, h_{sd} , h_{sr} and h_{rd} are mutually independent channel fading coefficients of the source-to-destination, source-to-relay and relay-to-destination channel links which have variances σ_{sd}^2 , σ_{sr}^2 and σ_{rd}^2 , respectively, and N_0 is the power of the additive white Gaussian noise (AWGN) component.

We consider the following two cases of the fading distributions for the source-to-relay and relay-to-destination channel links, namely:

- The source-to-relay channel experiences Rayleigh fading, while the relay-to-destination channel experiences Rician fading.
- The source-to-relay channel experiences Rician fading, while the relay-to-destination channel experiences Rayleigh fading.

In both cases of (a) and (b), we assume that the direct channel between the source and destination experiences Rayleigh fading.

If a channel experiences Rayleigh fading, then γ_{A} (with $\text{A} \in \{\text{sd}, \text{sr}, \text{rd}\}$) is an exponentially distributed random variable (RV) with probability density function (PDF) given by

$$p_{\gamma_{\text{A}}}(\gamma) = \frac{1}{\bar{\gamma}_{\text{A}}} e^{-\gamma/\bar{\gamma}_{\text{A}}} \quad (2)$$

where $\bar{\gamma}_{\text{A}} = \text{E}\left\{|h_{\text{A}}|^2\right\} P_{\text{S}} \big/ N_0$ is the average per hop SNR and $\text{E}\{\cdot\}$ is the statistical expectation.

Using the definition of MGF as $M_{\gamma}(s) = \text{E}\left(e^{-s\gamma}\right)$, it can be shown that the MGF of γ_{A} , $M_{\gamma_{\text{A}}}(s)$, can be expressed as

$$M_{\gamma_{\text{A}}}(s) = \left(1 + \bar{\gamma}_{\text{A}} s\right)^{-1} \quad (3)$$

If a channel experiences Rician fading, then γ_{A} is distributed according to a non-central- χ^2 distribution given by

$$p_{\gamma_{\text{A}}}(\gamma) = \frac{(K+1)e^{-K}}{\bar{\gamma}_{\text{A}}} e^{-\frac{(K+1)\gamma}{\bar{\gamma}_{\text{A}}}} I_0(2\sqrt{\frac{K(K+1)\gamma}{\bar{\gamma}_{\text{A}}}}) \quad (4)$$

where K is the Rician K -factor defined as the ratio of the powers of LoS component to scattered component and $I_0(\cdot)$ is the zero order modified Bessel function of the first kind. Using (4) and with the help of [12, Eq. (6.614.3)], the MGF of γ_{A} can be written as

$$M_{\gamma_{\text{A}}}(s) = \frac{(1+K)}{(1+K) + s\bar{\gamma}_{\text{A}}} \exp\left(\frac{-Ks\bar{\gamma}_{\text{A}}}{(1+K) + s\bar{\gamma}_{\text{A}}}\right) \quad (5)$$

III. SER PERFORMANCE ANALYSIS

SER is an important performance measure which is commonly used to characterize a wireless communication system. Next, we will analyze the SER performance of scenarios (a) and (b), respectively.

A. Scenario (a)

When M -PSK modulation is used, the probability that the relay correctly decodes the signals received from S, denoted as P_{c} , can be obtained from the MGF-based approach as follows

$$P_{\text{c}} = 1 - \frac{1}{\pi} \int_0^{(M-1)\pi/M} M_{\gamma_{\text{sr}}}\left(\frac{g}{\sin^2\theta}\right) d\theta \quad (6)$$

where $g=\sin^2(\pi/M)$. By substituting (3) in (6) and with the help of [13, Eq. (5A.15)], $P_{\rm c}$ can be expressed as

$$P_{\rm c}=1-\left(\frac{M-1}{M}\right)\left\{1-\sqrt{\frac{\bar{\gamma}_{sr}g}{1+\bar{\gamma}_{sr}g}}\left(\frac{M}{(M-1)\pi}\right)\right.$$
$$\left.\times\left[\frac{\pi}{2}+\tan^{-1}\left(\sqrt{\frac{\bar{\gamma}_{sr}g}{1+\bar{\gamma}_{sr}g}}\cot\frac{\pi}{M}\right)\right]\right\} \quad (7)$$

