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Outage probability of a relay strategy allowing intra-link errors utilizing Slepian-Wolf theorem

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Abstract

In conventional decode-and-forward (DF) one-way relay systems, a data block received at the relay node is discarded, if the information part is found to have errors after decoding. Such errors are referred to as intra-link errors in this article. However, in a setup where the relay forwards data blocks despite possible intra-link errors, the two data blocks, one from the source node and the other from the relay node, are highly correlated because they were transmitted from the same source. In this article, we focus on the outage probability analysis of such a relay transmission system, where source-destination and relay-destination links, Link 1 and Link 2, respectively, are assumed to suffer from the correlated fading variation due to block Rayleigh fading. The intra-link is assumed to be represented by a simple bit-flipping model, where some of the information bits recovered at the relay node are the *flipped* version of their corresponding original information bits at the source. The correlated bit streams are encoded separately by the source and relay nodes, and transmitted block-by-block to a common destination using different time slots, where the information sequence transmitted over Link 2 may be a noise-corrupted interleaved version of the original sequence. The joint decoding takes place at the destination by exploiting the correlation knowledge of the intra-link (source-relay link). It is shown that the outage probability of the proposed transmission technique can be expressed by a set of double integrals over the admissible rate range, given by the Slepian-Wolf theorem, with respect to the probability density function (*pdf*) of the instantaneous signal-to-noise power ratios (SNR) of Link 1 and Link 2. It is found that, with the Slepian-Wolf relay technique, so far as the correlation ρ of the complex fading variation is $|\rho| < 1$, the 2nd order diversity can be achieved only if the two bit streams are fully correlated. This indicates that the diversity order exhibited in the outage curve converges to 1 when the bit streams are not fully correlated. Moreover, the Slepian-Wolf outage probability is proved to be smaller than that of the 2nd order maximum ratio combining (MRC) diversity, if the average SNRs of the two independent links are the same. Exact as well as asymptotic expressions of the outage probability are theoretically derived in the article. In addition, the theoretical outage results are compared with the frame-error-rate (FER) curves, obtained by a series of simulations for the Slepian-Wolf relay system based on bit-interleaved coded modulation with iterative detection (BICM-ID). It is shown that the FER curves exhibit the same tendency as the theoretical results.

1 Introduction

In many wireless communication systems, channels are assumed to suffer from variations due to fading. One of the most reasonable and hence widely accepted model for block-wise transmission is the block Rayleigh fading channel, where the channel realization changes block-by-block. With the block fading assumption, if the channel state information (CSI) is unknown to the transmitter, achieving always error-free transmission is not possible. This is simply because the transmission chain parameter cannot be flexibly changed at the transmitter without the knowledge of CSI, which invokes the necessity of the outage analysis. The result of the outage analysis provides the system operators estimate with which probability the quality of service (QoS) requirement can be satisfied [1].

Relay systems [2] have been well studied in the recent years, assuming various relay strategies, such as amplify-and-forward (AF) and decode-and-forward (DF) techniques [3,4], etc. In the case of DF, the information bit streams recovered at the relay may contain errors

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occurring in the source-relay link, referred to as the intra-link in this article. In conventional DF systems, the recovered data block is discarded if the relay detects errors in the information part after decoding. However, in a setup where the relay forwards data blocks despite possible intra-link errors, the information streams received by the destination via the source-destination link (Link 1) and the relay-destination (Link 2) are highly correlated, because they were transmitted from the same source. In [5], the idea of the Slepian-Wolf coding is first introduced in wireless cooperation scenarios with the aim of exploiting the distributed correlated source coding concept. Reference [6] also formulates the issue from the viewpoint of the Slepian-Wolf theorem, in a different way from [5], where the intra-link error probability is used to express the source-relay correlation [6]. The intra-link error probability can be estimated and further utilized in the joint decoding process at the destination node, by utilizing a log-likelihood ratio (LLR) updating function [6].

The primary goal of this article is to theoretically analyze the outage probability of the relay system presented in [6] and its asymptotic properties, both based on the Slepian-Wolf theorem. Originally, the Slepian-Wolf theorem determines the admissible rate region for the compression of correlated sources. The theorem states that compared with the case where the information bit streams are assumed to be independent, higher compression rate can be achieved by exploiting the correlation knowledge of the sources. Furthermore, the two correlated source streams can be *separately* encoded at each transmitter side, and the compressed data received by the receiver are jointly decoded by a common decoder. According to the Slepian-Wolf theorem, by utilizing the correlation knowledge of the sources at the receiver, the joint decoder can achieve the same compression rate as in the case that the sources are encoded by optimum *joint* encoders. This theorem can be applied to many practical applications, such as the sensor networks where measurements of the same object are performed by the separated sensors, and hence, the results are correlated.

