Line-of-Sight Component Impact Analyses for Lossy Forward Relaying over Fading Channels Having Different Statistical Properties

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***Abstract*—The primary objective of this paper is to analyse the impact of line-of-sight (LOS) component in a lossy-forward (LF) relaying system. An exact outage probability bound, indicating the theoretical limit of diversity order and coding gains, is derived. The links are assumed to suffer from dissimilar fading variations. The source-destination link variation follows Rayleigh distribution, while the source-relay (S-R) and relay-destination (R-D) link variations follow either Rician or Nakagami-m distribution. The differences between the outage performances of the LF relaying with Rician and Nakagami-m fading, are investigated. It is found that the outage performances of LF relaying over Rician fading channel and that over Nakagami-m fading channel are similar. However, the gap between the outage curves with Rician and Nakagami-m distributions does not change monotonically (first increases and then decreases) as the LOS component ratio increases. It is also found that the system diversity order is determined by the minimum achieved diversity order of S-R and R-D links. The Kullback-Leibler divergence, which measures the difference between two probability distributions, is used to verify the performance difference on the outage curves with Rician and Nakagami-m distributions.**

I. Introduction

In wireless cooperative communication systems, a natural scenario of relaying is that the source-destination (S-D) link suffers from deep fading while the source-relay (S-R) and relay-destination (R-D) links suffer from moderate fading. Therefore, the destination (D) requests help from the relay for better performance.

The Rayleigh distribution is commonly used to describe random fading due to multipath effect which only has non-line-of-sight (NLOS) components. Since line-of-sight (LOS) path significantly changes the behavior of fading channels, Rician fading model is usually used to characterize the fading having LOS component (non-zero channel mean). However, Nakagami-m distribution is more practical in describing fading channels since it can better match experimental data than Rayleigh and Rician distributions [1].

Recently, a new decode-and-forward (DF) technique that allows S-R link errors has been proposed to overcome the drawback of the conventional DF scheme where the relay discards the received data block if an error is detected. This scheme is based on the source coding with side information theorem, where at D joint decoding takes place between two decoders associated with source (S) and relay (R) [2]. This system is referred to as lossy-forward (LF) relaying system.

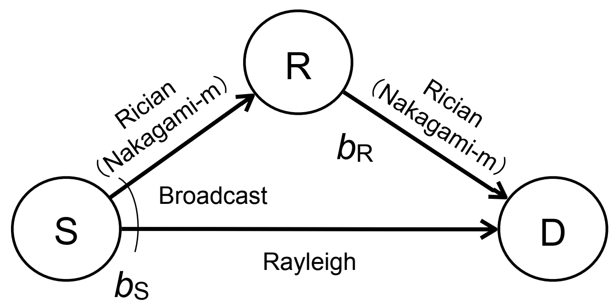

Fig. 1. Single relay lossy-forward relaying network.

Since the information received at D from S and R, respectively, is correlated, the exchange of log-likelihood ratio (LLR) information on the information bits through a global iteration improves decoding performance [3]. It has been proven that the LF relaying outperforms the conventional DF over additive white Gaussian noise (AWGN) channels in terms of bit error rate (BER) performance [3] and over Rayleigh fading channels in terms of outage probability [4]. In [5], the outage probability for the LF relaying is analysed, assuming the S-D and R-D links suffer from Rayleigh and Rician fading variations respectively. Since Nakagami-m distribution is derived from the measurement data gathered in real fields, it is quite meaningful to identify the impact difference on outage performance of the Rician and Nakagami-m fading models.

This paper focuses on the impact of LOS component to the LF relaying, and makes a comparison between the outage probabilities of LF relaying with two distributions of fading variation, Rician and Nakagami-m, to unearth the influence of the LOS component in the S-R and R-D links. Exact expressions of the outage probability bound of the LF relaying are derived. We find that the outage probability reduces monotonically as the LOS component ratio increases.

However, the diversity order will not increase unless the LOS component ratio of S-R and R-D links increases simultaneously. Consequently, the system diversity order is restricted by the minimum achieved order of S-R and R-D links. Moreover, Kullback-Leibler divergence, or distance (KLD) between the Rician and Nakagami-m distributions is calculated to investigate how significantly the outage is influenced by the difference between these two distributions.