Let $P_{\rm r}(\gamma_{\rm DF})$ and $P_{\rm r}(\gamma_{\rm AF})$ denote the average SER of the HC system operated in DF and AF modes, respectively. The average SER of the HC system, denoted as P_e, can be given as

$$P_e=P_{\rm c}P_{\rm r}(\gamma_{\rm DF})+(1-P_{\rm c})P_{\rm r}(\gamma_{\rm AF}) \quad (8)$$

where $\gamma_{\rm DF}$ and $\gamma_{\rm AF}$ denote the output SNR of the HC system under DF and AF modes, respectively.

From (1) and the assumption of statistical independence of all channels, $P_{\rm r}(\gamma_{\rm DF})$ can be expressed as

$$\begin{aligned}P_{\rm r}(\gamma_{\rm DF})&=\frac{1}{\pi}\int_0^{(M-1)\pi/M}M_{\gamma_{\rm DF}}\left(\frac{g}{\sin^2\theta}\right)d\theta\\&=\frac{1}{\pi}\int_0^{(M-1)\pi/M}M_{\gamma_{\rm sd}}\left(\frac{g}{\sin^2\theta}\right)M_{\gamma_{\rm rd}}\left(\frac{g}{\sin^2\theta}\right)d\theta\end{aligned} \quad (9)$$

When operated in DF mode, $\gamma_{\rm DF}$ is given as

$$\gamma_{\rm DF}=\gamma_{\rm sd}+\gamma_{\rm rd} \quad (10)$$

By applying (3), (5) and (10), the MGF of $\gamma_{\rm DF}$ can be determined by

$$\begin{aligned}M_{\gamma_{\rm DF}}(s)&=(1+\bar{\gamma}_{\rm sd}s)^{-1}\times\frac{(1+K)}{(1+K)+s\bar{\gamma}_{\rm rd}}\exp\left(\frac{-Ks\bar{\gamma}_{\rm rd}}{(1+K)+s\bar{\gamma}_{\rm rd}}\right)\\&=\frac{(1+K)}{(1+\bar{\gamma}_{\rm sd}s)\left[(1+K)+s\bar{\gamma}_{\rm rd}\right]}\exp\left(\frac{-Ks\bar{\gamma}_{\rm rd}}{(1+K)+s\bar{\gamma}_{\rm rd}}\right)\end{aligned} \quad (11)$$

Substituting (11) and $s=g/\sin^2\theta$ in (9), $P_{\rm r}(\gamma_{\rm DF})$ can be expressed as

$$\begin{aligned}P_{\rm r}(\gamma_{\rm DF})&=\frac{1}{\pi}\int_0^{(M-1)\pi/M}\frac{(1+K)}{(1+\bar{\gamma}_{\rm sd}s)\left[(1+K)+s\bar{\gamma}_{\rm rd}\right]}\\&\quad\times\exp\left(\frac{-Ks\bar{\gamma}_{\rm rd}}{(1+K)+s\bar{\gamma}_{\rm rd}}\right)d\theta\\&=\frac{1}{\pi}\int_0^{(M-1)\pi/M}\frac{\sin^4\theta(1+K)}{(\sin^2\theta+\bar{\gamma}_{\rm sd}g)\left[(1+K)\sin^2\theta+g\bar{\gamma}_{\rm rd}\right]}\\&\quad\times\exp\left(\frac{-Kg\bar{\gamma}_{\rm rd}}{(1+K)\sin^2\theta+g\bar{\gamma}_{\rm rd}}\right)\end{aligned} \quad (12)$$