This article assumes a bit-flipping model for the intra-link transmission [7], where some of the recovered bits b_2 at the relay node are *flipped* versions of their corresponding original information bits b_1 at the source node. Hence, $b_2 = b_1 \oplus e$ with probability $\Pr(e = 1) = p_e$, and since $\mu = \langle(2b_1 - 1)(2b_2 - 1)\rangle = 1 - 2p_e$, $(-1 \leq \mu \leq 1)$, with $\langle\cdot\rangle$ indicating the expectation operator, we use p_e and μ both equivalently describing the correlation between b_1 and b_2 [8]. In fact, the value of p_e depends on many parameters, related to the intra-link transmission such as modulation-and-detection schemes and/or encoding-and-decoding methods. However, this article uses p_e as a parameter. The p_e value can be estimated by the destination, block-by-block, as presented by [6], and hence, this assumption is reasonable in practical applications. On the other hand, if we would calculate the outage probability of the system where p_e is assumed to be a random variable, we would have to derive the distribution of p_e, which is not practical due to the fact described above. Hence, we assume that the intra-link is stable and hence p_e is a constant. The scenario under consideration is exemplified as depicted by Figure 1. In the assumed scenario, the channel gains of either one or both of the two links fade below the threshold values required for successful transmission, which defines the outage event. In this study, we show that the theoretical outage probability of the Slepian-Wolf relay system can be expressed by double integrals over the admissible rate region defined by the Slepian-Wolf theorem, with regard to the probability density function (*pdf*) of the instantaneous signal-to-noise power ratios (SNRs).

This article is organized as follows. The relay transmission model assumed in this article is introduced in Section 2. The admissible rate region is defined in Section 3, based on the Slepian-Wolf theorem, for the relay transmission model introduced in Section 2. The outage probabilities of the Slepian-Wolf relay system are then derived theoretically in Section 3, assuming that Link 1 and Link 2 are suffering from correlated block Rayleigh fading, where the fading variation of Link 1 and Link 2 are assumed to be correlated because of the scenarios assumption presented in Figure 1. The theoretical proofs of the asymptotic tendency of the outage curves are presented in Section 4. In Section 5, we apply the Slepian-Wolf relay technique provided in [6] to a bit-interleaved

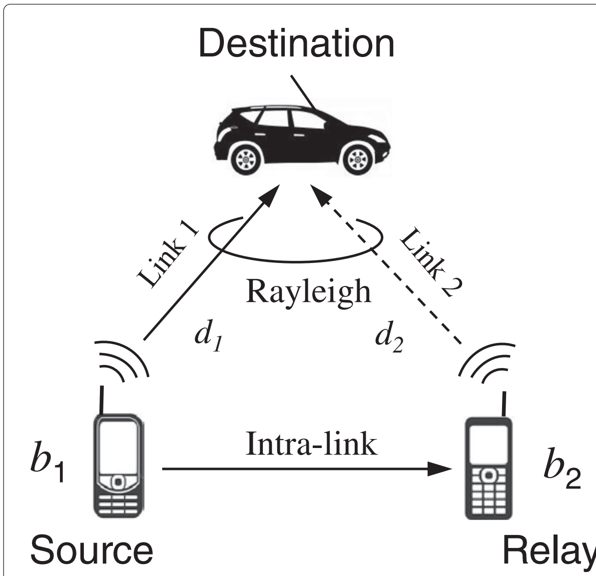

Figure 1 A simple relay system with bit-flipping model. The intra-link between the source and the relay nodes are assumed to be very stable, and therefore it is expressed by a bit-flipping model.

coded modulation with iterative detection (BICM-ID), as an example, to demonstrate how the correlation knowledge can be used. Numerical results are presented in Section 6, where it is verified that the performance tendency obtained by Section 5 is consistent to the simulated results. Conclusions are drawn in Section 7 with same concluding results.

2 System model

We consider a simple one-way relay transmission model, as shown in Figure 1. The original information bit stream b_1 is broadcasted from the source node during the first time slot. The relay aims to recover b_1 before re-encoding and forwarding it to the destination during the second time slot, as in the DF strategy. The recovery of b_1 might not be perfect, however, the proposed Slepian-Wolf relaying system will allow re-transmission despite possible intra-link errors.

Because of the reason described in the introduction, the intra-link error probability p_e is assumed to be constant, even though p_e can be estimated by the destination only [6], block-by-block, in practice. p_e does not have to represent the bit error probability of the *real* intra-link signal transmission. It represents the error probability of the *virtual* link between source and relay node: it may be before or after the decoding of the channel code. This article only uses the probability p_e as a parameter in theoretical analyzes regardless of the intra-link transmission scheme.

With d_1 and d_2 representing the lengths of Link 1 and Link 2, respectively, and with the geometrical gain [9] of Link 1, G_1, being normalized to 1, the geometric gain of Link 2, relative to Link 1, can be defined as

$$G_2 = \left(\frac{d_1}{d_2}\right)^{\alpha}, \tag{1}$$

where in this article the path loss factor α is set at 3.52 as in [10]. The received signals y_1 and y_2 at the destination, received via Link 1 and Link 2, respectively, are expressed as follows:

$$y_1 = \sqrt{G_1}h_1 s_1 + n_1, \tag{2}$$

$$y_2 = \sqrt{G_2}h_2 s_2 + n_2, \tag{3}$$

where s_1 and s_2 are the modulated symbols transmitted from the source and relay nodes, respectively, and n_i and h_i $(i = 1, 2)$ denote the zero-mean white additive Gaussian noises (AWGN) with the variance σ_i^2 per dimension and the complex channel gain of Link i, respectively. It is assumed that $\sigma_1^2 = \sigma_2^2 = \sigma^2$ and h_1 and h_2 are kept constant over one block duration due to the block Rayleigh fading assumption. With the definitions described above, the instantaneous SNR of Link i is denoted by $\gamma_i = G_i |h_i|^2 E_{s,i}/\left(2\sigma^2\right)$, where $E_{s,i}$ represents the per-symbol signal power of Link i. The joint decoding process then takes place for the received signals y_{sd} and y_{rd} at the destination node.