II. System Model

We consider a simple relaying system with three nodes as shown in Fig. 1. A source S communicates with a destination D with help of one relay R. In the first time slot, the original binary information sequences $b_{\rm S}$ broadcast from S. R attempts to recover $b_{\rm S}$. However, because of the fading of the S-R link, $b_{\rm R}$ obtained as the decoding result at R may contain errors. Nevertheless, R re-interleaves, re-encodes and forwards $b_{\rm R}$ to D during the second time slot. At D, the S-R link error probabilities are estimated from LLRs, and used as the correlation knowledge between the information sent from S and R. The LLRs of the information bits are exchanged between two decoders during an iterative decoding process.

Specifically, the S-R link is modeled as by a binary symmetric channel (BSC) [6] with a crossover probability p_f, where p_f represents the bit flipping probability of $b_{\rm R}$. Hence, $b_{\rm R} = b_{\rm S} \oplus e$, where $\oplus$ denotes the modulo-2 addition and e is a binary error variable with $\Pr(e = 1) = p_f$ fixed within each block. The error probability p_f changes block-by-block assuming block fading of the S-R link.

The S-D link is assumed to experience frequency non-selective block Rayleigh fading which only has NLOS component. The probability density function (PDF) with the instantaneous signal-to-noise ratio (SNR) $\gamma_{\rm SD}$ of the S-D link is given by

$$p(\gamma_{\rm SD}) = \frac{1}{\overline{\gamma}_{\rm SD}} \exp(-\frac{\gamma_{\rm SD}}{\overline{\gamma}_{\rm SD}}), \tag{1}$$

where $\overline{\gamma}_{\rm SD}$ represents the average SNR of the S-D link.

Both S-R and R-D links are assumed to suffer from block fading variation having LOS component, following either Rician or Nakagami-m distributions. The PDF of the instantaneous SNR γ_{ij} $(ij = {\rm SR}, {\rm RD})$ following Rician distribution is

$$p^{Rici}\left(\gamma_{ij}\right) = \left(\frac{(1+K_{ij})\, e^{-K_{ij}}}{\overline{\gamma}_{ij}}\right) \exp\left(-\frac{(1+K_{ij})\gamma_{ij}}{\overline{\gamma}_{ij}}\right) \cdot I_0\left(2\sqrt{\frac{K_{ij}\left(1+K_{ij}\right)\gamma_{ij}}{\overline{\gamma}_{ij}}}\right), \tag{2}$$

where $I_0(\cdot)$ is the zero-th order modified Bessel function of the first kind. Average SNR of the corresponding link is denoted as $\overline{\gamma}_{ij}$, and the ratio of the LOS component power-to-NLOS component average power is denoted as K_{ij}.

The PDF of the instantaneous SNR γ_{ij} $(ij = {\rm SR}, {\rm RD})$ following the Nakagami-m distribution is given by

$$p^{Naka}\left(\gamma_{ij}\right) = \frac{m_{ij}^{m_{ij}}\left(\gamma_{ij}\right)^{m_{ij}-1}}{\left(\overline{\gamma}_{ij}\right)^{m_{ij}}\Gamma\left(m_{ij}\right)} \exp\left(-\frac{m_{ij}\gamma_{ij}}{\overline{\gamma}_{ij}}\right), m_{ij} > 0.5, \tag{3}$$

where $\Gamma(\cdot)$ is the complete Gamma function, and shape factor m_{ij} represents the severity of the fading variation of the corresponding link. The Nakagami-m fading with factor m is approximated by Rician fading with factor K [7], [8], as

$$m = \frac{(K+1)^2}{2K+1}. \tag{4}$$

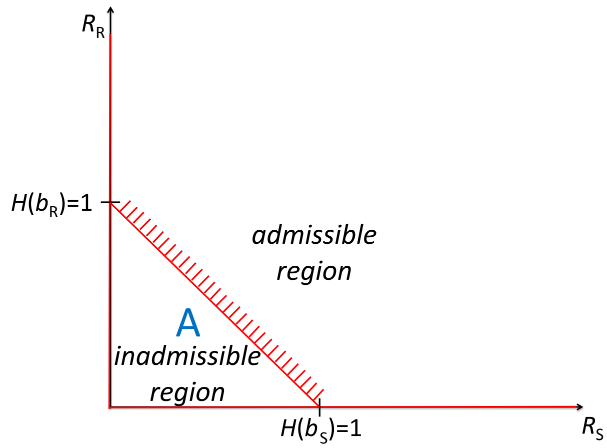

Fig. 2. Rate region for S and R when $p_f = 0$. The red solid lines separate the admissible and inadmissible regions.