When operated in AF mode, analytical evaluation of the SER for the HC system using $\gamma_{\rm eq}$ given in (1) is complicated. To make it more easily tractable, the SNR $\gamma_{\rm eq}$ can be approximated by its upper bound $\gamma_{\rm AF}$ as follows [14]

$$\gamma_{\rm eq}\le\gamma_{\rm AF}=\gamma_{\rm sd}+z \quad (13)$$

where $z=\min(\gamma_{\rm sr},\gamma_{\rm rd})$. This approximation is adopted in many recent papers and it is shown to be accurate enough. Further, using the fact that $\gamma_{\rm sd}$ and z are statistically independent, we can express $P_{\rm r}(\gamma_{\rm AF})$ as follows

$$\begin{aligned}P_{\rm r}(\gamma_{\rm AF})&=\frac{1}{\pi}\int_0^{(M-1)\pi/M}M_{\gamma_{\rm AF}}\left(\frac{g}{\sin^2\theta}\right)d\theta\\&=\frac{1}{\pi}\int_0^{(M-1)\pi/M}M_{\gamma_{\rm sd}}\left(\frac{g}{\sin^2\theta}\right)M_z\left(\frac{g}{\sin^2\theta}\right)d\theta\end{aligned} \quad (14)$$

With the help of [15, Eq. (7)], the cumulative distribution function (CDF) of z, denoted as $F_z(z)$, can be expressed as

$$\begin{aligned}F_z(z)&={\rm P_r}\left\{\min(\gamma_{\rm sr},\gamma_{\rm rd})\le {\rm z}\right\}\\&=1-\left\{1-F_{\gamma_{\rm sr}}({\rm z})\right\}\left\{1-F_{\gamma_{\rm rd}}({\rm z})\right\}\\&=1-e^{-z/\bar{\gamma}_{\rm sr}}Q\left(\sqrt{2K},\sqrt{\frac{2(1+K)z}{\bar{\gamma}_{\rm rd}}}\right)\end{aligned} \quad (15)$$

where $Q(\cdot,\cdot)$ is the first-order Marcum Q-function.

Then, with some manipulations, the MGF of z, denoted as $M_z(s)$, can be calculated as follows

$$\begin{aligned}M_z(s)&=E\left(e^{-sz}\right)=\int_0^\infty e^{-sz}f_z(z)dz\\&=\int_0^\infty e^{-sz}dF_z(z)\\&=e^{-sz}\times F_z(z)\big|_0^\infty+s\int_0^\infty F_z(z)e^{-sz}dz\\&=s\int_0^\infty F_z(z)e^{-sz}dz\end{aligned} \quad (16)$$

By substituting (15) in (16), $M_z(s)$ can be rewritten as

$$\begin{aligned}M_z(s)&=s\int_0^\infty[1-e^{-z/\bar{\gamma}_{\rm sr}}Q(\sqrt{2K},\sqrt{\frac{2(1+K)z}{\bar{\gamma}_{\rm rd}}})]e^{-sz}dz\\&=s\times\left[\int_0^\infty e^{-sz}dz-\int_0^\infty e^{-(s+1/\bar{\gamma}_{\rm sr})z}Q(\sqrt{2K},\sqrt{\frac{2(1+K)z}{\bar{\gamma}_{\rm rd}}})dz\right]\\&=1-s\times\int_0^\infty e^{-(s+1/\bar{\gamma}_{\rm sr})z}Q(\sqrt{2K},\sqrt{\frac{2(1+K)z}{\bar{\gamma}_{\rm rd}}})dz\end{aligned} \quad (17)$$

Let $I=\int_0^\infty e^{-(s+1/\bar{\gamma}_{\rm sr})z}Q(\sqrt{2K},\sqrt{\frac{2(1+K)z}{\bar{\gamma}_{\rm rd}}})dz$ and with the help of [16, Eq. (40)], it can be shown that I can be expressed as

$$\begin{aligned}I&=\int_0^\infty e^{-(s+1/\bar{\gamma}_{\rm sr})z}Q(\sqrt{2K},\sqrt{\frac{2(1+K)z}{\bar{\gamma}_{\rm rd}}})dz\\&=2\int_0^\infty te^{-2(s+1/\bar{\gamma}_{\rm sr})t^2/2}Q(\sqrt{2K},\sqrt{\frac{2(1+K)}{\bar{\gamma}_{\rm rd}}}t)dt\end{aligned}$$