3 Outage probability derivation

3.1 Outage definition

The definition of the outage probability of the proposed Slepian-Wolf relay system is derived in this subsection. Let R_1 and R_2 denote the rates of the bit streams from the source and relay nodes, respectively. According to the Slepian-Wolf theorem [11], if R_1 and R_2 satisfy the following three inequalities, the transmitted data can be recovered with arbitrary low error probability.

$$R_1 \geqslant H(b_1 \mid b_2), \tag{4}$$

$$R_2 \geqslant H(b_2 \mid b_1), \tag{5}$$

$$R_1 + R_2 \geqslant H(b_1, b_2), \tag{6}$$

where $H(b_1 \mid b_2)$ and $H(b_2 \mid b_1)$ denote the conditional entropy of b_1 and b_2, given b_2 and b_1, respectively, and $H(b_1, b_2)$ denotes the joint entropy of the correlated information b_1 and b_2. When the rate R_1 for transmitting the information stream b_1 is equal to its entropy $H(b_1)$, the rate R_2 for transmitting the information stream b_2 can be less than its entropy $H(b_2)$, but it has to be larger than the conditional entropy $H(b_2 \mid b_1)$, as indicated by the point X_1 in Figure 2. Similarly, when b_2 is transmitted at the rate $H(b_2)$, then b_1 can be transmitted at the rate which is less than $H(b_1)$ but should be larger than $H(b_1 \mid b_2)$ as indicated by the point X_2 in Figure 2. Since the binary symmetric source model (Pr(1)=Pr(0)=0.5) is assumed in this article, $H(b_1) = H(b_2) = 1$, $H(b_1 \mid b_2) = H(b_2 \mid b_1) = H(p_e)$, $H(b_1, b_2) = 1 + H(p_e)$ with

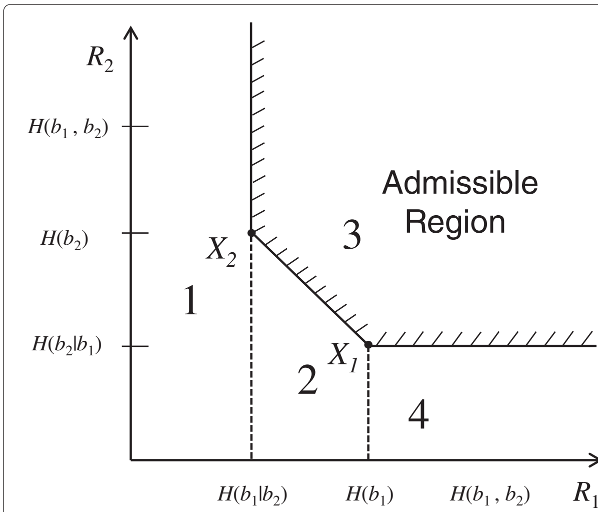

Figure 2 Admissible Slepian-Wolf rate region. The whole rate region is comprised of four parts, Part 1–Part 4.

$H(p_e) = -p_e \log_2(p_e) - (1-p_e)\log_2(1-p_e)$. Assume that a channel capacity-achieving code is used for the transmission over Link i. The relationship between the threshold instantaneous SNR and its corresponding rate R_i is given by

$$R_i = \frac{1}{R_{ci}} \log(1+\gamma_i), \quad i = 1, 2 \tag{7}$$

where R_{ci} represents the spectrum efficiency of the transmission chain, including the channel coding scheme and the modulation multiplicity within Link i [7].

As shown in Figure 2, the entire rate region for the rate pair R_1 and R_2 can be divided into four parts, with $P_j, j = \{1, 2, 3, 4\}$, representing the probability that R_1 and R_2 fall into Part j. The common admissible rate region for the case of two correlated sources can be expressed by an unbounded polygon, which corresponds to Part 3 of the rate region shown in Figure 2. The two correlated bit streams cannot be successfully recovered if the rates R_1 and R_2 are not within the admissible region Part 3. Hence, the outage event happens when R_1 and R_2 fall outside the Slepian-Wolf admissible region, with the probability of

$$\begin{aligned} P_{\text{out,sw}} &= 1 - P_3, \\ &= P_1 + P_2 + P_4. \end{aligned} \tag{8}$$

However, in this article, both Part 3 and Part 4 are supposed to be included as the admissible rate region [12], because in the one-way Slepian-Wolf relay system investigated in this article, we only focus on the transmission of the source information b_1. The data to be transmitted from the relay node actually is the erroneous copy of the original information bit stream, interleaved by Π_0 as shown in Figure 3a. Therefore, analyzing the impact of Link 2 on the outage probability is our target. In other words, an arbitrary value of R_2 is satisfactory as long as R_1 is larger than $H(b_1)$. In this case, the *individual* outage event happens when the pair (R_1, R_2) falls in Part 1 or Part 2, and the outage probability of the Slepian-Wolf relay model considered in this article is defined as

$$\begin{aligned} P_{\text{out, relay}} &= 1 - P_3 - P_4, \\ &= P_1 + P_2. \end{aligned} \tag{9}$$

Thus, the conditions on R_1 and R_2 to achieve arbitrary low bit error rate are given by[a]

$$\begin{aligned} P_1 &= \Pr\left[0 < R_1 < H(b_1 \mid b_2), R_2 > 0\right], \\ &= \Pr\left[0 < \gamma_1 < 2^{R_{c1}H(b_1|b_2)} - 1, \gamma_2 > 0\right]. \end{aligned} \tag{10}$$

$$\begin{aligned} P_2 &= \Pr\left[H(b_1 \mid b_2) < R_1 < H(b_1), R_1 + R_2 < H(b_1, b_2)\right], \\ &= \Pr\Big[2^{R_{c1}H(b_1|b_2)} - 1 < \gamma_1 < 2^{R_{c1}H(b_1)} - 1, \\ &\qquad 0 < \gamma_2 < 2^{\left[R_{c2}H(b_1,b_2) - \frac{R_{c2}}{R_{c1}}\log(1+\gamma_1)\right]} - 1\Big]. \end{aligned} \tag{11}$$