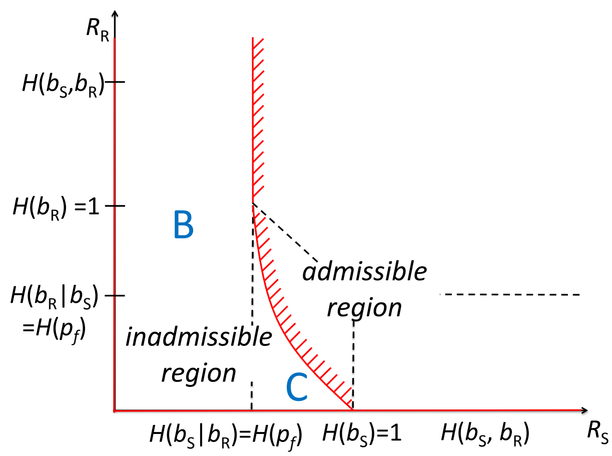

Fig. 3. Rate region for S and R when $p_f \neq 0$. The red solid lines separate the admissible and inadmissible regions.

III. Outage Probability Derivation

According to the theorem of source coding with side information [9], $b_{\rm S}$ can be reconstructed losslessly at D if the source coding rates of $b_{\rm S}$ and $b_{\rm R}$, $R_{\rm S}$ and $R_{\rm R}$ respectively, satisfy the following inequalities:

$$\begin{cases} R_{\rm S} & \geq H(b_{\rm S}|\hat{b}_{\rm R}), \\ R_{\rm R} & \geq I(b_{\rm R};\hat{b}_{\rm R}), \end{cases} \tag{5}$$

where $\hat{b}_{\mathrm{R}}$ is the estimate of b_{R} at D, and $H(\cdot|\cdot)$ and $I(\cdot;\cdot)$ denote the conditional entropy and the mutual information between the arguments, respectively.

When $p_f = 0$, which indicates perfect decoding at R, we have $H(b_{\mathrm{S}}|b_{\mathrm{R}}) = H(b_{\mathrm{R}}|b_{\mathrm{S}}) = 0$. Hence, the inadmissible rate region becomes the triangle area A as shown in Fig. 2. When $0 < p_f \le 0.5$, the inadmissible region is shown in Fig. 3 which can be divided into two areas, B and C.

The rate region defined in (5) indicates that, even b_{R} containing errors, with $0 \le R_{\mathrm{R}} \le H(b_{\mathrm{R}})$, it can serve as the side information for losslessly recovering b_{S}. In the case $R_{\mathrm{R}} > H(b_{\mathrm{R}})$, the condition becomes to $R_{\mathrm{S}} \ge H(p_f)$.

If the rate pair (R_{S}, R_{R}) falls into the inadmissible region, the outage event occurs, and D cannot reconstruct b_{S} with an arbitrarily small error probability. Since $p_f = 0$ and $0 < p_f \le 0.5$ are distinctive, the outage probability of the LF relaying can be expressed as

$$P_{\mathrm{out}} = P_{\mathrm{A}} + P_{\mathrm{B}} + P_{\mathrm{C}}, \tag{6}$$

where P_{A}, P_{B}, and P_{C} denote the probabilities that (R_{S}, R_{R}) falls into the inadmissible areas A, B, and C, respectively. Taking into account the impact of p_f, P_{A}, P_{B}, and P_{C} can further be expressed as

$$P_{\mathrm{A}} = \Pr[p_f = 0, 0 \le R_{\mathrm{S}} < 1, 0 \le R_{\mathrm{R}} < H(p_f * p_f')], \tag{7}$$
$$P_{\mathrm{B}} = \Pr[0 < p_f \le 0.5, 0 \le R_{\mathrm{S}} < H(p_f), R_{\mathrm{R}} \ge 0], \tag{8}$$
$$P_{\mathrm{C}} = \Pr[0 < p_f \le 0.5, H(p_f) \le R_{\mathrm{S}} < 1, \quad 0 \le R_{\mathrm{R}} < H(p_f * p_f')], \tag{9}$$

where a BSC model is also used to represent the R-D link (helper channel) with flipping probability p_f', with $p_f * p_f' = (1-p_f)p_f' + (1-p_f')p_f$.