$$= \frac{1}{\left(s+1/\bar{\gamma}_{\text{sr}}\right)}\left[1-\frac{\left(1+K\right)}{\left(s+1/\bar{\gamma}_{\text{sr}}\right)\bar{\gamma}_{\text{rd}}+\left(1+K\right)} \times\exp\left(\frac{-\left(s+1/\bar{\gamma}_{\text{sr}}\right)K\bar{\gamma}_{\text{rd}}}{\left(s+1/\bar{\gamma}_{\text{sr}}\right)\bar{\gamma}_{\text{rd}}+\left(1+K\right)}\right)\right] \tag{18}$$

where during the above derivation, we made a variable change as $t=\sqrt{z}$ in the second equation. Then, by applying (18), (17) can be written as

$$M_z(s) = 1-\frac{s}{\left(s+1/\bar{\gamma}_{\text{sr}}\right)}\left[1-\frac{\left(1+K\right)}{\left(s+1/\bar{\gamma}_{\text{sr}}\right)\bar{\gamma}_{\text{rd}}+\left(1+K\right)} \times\exp\left(\frac{-\left(s+1/\bar{\gamma}_{\text{sr}}\right)K\bar{\gamma}_{\text{rd}}}{\left(s+1/\bar{\gamma}_{\text{sr}}\right)\bar{\gamma}_{\text{rd}}+\left(1+K\right)}\right)\right] \tag{19}$$

Then, according to (13), the MGF of γ_{AF} can be expressed as

$$\begin{aligned} M_{\gamma_{\text{AF}}}\left(s\right) &= M_{\gamma_{\text{sd}}}\left(s\right)M_z\left(s\right) \\ &= \frac{1}{\bar{\gamma}_{\text{sd}}s+1}\times\left\{1-\frac{s}{\left(s+1/\bar{\gamma}_{\text{sr}}\right)}\left[1-\frac{\left(1+K\right)}{\left(s+1/\bar{\gamma}_{\text{sr}}\right)\bar{\gamma}_{\text{rd}}+\left(1+K\right)} \times\exp\left(\frac{-\left(s+1/\bar{\gamma}_{\text{sr}}\right)K\bar{\gamma}_{\text{rd}}}{\left(s+1/\bar{\gamma}_{\text{sr}}\right)\bar{\gamma}_{\text{rd}}+\left(1+K\right)}\right)\right]\right\} \end{aligned} \tag{20}$$

By substituting (20) in (14), $P_{\text{r}}(\gamma_{\text{AF}})$ can be written as

$$\begin{aligned} P_{\text{r}}(\gamma_{\text{AF}}) &= \frac{1}{\pi}\int_0^{(M-1)\pi/M}\frac{1}{\bar{\gamma}_{\text{sd}}s+1}\times\left\{\frac{1/\bar{\gamma}_{\text{sr}}}{s+1/\bar{\gamma}_{\text{sr}}} + \frac{s\left(1+K\right)}{(s+1/\bar{\gamma}_{\text{sr}})^2\bar{\gamma}_{\text{rd}}+(s+1/\bar{\gamma}_{\text{sr}})(1+K)} \times\exp\left[\frac{-(s+1/\bar{\gamma}_{\text{sr}})K\bar{\gamma}_{\text{rd}}}{(s+1/\bar{\gamma}_{\text{sr}})\bar{\gamma}_{\text{rd}}+(K+1)}\right]\right\}d\theta \\ &= I_1+I_2 \end{aligned} \tag{21}$$

where

$$I_1 = \frac{1}{\pi}\int_0^{(M-1)\pi/M}\frac{1}{\bar{\gamma}_{\text{sd}}s+1}\times\frac{1}{\bar{\gamma}_{\text{sr}}s+1}d\theta$$

$$I_2 = \frac{1}{\pi}\int_0^{(M-1)\pi/M}\frac{1}{\bar{\gamma}_{\text{sd}}s+1}\times\frac{\bar{\gamma}_{\text{sr}}^2 s(1+K)}{(\bar{\gamma}_{\text{sr}}s+1)^2\bar{\gamma}_{\text{rd}}+\bar{\gamma}_{\text{sr}}(\bar{\gamma}_{\text{sr}}s+1)(1+K)} \times\exp\left[\frac{-(\bar{\gamma}_{\text{sr}}s+1)K\bar{\gamma}_{\text{rd}}}{(\bar{\gamma}_{\text{sr}}s+1)\bar{\gamma}_{\text{rd}}+\bar{\gamma}_{\text{sr}}(1+K)}\right]d\theta$$

and $s=g/\sin^2\theta$.