3.2 Outage calculation

3.2.1 Independent links

In this section, the outage probability is derived, based on the Slepian-Wolf relay model. With an assumption that both Link 1 and Link 2 suffer from statistically independent block Rayleigh fading, the joint *pdf* of the instantaneous SNR can be expressed as $p(\gamma_1, \gamma_2) = p(\gamma_1)p(\gamma_2)$, with [13]

$$p(\gamma_i) = \frac{1}{\Gamma_i} \exp\left(-\frac{\gamma_i}{\Gamma_i}\right), \quad i = 1, 2 \tag{12}$$

where $\Gamma_i = G_i E_{s,i} / \left(2\sigma^2\right)$, which represents the normalized average SNR of the *i-th* link. Based on (10) and (11), the probabilities P_1 and P_2 can be mathematically derived as follows

$$\begin{aligned} P_1 &= \int_{\gamma_1=0}^{2^{R_{c1}H(b_1|b_2)}-1} \int_{\gamma_2=0}^{\infty} p(\gamma_1)\, p(\gamma_2)\, d\gamma_1 d\gamma_2, \\ &= \int_{\gamma_1=0}^{2^{R_{c1}H(b_1|b_2)}-1} \frac{1}{\Gamma_1} \exp\left(-\frac{\gamma_1}{\Gamma_1}\right) d\gamma_1, \\ &= 1 - \exp\left[-\frac{2^{R_{c1}H(b_1|b_2)} - 1}{\Gamma_1}\right], \end{aligned} \tag{13}$$

and

$$\begin{aligned} P_2 &= \int_{\gamma_1=2^{R_{c1}H(b_1|b_2)}-1}^{2^{R_{c1}H(b_1)}-1} \\ &\times \int_{\gamma_2=0}^{2^{\left[R_{c2}H(b_1,b_2)-\frac{R_{c2}}{R_{c1}}\log(1+\gamma_1)\right]}-1} p(\gamma_1)\, p(\gamma_2)\, d\gamma_1 d\gamma_2, \\ &= \int_{\gamma_1=2^{R_{c1}H(b_1|b_2)}-1}^{2^{R_{c1}H(b_1)}-1} \\ &\times p(\gamma_1)\left[-\exp\left(-\frac{\gamma_2}{\Gamma_2}\right)\right]_{\gamma_2=0}^{2^{\left[R_{c2}H(b_1,b_2)-\frac{R_{c2}}{R_{c1}}\log(1+\gamma_1)\right]}-1} d\gamma_1, \\ &= \int_{\gamma_1=2^{R_{c1}H(b_1|b_2)}-1}^{2^{R_{c1}H(b_1)}-1} \frac{1}{\Gamma_1} \exp\left(-\frac{\gamma_1}{\Gamma_1}\right) \\ &\times \left[1 - \exp\left(-\frac{2^{\left[R_{c2}H(b_1,b_2)-\frac{R_{c2}}{R_{c1}}\log(1+\gamma_1)\right]}-1}{\Gamma_2}\right)\right] d\gamma_1, \\ &= \frac{1}{\Gamma_1} \int_{\gamma_1=2^{R_{c1}H(b_1|b_2)}-1}^{2^{R_{c1}H(b_1)}-1} \left[\exp\left(-\frac{\gamma_1}{\Gamma_1}\right) \right. \\ &\left. - \exp\left(-\frac{\gamma_1}{\Gamma_1} + \frac{1}{\Gamma_2} - \frac{2^{R_{c2}H(b_1,b_2)}}{\Gamma_2 (1+\gamma_1)^{\frac{R_{c2}}{R_{c1}}}}\right)\right] d\gamma_1. \end{aligned} \tag{14}$$

Unfortunately, the derivation of an explicit expression of (14) may not be possible. Hence, instead, the trapezoidal numerical integration [14] method is used to calculate P_2 in Section 4.