Based on the Shannon's lossless source channel separation theorem, the relationship between the instantaneous channel SNR γ_{ij} ($ij = \mathrm{SD}, \mathrm{RD}$) and its corresponding rate R_k is given by[1]

$$R_k \le \Theta(\gamma_{ij}) = \log_2\left(1+\gamma_{ij}\right), \tag{10}$$

with its inverse function

$$\gamma_{ij} \ge \Theta^{-1}(R_k) = \left(2^{R_k} - 1\right), (k = \mathrm{S}, \mathrm{R}). \tag{11}$$

Based on the Shannon's lossy source channel separation theorem, the relationship between p_f and the instantaneous channel SNR γ_{SR} is given as

$$p_f = \Lambda(\gamma_{\mathrm{SR}}) = H_2^{-1}\left(1 - \log_2\left(1+\gamma_{\mathrm{SR}}\right)\right), \tag{12}$$

with $H_2^{-1}(\cdot)$ denoting the inverse function of the binary entropy. The minimum distortion is equivalent to p_f [9].

Solving (7), (8) and (9) based on the PDFs of the instantaneous SNR of the corresponding channels, the outage probabilities of the LF relaying with the fading variations of the S-R and R-D links following the Rician distribution can be expressed as

$$\begin{aligned} P_{\mathrm{A}}^{Rici} =& \int_{\gamma_{\mathrm{SR}}=\Theta^{-1}(1)}^{\Theta^{-1}(\infty)} \int_{\gamma_{\mathrm{SD}}=\Theta^{-1}(0)}^{\Theta^{-1}(1)} \int_{\gamma_{\mathrm{RD}}=\Theta^{-1}(0)}^{\Theta^{-1}(1-\Theta(\gamma_{\mathrm{SD}}))} \\ & p^{Rici}(\gamma_{\mathrm{SR}}) p(\gamma_{\mathrm{SD}}) p^{Rici}(\gamma_{\mathrm{RD}}) d\gamma_{\mathrm{SR}} d\gamma_{\mathrm{SD}} d\gamma_{\mathrm{RD}} \\ =& \frac{1}{\overline{\gamma}_{\mathrm{SD}}} Q_1\left(\sqrt{2K_{\mathrm{SR}}}, \sqrt{\frac{2(1+K_{\mathrm{SR}})}{\overline{\gamma}_{\mathrm{SR}}}}\right) \\ & \cdot \int_{\gamma_{\mathrm{SD}}=\Theta^{-1}(0)}^{\Theta^{-1}(1)} \exp\left(-\frac{\gamma_{\mathrm{SD}}}{\overline{\gamma}_{\mathrm{SD}}}\right) \left[1 - Q_1\left(\sqrt{2K_{\mathrm{RD}}}, \right.\right. \\ & \left.\left. \sqrt{2\left(1+K_{\mathrm{RD}}\right) \frac{\Theta^{-1}(1-\Theta(\gamma_{\mathrm{SD}}))}{\overline{\gamma}_{\mathrm{RD}}}}\right)\right] d\gamma_{\mathrm{SD}}, \end{aligned} \tag{13}$$

$$\begin{aligned} P_{\mathrm{B}}^{Rici} =& \int_{\gamma_{\mathrm{SR}}=\Theta^{-1}(0)}^{\Theta^{-1}(1)} \int_{\gamma_{\mathrm{SD}}=\Theta^{-1}(0)}^{\Theta^{-1}(1-\Lambda(\gamma_{\mathrm{SR}}))} \int_{\gamma_{\mathrm{RD}}=\Theta^{-1}(0)}^{\Theta^{-1}(\infty)} \\ & p^{Rici}(\gamma_{\mathrm{SR}}) p(\gamma_{\mathrm{SD}}) p^{Rici}(\gamma_{\mathrm{RD}}) d\gamma_{\mathrm{SR}} d\gamma_{\mathrm{SD}} d\gamma_{\mathrm{RD}} \\ =& \int_{\gamma_{\mathrm{SR}}=\Theta^{-1}(0)}^{\Theta^{-1}(1)} \exp\left(-\frac{(1+K_{\mathrm{SR}})\gamma_{\mathrm{SR}}}{\overline{\gamma}_{\mathrm{SR}}}\right) \\ & \cdot \left(\frac{\left(1+K_{\mathrm{SR}}\right) e^{-K_{\mathrm{SR}}}}{\overline{\gamma}_{\mathrm{SR}}}\right) I_0\left(2\sqrt{\frac{K_{\mathrm{SR}}\left(1+K_{\mathrm{SR}}\right)\gamma_{\mathrm{SR}}}{\overline{\gamma}_{\mathrm{SR}}}}\right) \\ & \cdot \left[1 - \exp\left(-\frac{\Theta^{-1}(1-\Lambda(\gamma_{\mathrm{SR}}))}{\overline{\gamma}_{\mathrm{SD}}}\right)\right] d\gamma_{\mathrm{SR}} \end{aligned} \tag{14}$$