Using a fractional decomposition, I_1 can be expressed as

$$I_1 = \frac{1}{\pi}\int_0^{(M-1)\pi/M}\left(\frac{A}{\bar{\gamma}_{\text{sd}}s+1}+\frac{B}{\bar{\gamma}_{\text{sr}}s+1}\right)d\theta \tag{22}$$

In (22), the residues are given by $A=\bar{\gamma}_{\text{sd}}/\left(\bar{\gamma}_{\text{sd}}-\bar{\gamma}_{\text{sr}}\right)$ and $B=\bar{\gamma}_{\text{sr}}/\left(\bar{\gamma}_{\text{sr}}-\bar{\gamma}_{\text{sd}}\right)$.

Then, by substituting A, B and $s=g/\sin^2\theta$ in (22), I_1 can be given as

$$\begin{aligned} I_1 &= \frac{1}{\pi}\int_0^{(M-1)\pi/M}\left[\frac{A\sin^2\theta}{\left(\bar{\gamma}_{\text{sd}}g+\sin^2\theta\right)}+\frac{B\sin^2\theta}{\left(\bar{\gamma}_{\text{sr}}g+\sin^2\theta\right)}\right]d\theta \\ &= A\zeta\left\{1-\sqrt{\frac{\bar{\gamma}_{\text{sd}}g}{1+\bar{\gamma}_{\text{sd}}g}}\left(\frac{1}{\pi\zeta}\right)\left[\frac{\pi}{2}+\tan^{-1}\left(\sqrt{\frac{\bar{\gamma}_{\text{sd}}g}{1+\bar{\gamma}_{\text{sd}}g}}\psi\right)\right]\right\} \\ &+ B\zeta\left\{1-\sqrt{\frac{\bar{\gamma}_{\text{sr}}g}{1+\bar{\gamma}_{\text{sr}}g}}\left(\frac{1}{\pi\zeta}\right)\left[\frac{\pi}{2}+\tan^{-1}\left(\sqrt{\frac{\bar{\gamma}_{\text{sr}}g}{1+\bar{\gamma}_{\text{sr}}g}}\psi\right)\right]\right\} \end{aligned} \tag{23}$$

where $\zeta=\left(M-1\right)/M$ and $\psi=\cot\left(\pi/M\right)$.

Finally, by substituting (7), (12) and (21) into (8), the average SER P_e in scenario (a) can be acquired.

B. Scenario (b)

In the case of scenario (b), by using (5) in (6), we can express P_{c} as

$$P_{\text{c}} = 1-\frac{1}{\pi}\int_0^{(M-1)\pi/M}\frac{\left(1+K\right)}{\left(1+K\right)+s\bar{\gamma}_{\text{sr}}}\exp\left(\frac{-Ks\bar{\gamma}_{\text{sr}}}{\left(1+K\right)+s\bar{\gamma}_{\text{sr}}}\right)d\theta \tag{24}$$