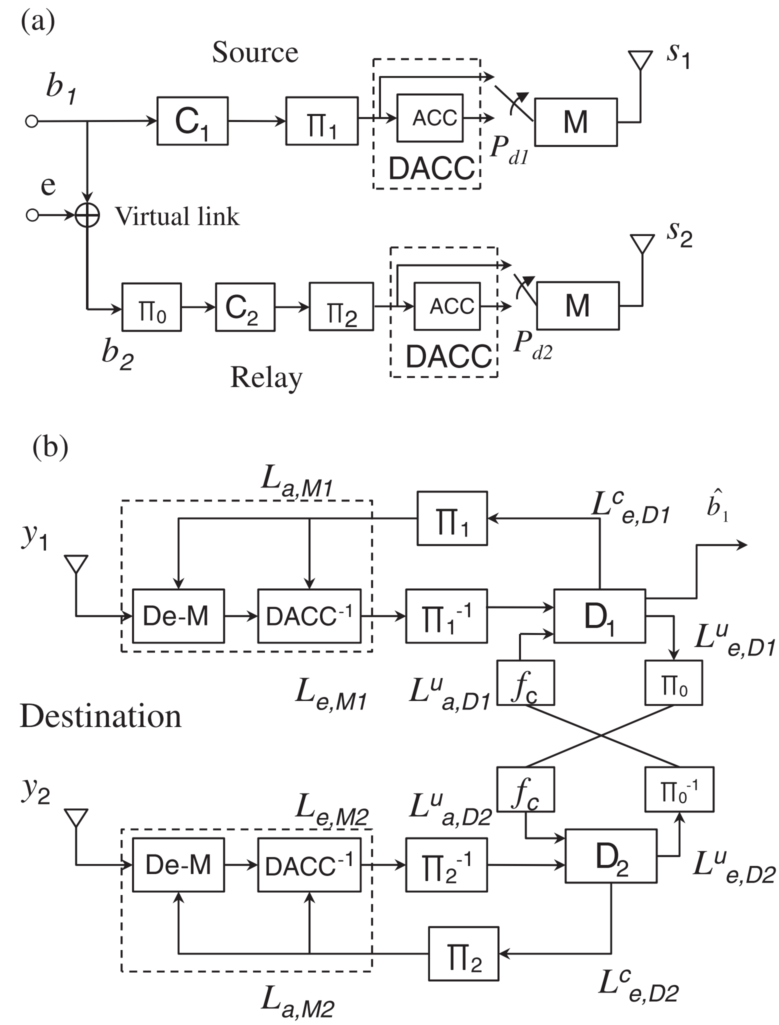

Figure 3 The schematic diagram of the proposed Slepian-Wolf relay system. (a) The source and the relay nodes. **(b)** The destination node. The BICM-ID demapper and the channel decoder exchange soft information via horizontal iterations (HI), while the two channel decoders also exchange information by exploiting the source-relay correlation, via vertical iterations (VI).

3.2.2 Correlated links

This section derives P_1 and P_2 taking into account the correlation $\rho = \langle h_1 h_2^* \rangle$ of the fading variations. According to [13], when Link 1 and Link 2 are correlated, the signal amplitudes A_1 and A_2 ($A_i = \sqrt{G_i \, |h_i|^2 \, E_{s,i}}$) follow the *joint pdf* $p(A_1, A_2)$, as shown in (15):

$$p(A_1,A_2) = \frac{4A_1A_2}{P_{r1}P_{r2}(1-|\rho|^2)} I_0\left[\frac{2\,|\rho|\,A_1A_2}{\sqrt{P_{r1}P_{r2}}(1-|\rho|^2)}\right] \times \exp\left[-\frac{1}{1-|\rho|^2}\left(\frac{A_1^2}{P_{r1}}+\frac{A_2^2}{P_{r2}}\right)\right], \quad (15)$$

where $I_0(\cdot)$ is the zeroth order modified Bessel's function of the first kind. We define the average SNR of the ith channel as $\Gamma_i = P_{ri}/\left(2\sigma^2\right)$, where $P_{ri} = \left\langle |h_i|^2 \, E_i \right\rangle$, denoting the average received signal power of Link i. Since $I_0(x)$ can be expanded into a series $I_0(x) = \sum_{n=0}^{\infty} \frac{(x/2)^{2n}}{(n!)^2}$, (15) can be re-written as [15]

$$\begin{aligned} p(A_1,A_2) =& \frac{4A_1A_2}{P_{r1}P_{r2}(1-|\rho|^2)} \exp\left(-\frac{A_1^2/P_{r1}}{1-|\rho|^2} - \frac{A_2^2/P_{r2}}{1-|\rho|^2}\right), \\ & \sum_{n=0}^{\infty} \frac{1}{(n!)^2}\left(\frac{|\rho|\,A_1A_2}{\sqrt{P_{r1}P_{r2}}(1-|\rho|^2)}\right)^{2n}, \\ =& \sum_{n=0}^{\infty} q_1^{(n)} q_2^{(n)}, \end{aligned} \quad (16)$$

where $q_1^{(n)}$ and $q_2^{(n)}$ can be expressed as

$$q_1^{(n)} = \frac{2A_1^{2n+1}\,|\rho|^n}{P_{r1}^{n+1}(1-|\rho|^2)^{n+1/2}} \exp\left(-\frac{A_1^2/P_{r1}}{1-|\rho|^2}\right)\left(\frac{1}{n!}\right), \quad (17)$$

$$q_2^{(n)} = \frac{2A_2^{2n+1}|\rho|^n}{P_{r2}^{n+1}(1-|\rho|^2)^{n+1/2}} \exp\left(-\frac{A_2^2/P_{r2}}{1-|\rho|^2}\right)\left(\frac{1}{n!}\right). \tag{18}$$

Since $p(A_1, A_2)$ can be factored into a product of two independent terms, each for its corresponding random variable, it is easy to calculate P_1 and P_2 by substituting (16)–(18) and $\gamma_i = A_i^2/\left(2\sigma^2\right)$ into (13) and (14), with the aid of the trapezoidal methods.