and

$$\begin{aligned} P_{\mathrm{C}}^{Rici} =& \int_{\gamma_{\mathrm{SR}}=\Theta^{-1}(0)}^{\Theta^{-1}(1)} \int_{\gamma_{\mathrm{SD}}=\Theta^{-1}(1-\Lambda(\gamma_{\mathrm{SR}}))}^{\Theta^{-1}(1)} \int_{\gamma_{\mathrm{RD}}=\Theta^{-1}(0)}^{\Theta^{-1}[\xi(\gamma_{\mathrm{SD}},\gamma_{\mathrm{SR}})]} \\ & p^{Rici}(\gamma_{\mathrm{SR}}) p(\gamma_{\mathrm{SD}}) p^{Rici}(\gamma_{\mathrm{RD}}) d\gamma_{\mathrm{SR}} d\gamma_{\mathrm{SD}} d\gamma_{\mathrm{RD}} \\ =& \frac{1}{\overline{\gamma}_{\mathrm{SD}}} \left(\frac{\left(1+K_{\mathrm{SR}}\right) e^{-K_{\mathrm{SR}}}}{\overline{\gamma}_{\mathrm{SR}}}\right) \int_{\gamma_{\mathrm{SD}}=\Theta^{-1}(1-\Lambda(\gamma_{\mathrm{SR}}))}^{\Theta^{-1}(1)} \\ & \cdot \int_{\gamma_{\mathrm{SR}}=\Theta^{-1}(0)}^{\Theta^{-1}(1)} \exp\left(\frac{-\gamma_{\mathrm{SD}}}{\overline{\gamma}_{\mathrm{SD}}}\right) \exp\left(-\frac{(1+K_{SR})\gamma_{\mathrm{SR}}}{\overline{\gamma}_{\mathrm{SR}}}\right) \\ & \cdot I_0\left(2\sqrt{\frac{K_{\mathrm{SR}}\left(1+K_{\mathrm{SR}}\right)\gamma_{\mathrm{SR}}}{\overline{\gamma}_{\mathrm{SR}}}}\right) \left[1 - Q_1\left(\sqrt{2K_{\mathrm{RD}}}, \right.\right. \\ & \left.\left. \sqrt{2\left(1+K_{\mathrm{RD}}\right) \frac{\Theta^{-1}[\xi(\gamma_{\mathrm{SD}}, \gamma_{\mathrm{SR}})]}{\overline{\gamma}_{\mathrm{RD}}}}\right)\right] d\gamma_{\mathrm{SD}} d\gamma_{\mathrm{SR}}, \end{aligned} \tag{15}$$

where $\xi(\gamma_{\mathrm{SD}}, \gamma_{\mathrm{SR}}) = H\{H^{-1}[1-\Theta(\gamma_{\mathrm{SD}})] * H^{-1}[1-\Lambda(\gamma_{\mathrm{SR}})]\}$ and $Q_1(\cdot,\cdot)$ is the Marcum Q-Function.

The outage probability of the LF relaying with the S-R and R-D links following the Nakagami-m fading can be derived in the same way as for the Rician case, as

[1]The spectrum efficiency of the transmission chain, including the channel coding scheme and modulation multiplicity in all of the links are set to the unity.

$$P_{\mathrm{A}}^{Naka} = \frac{1}{\overline{\gamma}_{\mathrm{SD}}} \left(1 - \left[\frac{\gamma\left(m_{\mathrm{SR}}, m_{\mathrm{SR}} \frac{1}{\overline{\gamma}_{\mathrm{SR}}}\right)}{\Gamma\left(m_{\mathrm{SR}}\right)}\right]\right) \cdot \int_{\gamma_{\mathrm{SD}}=\Theta^{-1}(0)}^{\Theta^{-1}(1)} \exp\left(-\frac{\gamma_{\mathrm{SD}}}{\overline{\gamma}_{\mathrm{SD}}}\right) \cdot \left[\frac{\gamma\left(m_{\mathrm{RD}}, m_{\mathrm{RD}} \frac{\Theta^{-1}(1-\Theta(\gamma_{\mathrm{SD}}))}{\overline{\gamma}_{\mathrm{RD}}}\right)}{\Gamma\left(m_{\mathrm{RD}}\right)}\right] d\gamma_{\mathrm{SD}}, \quad (16)$$