Then, by substituting (3) (with $\text{A}\in\{\text{sd},\text{rd}\}$) in (9) and using a fractional decomposition, $P_{\text{r}}(\gamma_{\text{DF}})$ can be expressed as

$$\begin{aligned} P_{\text{r}}(\gamma_{\text{DF}}) &= \frac{1}{\pi}\int_0^{(M-1)\pi/M}M_{\gamma_{\text{sd}}}\left(\frac{g}{\sin^2\theta}\right)M_{\gamma_{\text{rd}}}\left(\frac{g}{\sin^2\theta}\right)d\theta \\ &= \frac{1}{\pi}\int_0^{(M-1)\pi/M}\frac{\sin^2\theta}{\sin^2\theta+\bar{\gamma}_{\text{sd}}g}\times\frac{\sin^2\theta}{\sin^2\theta+\bar{\gamma}_{\text{rd}}g}d\theta \\ &= \frac{1}{\pi}\int_0^{(M-1)\pi/M}\left[\frac{C\times\sin^2\theta}{\sin^2\theta+\bar{\gamma}_{\text{sd}}g}+\frac{D\times\sin^2\theta}{\sin^2\theta+\bar{\gamma}_{\text{rd}}g}\right]d\theta \\ &= C\zeta\left[1-\sqrt{\frac{\bar{\gamma}_{\text{sd}}g}{1+\bar{\gamma}_{\text{sd}}g}}\left(\frac{1}{\pi\zeta}\right)\left[\frac{\pi}{2}+\tan^{-1}\left(\sqrt{\frac{\bar{\gamma}_{\text{sd}}g}{1+\bar{\gamma}_{\text{sd}}g}}\psi\right)\right]\right] \\ &+ D\zeta\left[1-\sqrt{\frac{\bar{\gamma}_{\text{rd}}g}{1+\bar{\gamma}_{\text{rd}}g}}\left(\frac{1}{\pi\zeta}\right)\left[\frac{\pi}{2}+\tan^{-1}\left(\sqrt{\frac{\bar{\gamma}_{\text{rd}}g}{1+\bar{\gamma}_{\text{rd}}g}}\psi\right)\right]\right] \end{aligned} \tag{25}$$

where the residues are given by $C=\bar{\gamma}_{\text{sd}}/\left(\bar{\gamma}_{\text{sd}}-\bar{\gamma}_{\text{rd}}\right)$ and $D=\bar{\gamma}_{\text{rd}}/\left(\bar{\gamma}_{\text{rd}}-\bar{\gamma}_{\text{sd}}\right)$.

Moreover, because of the symmetry of γ_{sr} and γ_{rd} in AF mode, the computation for $P_{\text{r}}(\gamma_{\text{AF}})$ is similar to that of in scenario (a), and in this situation, $P_{\text{r}}(\gamma_{\text{AF}})$ can be expressed as

$$P_{\text{r}}\left(\gamma_{\text{AF}}\right) = \frac{1}{\pi}\int_0^{(M-1)\pi/M}\frac{1}{\bar{\gamma}_{\text{sd}}s+1}\times\left\{\frac{1/\bar{\gamma}_{\text{rd}}}{s+1/\bar{\gamma}_{\text{rd}}} + \frac{s\left(1+K\right)}{(s+1/\bar{\gamma}_{\text{rd}})^2\bar{\gamma}_{\text{sr}}+(s+1/\bar{\gamma}_{\text{rd}})(1+K)} \times\exp\left[\frac{-(s+1/\bar{\gamma}_{\text{rd}})K\bar{\gamma}_{\text{sr}}}{(s+1/\bar{\gamma}_{\text{rd}})\bar{\gamma}_{\text{sr}}+(1+K)}\right]\right\}d\theta \tag{26}$$

Finally, by applying (24), (25) and (26) in (8), the average SER P_e in scenario (b) can be acquired.

IV. Numerical Results

In this section, we present numerical results to verify our theoretical analysis. The results are obtained by setting $P_{\mathrm{S}} = P_{\mathrm{R}} = P/2$, where P is the total power of the source and the relay. During the simulations, without loss of generality, we assume that the variances of the noises at each of the nodes are same and equal one. The channel variance between the source and destination is normalized to one (i.e. $\sigma_{sd}^2 = 1$).