3.2.3 Outage of MRC

For a comparison with our proposed Slepian-Wolf relay system, the outage probability of the maximum ratio combining (MRC) scheme is derived with the assumptions that $p_e = 0^{\mathrm{b}}$, $\rho = 0$ and $\Gamma_1 = \Gamma_2$. It is well known that the output of the MRC combiner is a weighted sum of signals received via all the transmission links. The *pdf* $p_{\gamma_\Sigma}(\gamma)$ of the instantaneous SNR γ in the block Rayleigh channel after the MRC combining is given by [16]

$$p_{\gamma_\Sigma}(\gamma) = \frac{\gamma^{N-1}\exp\left(-\frac{\gamma}{\Gamma}\right)}{\Gamma^N (N-1)!}, \tag{19}$$

where N denotes the diversity order, and we have assumed each channel has the same average SNR Γ. The outage probability of MRC is defined as the probability that the instantaneous SNR after combining is less than a given threshold. For a fair comparison, the threshold of the transmission rate is chosen to be $R_{c1}H(b_1)$. Then, the outage probability of the 2nd order MRC diversity can be calculated as follows

$$\begin{aligned} P_{\text{out,mrc}} &= \int_{\gamma=0}^{2^{R_{c1}H(b_1)}-1} p_{\gamma_\Sigma}(\gamma)d\gamma_1, \\ &= \int_{\gamma=0}^{2^{R_{c1}H(b_1)}-1} \frac{\gamma\exp\left(-\frac{\gamma}{\Gamma}\right)}{\Gamma^2}d\gamma, \\ &= 1-\exp\left(\frac{1-2^{R_{c1}H(b_1)}}{\Gamma}\right) \\ &\quad\times\sum_{k=1}^{2}\frac{\left[(2^{R_{c1}H(b_1)}-1)/\Gamma\right]^{k-1}}{(k-1)!}. \end{aligned} \tag{20}$$

4 Asymptotic tendency analysis

4.1 Tendency 1: In the case $p_e = 0$

This section provides the proof of the fact that, when b_1 and b_2 are fully correlated ($p_e = 0$), the 2nd order diversity of the outage curves can be achieved. In this case, we have $H(b_1 \mid b_2) = 0$, $H(b_1, b_2) = 1$ and the value of P_1 is always equal to 0 as found from (13). Hence, the outage probability is determined by P_2 only. By assuming that the fading variations of the two links are statistically independent ($\rho = 0$) and $R_{c1} = R_{c2} = 1$, the derivation of P_2 can be reduced to

$$\begin{aligned} P_2 &= \int_{\gamma_1=0}^{1}\int_{\gamma_2=0}^{2^{[1-\log_2(1+\gamma_1)]}-1} p(\gamma_1)p(\gamma_2)d\gamma_1 d\gamma_2, \\ &= \int_0^1 p(\gamma_1)d\gamma_1\left[-\exp\left(-\frac{\gamma_2}{\Gamma_2}\right)\right]_0^{2^{[1-\log_2(1+\gamma_1)]}-1} \\ &= \frac{1}{\Gamma_1}\int_0^1\left[\exp\left(-\frac{\gamma_1}{\Gamma_1}\right)\right. \\ &\quad\left.-\exp\left(-\frac{\gamma_1}{\Gamma_1}+\frac{1}{\Gamma_2}-\frac{2}{\Gamma_2(1+\gamma_1)}\right)\right]d\gamma_1. \end{aligned} \tag{21}$$

By using (22) when x is very small:

$$e^{-x} = \sum_{n=0}^{\infty}\frac{(-x)^n}{n!} \approx 1-x, \tag{22}$$

(21) can be approximated as

$$\begin{aligned} P_2 &\approx \frac{1}{\Gamma_1}\int_0^1\left[\left(1-\frac{\gamma_1}{\Gamma_1}\right)\right. \\ &\quad\left.-\left(1-\frac{\gamma_1}{\Gamma_1}+\frac{1}{\Gamma_2}-\frac{2}{\Gamma_2(1+\gamma_1)}\right)\right]d\gamma_1 \\ &= \frac{1}{\Gamma_1}\int_0^1\left[-\frac{1}{\Gamma_2}+\frac{2}{\Gamma_2(1+\gamma_1)}\right]d\gamma_1 \\ &= \frac{1}{\Gamma_1}\left[\frac{2\ln(1+\gamma_1)-\gamma_1}{\Gamma_2}\right]_0^1 \\ &= \frac{2\ln 2-1}{\Gamma_1\Gamma_2}. \end{aligned} \tag{23}$$

Obviously, the final result shows that with $p_e = 0$, the outage probability curve is inversely proportional to the product of Γ_1 and Γ_2, which achieves the 2nd order diversity.

4.2 Tendency 2: Slepian-Wolf relay versus MRC

In this section, the proof of the advantage of the Slepian-Wolf relay system over MRC is presented, assuming that $\Gamma_1 = \Gamma_2$ in both the schemes with $p_e = 0$, $\rho = 0$ and $R_{c1} = R_{c2} = 1$. Then, (14) and (20) can be further reduced to

$$\begin{aligned} P_2 = \frac{1}{\Gamma_1}\int_{\gamma_1=0}^{1}&\left\{\exp\left(-\frac{\gamma_1}{\Gamma_1}\right)\right. \\ &\left.\times-\exp\left[\frac{1}{\Gamma_1}\left(1-\gamma_1-\frac{2}{1+\gamma_1}\right)\right]\right\}d\gamma_1, \end{aligned} \tag{24}$$

and

$$P_{\text{out,mrc}} = \frac{1}{\Gamma_1}\int_{\gamma_1=0}^{1}\frac{\gamma_1}{\Gamma_1}\exp\left(-\frac{\gamma_1}{\Gamma_1}\right)d\gamma_1. \tag{25}$$