$$P_{\mathrm{B}}^{Naka} = \int_{\gamma_{\mathrm{SR}}=\Theta^{-1}(0)}^{\Theta^{-1}(1)} \frac{m_{\mathrm{SR}}^{m_{\mathrm{SR}}} \left(\gamma_{\mathrm{SR}}\right)^{m_{\mathrm{SR}}-1}}{\left(\overline{\gamma}_{\mathrm{SR}}\right)^{m_{\mathrm{SR}}} \Gamma\left(m_{\mathrm{SR}}\right)} \exp\left(-\frac{m_{\mathrm{SR}}\gamma_{\mathrm{SR}}}{\overline{\gamma}_{\mathrm{SR}}}\right) \cdot \left[1 - \exp\left(-\frac{\Theta^{-1}(1-\Lambda(\gamma_{\mathrm{SR}}))}{\overline{\gamma}_{\mathrm{SD}}}\right)\right] d\gamma_{\mathrm{SR}}, \quad (17)$$

and

$$P_{\mathrm{C}}^{Naka} = \frac{1}{\overline{\gamma}_{\mathrm{SD}}} \int_{\gamma_{\mathrm{SR}}=\Theta^{-1}(0)}^{\Theta^{-1}(1)} \int_{\gamma_{\mathrm{SD}}=\Theta^{-1}(1-\Lambda(\gamma_{\mathrm{SR}}))}^{\Theta^{-1}(1)} \exp\left(\frac{-\gamma_{\mathrm{SD}}}{\overline{\gamma}_{\mathrm{SD}}}\right) \frac{m_{\mathrm{SR}}^{m_{\mathrm{SR}}} \left(\gamma_{\mathrm{SR}}\right)^{m_{\mathrm{SR}}-1}}{\left(\overline{\gamma}_{\mathrm{SR}}\right)^{m_{\mathrm{SR}}} \Gamma\left(m_{\mathrm{SR}}\right)} \exp\left(-\frac{m_{\mathrm{SR}}\gamma_{\mathrm{SR}}}{\overline{\gamma}_{\mathrm{SR}}}\right) \cdot \left[\frac{\gamma\left(m_{\mathrm{RD}}, m_{\mathrm{RD}} \frac{\xi(\gamma_{\mathrm{SD}},\gamma_{\mathrm{SR}})}{\overline{\gamma}_{\mathrm{RD}}}\right)}{\Gamma\left(m_{\mathrm{RD}}\right)}\right] d\gamma_{\mathrm{SD}} d\gamma_{\mathrm{SR}}, \quad (18)$$

where $\gamma(\cdot,\cdot)$ is the lower incomplete gamma function. Note that the factor K of Rician fading is connected to the factor m of Nakagami-m fading by (4), the impact of the difference in the statistical characteristics between the Rician and Nakagami-m fading on the outage performance can be evaluated by adjusting the factor K in Rician fading and the factor m in Nakagami-m fading.

IV. Kullback-Leibler Distance (KLD)

The Kullback-Leibler distance (KLD) is used to measure the difference between probability distributions. Based on (2) and (3), the KLD of Rician relative to Nakagami-m distribution is given as [10]

$$d_{\mathrm{KL}}(p^{\mathrm{Rici}}(\gamma) \| p^{\mathrm{Naka}}(\gamma)) = \int_{\gamma} p^{\mathrm{Rici}}(\gamma) \ln \frac{p^{\mathrm{Rici}}(\gamma)}{p^{\mathrm{Naka}}(\gamma)} d\gamma. \quad (19)$$

Relatively, the KLD of Nakagami-m relative to Rician distribution is defined as

$$d_{\mathrm{KL}}(p^{\mathrm{Naka}}(\gamma) \| p^{\mathrm{Rici}}(\gamma)) = \int_{\gamma} p^{\mathrm{Naka}}(\gamma) \ln \frac{p^{\mathrm{Naka}}(\gamma)}{p^{\mathrm{Rici}}(\gamma)} d\gamma. \quad (20)$$