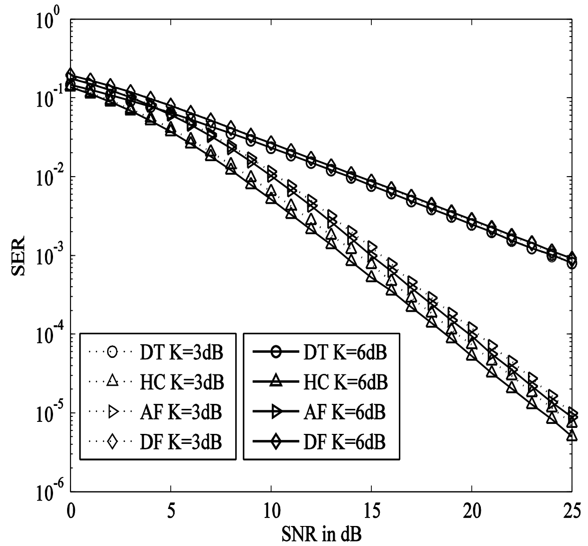

Fig. 2. SER performance versus SNR for HC, AF, DF and direct transmission in scenario (a).

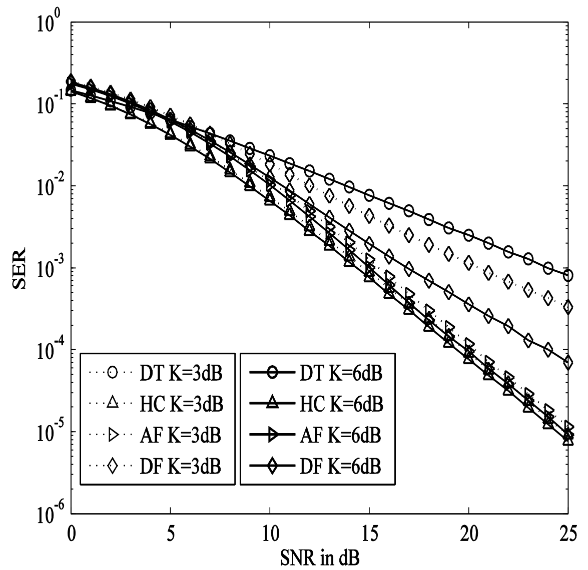

Fig. 3. SER performance versus SNR for HC, AF, DF and direct transmission in scenario (b).

Fig. 2 and Fig. 3 show the SER performance of the HC, AF, DF and direct transmission systems with binary phase shift keying (BPSK) modulation with $\sigma_{sr}^2 = \sigma_{rd}^2 = 1$ and $K = 3{,}6$ dB in scenario (a) and scenario (b), respectively. From these two figures, we can see that HC system can get the best SER performance compared to other schemes in the whole SNR range. The performance of the AF scheme is better than DF and direct transmission in both scenarios. However, the performance improvement of the HC scheme over the AF scheme in Scenario (a) is larger than in Scenario (b). This is because that in Scenario (a), the S-R link is relatively poor compared with the R-D link, so the performance of the relay link (S-R-D) is dominated by the S-R link. Moreover, since the HC system depends largely on the channel quality of the S-R link, so in this case the advantage of HC can be utilized effectively. While in Scenario (b), because the channel quality of the S-R link is relatively better (with LOS component), so the performance of the relay link (S-R-D) is dominated by the R-D link. In this situation, the relay will mainly work in DF mode, so the advantage of HC can not be utilized effectively. This can also be seen from Fig. 3 where with the increase of Rician factors, the performance of the DF scheme improved significantly and the gap between the DF scheme and the HC scheme decreases. We can also see from Fig. 2 that the performance of the DF scheme is almost the same as the direct transmission and this is due to the error propagation caused by the incorrect decoding at the relay. While in Scenario (b), the performance of the DF scheme is better than direct transmission and this is due to the decreased impact of error propagation on system performance (i.e. the relay has larger probability to decode the signal received from the source correctly). With the increase of the Rician factors, the performance gap between the DF scheme and direct transmission becomes larger in Scenario (b), while it is almost unchanged in Scenario (a).