To prove that $P_{\text{out,mrc}} - P_2 > 0$, we define $P_{\text{gap}} = P_{\text{out,mrc}} - P_2$

$$\begin{aligned} P_{\text{gap}} &= \frac{1}{\Gamma_1} \int_{\gamma_1=0}^{1} \left\{ \exp\left[\frac{1}{\Gamma_1}\left(1-\gamma_1-\frac{2}{1+\gamma_1}\right)\right] \right. \\ &\quad \left. + \left(\frac{\gamma_1}{\Gamma_1}-1\right)\exp\left(-\frac{\gamma_1}{\Gamma_1}\right)\right\} d\gamma_1 \\ &= \frac{1}{\Gamma_1}\left\{\int_{\gamma_1=0}^{1} \exp\left[\frac{1}{\Gamma_1}\left(1-\gamma_1-\frac{2}{1+\gamma_1}\right)\right]\right. \\ &\quad \left. \times d\gamma_1 - \exp\left(-\frac{1}{\Gamma_1}\right)\right\}. \end{aligned} \tag{26}$$

Let $y_1(x) = \exp\left(1 - x - \frac{2}{1+x}\right)$. It is found that $y_1(x) \geqslant -1$ within the range of [0, 1] if $y_1(x)$ is concave, since $y_1(x) \geqslant min\left\{y_1(0), y_1(1)\right\} = -1$, according to the property of the concave function. $y_1(x)$ can be proven to be concave by showing that

$$\begin{aligned} y_1(x)'' &= \exp\left(1-x-\frac{2}{1+x}\right)\left[\frac{2}{(1+x)^2}-1\right]^2 \\ &\quad - \frac{4\exp(1-x-\frac{2}{1+x})}{(1+x)^3} < 0. \end{aligned} \tag{27}$$

By ignoring the common exponential terms in (27), because they are positive, it is found that giving a proof to (27) is equivalent to proving that $y_2(x) = \left[2-(1+x)^2\right]^2 - 4(1+x) < 0$. Let $t = 1 + x$ $(t \in [1, 2])$. Then, $y_2(t) = \left(2-t^2\right)^2 - 4t = t^4 - 4t^2 - 4t + 4$. The second-order derivative of $y_2(t)$ can be expressed as

$$y_2(t)'' = 12t^2 - 8. \tag{28}$$

Obviously, $y_2(t)'' > 0$ within the range of $[1, 2]$. Therefore $y_2(t)$ is convex, and $y_2(t) < \max\left\{y_2(1), y_2(2)\right\} = -3$. Hence, $y_2(t) < 0$, which is equivalent to $y_1(x)'' < 0$. Now $y_1(x)$ is proved to be concave, and consequently P_{gap} is proved to be positive. As a result, Slepian-Wolf relaying yields a lower outage.

4.3 Tendency 3: in the case $p_e \neq 0$

When b_1 and b_2 are not fully correlated ($p_e \neq 0$), the asymptotic tendency of the outage curve is proven to converge into that of the 1st order diversity. With $\rho = 0$, when $\Gamma_1 \to \infty$ and $\Gamma_2 \to \infty$, $P_2 \to 0$ according to (11). Therefore only P_1 dominates the outage probability. Assuming $R_{c1} = 1$, (10) can be approximated by using (22), as

$$\begin{aligned} P_1 &= 1 - \exp\left[-\frac{2^{H(b_1|b_2)}-1}{\Gamma_1}\right] \\ &\approx \frac{2^{H(b_1|b_2)}-1}{\Gamma_1}. \end{aligned} \tag{29}$$

Obviously, when the average SNRs Γ_1 and Γ_2 become large, the value of P_1 is inversely in proportion to Γ_1 and hence the diversity order converges into 1.

4.4 Tendency 4: correlated link variation

In the presence of the correlation $\rho \neq 0$ of the fading variation, regardless of the source correlation μ, increasing the average SNRs Γ_1 and Γ_2, or equivalently increasing P_{r1} and P_{r2} yields [15]:

$$\frac{2|\rho| A_1 A_2}{\sqrt{P_{r1}P_{r2}}(1-|\rho|^2)} \approx 0 \quad (P_{r1} \to \infty,\ P_{r2} \to \infty) \tag{30}$$

Hence, with $I_0(0) \to 1$, (15) can be approximated as

$$\begin{aligned} p(A_1, A_2) &\approx \frac{4A_1A_2}{P_{r1}P_{r2}(1-|\rho|^2)} \exp\left(-\frac{A_1^2/P_{r1}}{1-|\rho|^2} - \frac{A_2^2/P_{r2}}{1-|\rho|^2}\right) \\ &= \frac{2A_1}{P_{r1}\sqrt{1-|\rho|^2}} \exp\left(-\frac{A_1^2}{P_{r1}(1-|\rho|^2)}\right) \\ &\quad \frac{2A_2}{P_{r2}\sqrt{1-|\rho|^2}} \exp\left(-\frac{A_2^2}{P_{r2}(1-|\rho|^2)}\right) \\ &= p(A_1')p(A_2'), \end{aligned} \tag{31}$$

where $A_1' = A_1\sqrt{1-|\rho|^2}$ and $A_2' = A_2\sqrt{1-|\rho|^2}$, with $P_{r1}' = P_{r1}(1-|\rho|^2)$ and $P_{r2}' = P_{r2}(1-|\rho|^2)$. Obviously, $p(A_i') = \frac{2A_i'}{P_{ri}'} \exp\left(-\frac{A_i'^2}{P_{ri}'}\right)$, which corresponds to the well-known *pdf* of the Rayleigh-distributed signal envelope of Link i [16]. Hence, with $P_{r1} \to \infty$ and $P_{r2} \to \infty$ (equivalently, $P_{r1}' \to \infty$ and $P_{r2}' \to \infty$), the asymptotic property of the outage probability exhibits the same tendency as in the case of independent channels, which indicates that the tendency of the diversity order only depends on the source correlation.