When $K = 0$ and $m = 1$, $d_{\mathrm{KL}}(p^{\mathrm{Rici}}(\gamma) \| p^{\mathrm{Naka}}(\gamma)) = 0, d_{\mathrm{KL}}(p^{\mathrm{Naka}}(\gamma) \| p^{\mathrm{Rici}}(\gamma)) = 0$, which indicates that the Rician and Nakagami-m distributions converge to the identical Rayleigh distribution. Fig. 4 shows the KLD curves, $d_{\mathrm{KL}}\left(p^{\mathrm{Rici}}(\gamma) \| p^{\mathrm{Naka}}(\gamma)\right)$, as well as the $d_{\mathrm{KL}}(p^{\mathrm{Naka}}(\gamma) \| p^{\mathrm{Rici}}(\gamma))$, as a function of the factor K (its corresponding m value follows (4)). We can easily find that $d_{\mathrm{KL}}\left(p^{\mathrm{Rici}}(\gamma) \| p^{\mathrm{Naka}}(\gamma)\right)$ and $d_{\mathrm{KL}}(p^{\mathrm{Naka}}(\gamma) \| p^{\mathrm{Rici}}(\gamma))$ are not identical to each other, because of the asymmetricity of KLD. We can also see from Fig. 4 that $d_{\mathrm{KL}}\left(p^{\mathrm{Rici}}(\gamma) \| p^{\mathrm{Naka}}(\gamma)\right)$ and $d_{\mathrm{KL}}(p^{\mathrm{Naka}}(\gamma) \| p^{\mathrm{Rici}}(\gamma))$ increase as K (m) increase until a point between 2 and 3 for K (between 1.8 and 2.3 for m). After that, the KLDs gradually reduce as K (and hence m) further increases.

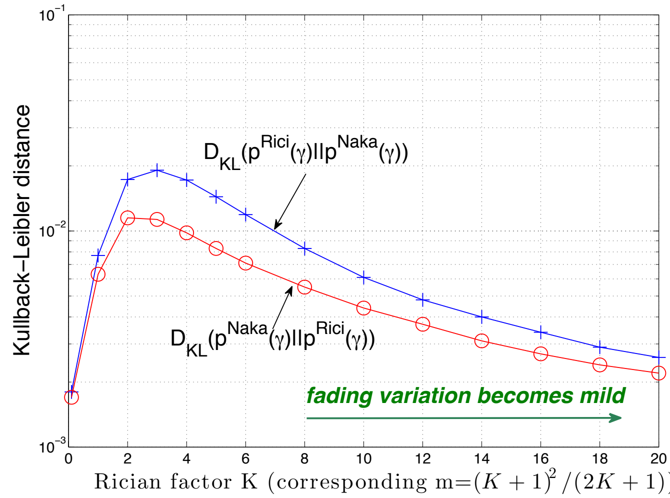

Fig. 4. KLD between Rician and Nakagami-m distributions

V. Numerical Results

The theoretical outage probabilities of the LF relaying system with R-D link suffering from Rician fading are presented in Fig. 5, where the outage probability is denoted as $P_{\mathrm{out}}^{\mathrm{Rici}}$. Also, the theoretical outage probabilities with the R-D link undergoing Nakagami-m fading, denoted as $P_{\mathrm{out}}^{\mathrm{Naka}}$, are shown in Fig. 5. Both the S-D and S-R links suffer from Rayleigh fading ($K_{\mathrm{SR}} = 0$ for $P_{\mathrm{out}}^{\mathrm{Rici}}$, $m_{\mathrm{SR}} = 1$ for $P_{\mathrm{out}}^{\mathrm{Naka}}$). We can see that the $P_{\mathrm{out}}^{\mathrm{Rici}}$ and $P_{\mathrm{out}}^{\mathrm{Naka}}$ curves have similar tendency: the larger the K_{RD} (m_{RD}) values are, the smaller the outage probability is, for a given average SNR value. This indicates that as the channel variation of the R-D link becomes milder, lower outage probability can be achieved. This is due to the contribution of the increased LOS component power in the R-D link. However, as shown in Fig. 5, the diversity order remains with a higher ratio of the R-D link LOS component. This is because the S-R and S-D link variations follow Rayleigh distribution and can only achieve 1st order diversity. Even though higher order diversity can be achieved over the R-D link with the increased LOS component power, it is obvious that the whole relaying system cannot 2nd order diversity according to max-flow min-cut theorem, which is widely used for network performance evaluation.

Fig. 6 shows the theoretical outage probability $P_{\mathrm{out}}^{\mathrm{Rici}}$ and $P_{\mathrm{out}}^{\mathrm{Naka}}$ versus the average SNR, where $K_{\mathrm{SR}} = K_{\mathrm{RD}}$ ($m_{\mathrm{SR}} = m_{\mathrm{RD}}$). It is found that the outage curves can achieve sharper decay than that with 2nd order diversity, when the LOS component ratio of the both the S-R and R-D links increases