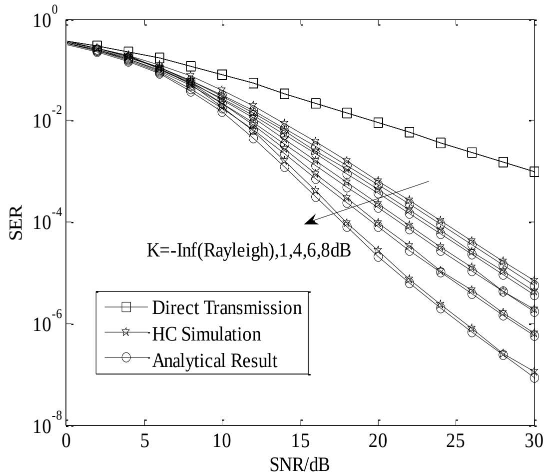

Fig. 4. SER for various K factors with $\sigma_{\mathrm{sr}}^2 = 5\sigma_{\mathrm{rd}}^2$ in scenario (a).

Fig. 4 shows the average SER versus the SNR of the transmitted signal (P/N_0 dB) in scenario (a) for different K factors with Quadrature phase shift keying (QPSK) modulation. We have also plotted the performance curve of Rayleigh/Rayleigh fading for comparison purpose. It can be observed from Fig. 4 that with the increase of Rician K -factors, the SERs decrease. This illustrates that the quality of the relay-to-destination channel has certain effect on the SER performance of the HC system and this is because that with the increase of the Rician K -factors, the effects of error propagation in DF mode and noise amplification in AF mode can be suppressed effectively in this scenario. The theoretical result provides a lower bound of the SER performance, and we can see that it is tight compared to the actual simulation results.

Fig. 5 shows the average SER performance of the HC system for various K -factors in scenario (b) with QPSK modulation. We can see from Fig. 5 that with the increase of Rician K -factors, the SER performance almost unchanged. This is because that with the increase of Rician K -factors, the channel quality between the source and the relay becomes better, so the relay has larger probability to decode correctly (i.e. $P_{\rm c} \to 1$) and in this situation, the relay will mainly operate in DF mode, as a result, the advantages of HC can not be utilized fully. This can also be observed from Equation (8), where when $P_{\rm c} \to 1$, we have $P_e \approx P_{\rm r}(\gamma_{\rm DF})$. We can also see from Fig. 5 that in all cases, theoretical SER result provides a lower bound of the system SER and we can see that it is tight.

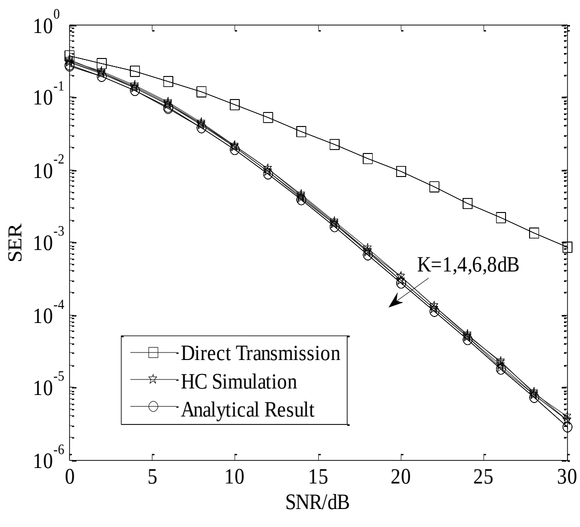

Fig. 5. SER for various K factors with $\sigma_{\rm sr}^2 = 5\sigma_{\rm rd}^2$ in scenario (b).

V. Conclusions

In this paper, analytical MGF expressions of the end-to-end SNR for HC system were derived under Rayleigh/Rician and Rician/Rayleigh fading environments, respectively. Based on the derived expressions, the average SERs of the HC system were evaluated with different Rician K -factors. Numerical examples of the system under different Rician K factors were presented. The results demonstrate that the HC system exhibits an improved performance with the increase of Rician K -factors in Rayleigh/Rician (source-to-relay channel/relay-to-destination channel) environment. While the SER performance almost unchanged with the increase of Rician K -factors in Rician/Rayleigh (source-to-relay channel/relay-to-destination channel) environment. The theoretical result provides a lower bound of the SER performance of the HC system and it is tight compared to actual simulation.

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