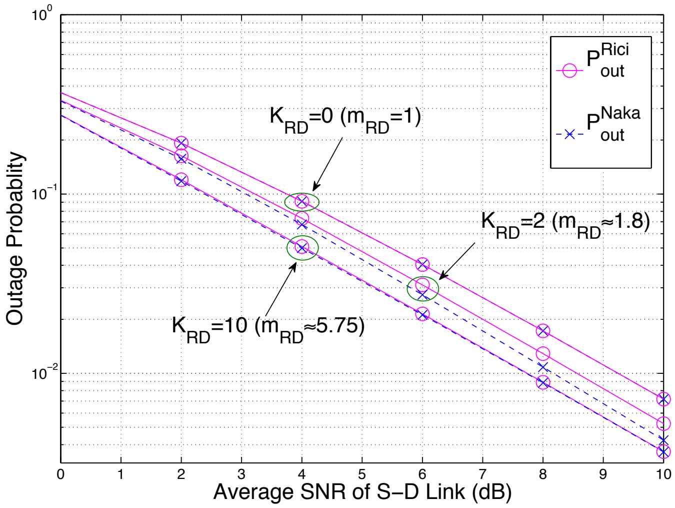

Fig. 5. Outage probability with Rician and Nakagami-m fading in the R-D link. The S-R link is Rayleigh fading: $K_{\rm SR} = 0$ ($m_{\rm SR} = 1$).

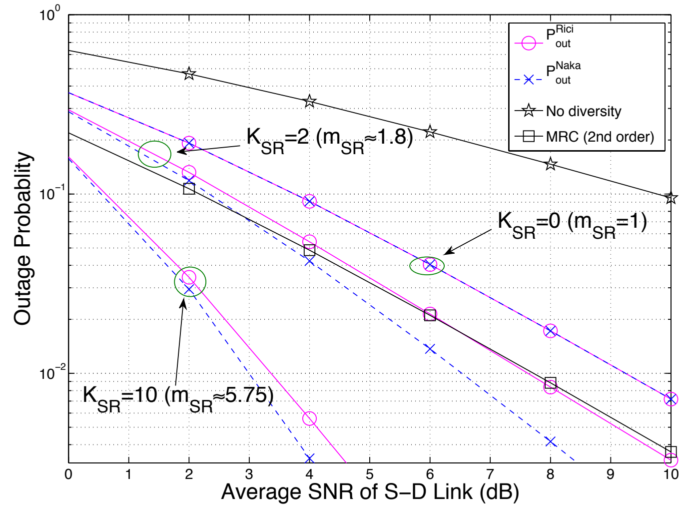

Fig. 6. Outage probability with Rician and Nakagami-m fading in both S-R and R-D links. $K_{\rm SR} = K_{\rm RD}$, $m_{\rm SR} = m_{\rm RD}$.

simultaneously. It is reasonable since the bottleneck of S-R and R-D links magnifies as the LOS component getting stronger, according to the max-flow min-cut theorem.

From Figs. 5 and 6 we found that, when $K_{\rm RD} = 0$ ($m_{\rm RD} = 1$), $P_{\rm out}^{\rm Rici}$ and $P_{\rm out}^{\rm Naka}$ show the same performance. This is because obviously, with $K_{\rm RD} = 0$ ($m_{\rm RD} = 1$), Rician (Nakagami-m) fading with R-D link reduces to Rayleigh fading. However, when the $K_{\rm RD}$ ($m_{\rm RD}$) values increase, e.g., $K_{\rm RD} = 2$ ($m_{\rm RD} \approx 1.8$), the outage curves exhibit different tendencies. Again, the difference diminishes when $K_{\rm RD}$ ($m_{\rm RD}$) becomes larger, e.g., $K_{\rm RD} = 10$ ($m_{\rm RD} \approx 5.76$). This observation can be verified by the KLD analysis given in section V.

VI. Conclusion

The impact of the LOS component on outage probability for the LF relaying has been investigated. The S-D link has been assumed to suffer from block Rayleigh fading whereas the S-R and R-D links undergo block Rician or Nakagami-m fading. The exact outage probability bound has been derived. The impact difference of Rician and Nakagami-m fading on outage performance has been evaluated, based on KLD analysis between the Rician and Nakagami-m distributions.

The majority of factor m value estimated in typical urban areas vary from 0.5 to 3.5 [11]. The relatively large KLD between Rician and Nakagami-m distributions can be observed in this range. Therefore, the outage difference between the LF relaying with Rician and Nakagami-m model is correspondingly large. This observation indicates the flaw that Nakagami-m fading model cannot be precisely represented by Rician fading model for designing and/or evaluating the theoretical limit approaching techniques with the LF relaying.

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