5 BICM-ID based Slepian-Wolf relay system

In this section, we apply the Slepian-Wolf relay technique presented in [6] to a system utilizing BICM-ID for Link 1 and Link 2 transmission [17], to demonstrate how the correlation knowledge can be utilized in [6]. The FER performance is then compared with the theoretical results in the next section. The block diagrams of the BICM-ID based Slepian-Wolf relay system are shown in Figure 3a,b. The system block diagram of the source and relay nodes is shown in Figure 3a, where the original information bits b_1 at the source node are channel-encoded by C_1, interleaved by Π_1, and further encoded by a doped accumulator (DACC). DACC has the same structure as memory-1 half rate systematic recursive convolutional code (SRCC), however, its outputs are mostly the systematic bits where only the every P_{d1}th systematic bit is replaced by the accumulated coded bit (P_{d1} denotes the doping ratio). It should be noticed that DACC does not change the code rate. It should be noticed further that the extrinsic information transfer (EXIT) curve of the corresponding decoder DACC^{-1} reaches until a point very close to the (1,1) mutual information point [8,18]. Finally, the bit stream output from the DACC is mapped onto symbols s_1 according to the specified modulation rule and broadcasted to both the relay and destination nodes during the first time slot.

After receiving the signals via the intra-link, the relay node aims to recover the original information bits, according to the DF strategy. However, the relay is not necessarily able to totally eliminate the errors happening in the intra-link [6], and hence some errors may remain in the recovered information b_2. The purpose of the simulation is to verify the consistency in the performance tendency to the theoretical results, and hence the bit-flipping model is used to simplify the intra-link transmission errors occurring in the information part of the recovered bit stream, as shown in Figure 3a[c]. The recovered information bit stream has to be interleaved by Π_0 before being re-encoded by C_2. This process plays the crucial role in the sense that it converts the relay system to a form of distributed turbo code (DTC) [19]. The re-encoded stream is further interleaved by Π_2, and fed into DACC (with a doping ratio P_{d2}). Finally, the DACC output is modulated with a specified mapping rule and the symbols s_2 at the relay node are sent to the destination during the second time slot.

At the destination as shown in Figure 3b, the received signals from both Link 1 and Link 2 are first demapped based on the BICM-ID principle, as [20,21]:

$$L_e(b_v) = \ln \frac{P(b_v = 1 \mid y)}{P(b_v = 0 \mid y)} = \ln \frac{\sum_{s \epsilon S_1} \left\{ \exp\left(-\frac{\left| y - \sqrt{G} h s \right|^2}{2\sigma^2} \right) \prod_{w \neq v}^{M} \exp\left[b_w L_a(b_w) \right] \right\}}{\sum_{s \epsilon S_0} \left\{ \exp\left(-\frac{\left| y - \sqrt{G} h s \right|^2}{2\sigma^2} \right) \prod_{w \neq v}^{M} \exp\left[b_w L_a(b_w) \right] \right\}}, \tag{32}$$

where v is the position of the detecting bit in the symbol[d]. M is the number of bits per symbol and $L_a(b_w)$ denotes the a priori LLRs of the wth bit in symbol s, fed back from the channel decoder. DACC^{-1}, and the decoders D_1 and D_2 for the channel encoders C_1 and C_2, respectively, use the Bahl, Cocke, Jelinek, and Raviv (BCJR) algorithm [22]. S_0 and S_1 are the sets of symbols having the vth bit being zero or one, respectively. The output extrinsic LLRs of the demapper are brought to DACC^{-1}, followed by the channel decoder via Π_1 and Π_2 for the first and second time slots, respectively. This process is referred to as the horizontal iterations (HI), as shown in Figure 3b.

Furthermore, the channel decoders D_1 and D_2 also exchange soft information with each other. This process is referred to as the vertical iterations (VI). It should be noticed that the LLR updating function is used in the VI, as illustrated in Figure 3b), where the knowledge of correlation μ (equivalently, the information bit flipping probability p_e of the intra-link) is utilized. Furthermore according to [6], the intra-link error probability representing the correlation can be estimated at the destination, as

$$\hat{p}_e = \frac{1}{N} \sum_{n=1}^{N} \frac{e^{L^u_{p,D_1}} + e^{L^u_{p,D_2}}}{\left(1 + e^{L^u_{p,D_1}}\right)\left(1 + e^{L^u_{p,D_2}}\right)}, \tag{33}$$

where $\hat{p}_e$ is the estimate of p_e, and $L^u_{p,D1}$ and $L^u_{p,D2}$ are the a posteriori LLRs of the uncoded information bits, output from the decoders D_1 and D_2, respectively. A threshold has to be set appropriately, as shown in [6], to select only the reliable LLRs when calculating $\hat{p}_e$ using (33). N represents the number of the reliable a posteriori LLR pairs $L^u_{p,D1}$ and $L^u_{p,D2}$. The estimate $\hat{p}_e$ of the intra-link error probability p_e is used to modify the bit probability, taking into account the intra-link errors, as [8]:

$$\begin{aligned} \Pr(b_2 = 0) &= (1 - p_e)\Pr(b_1 = 0) + p_e \Pr(b_1 = 1), \\ \Pr(b_2 = 1) &= (1 - p_e)\Pr(b_1 = 1) + p_e \Pr(b_1 = 0), \end{aligned} \tag{34}$$

which leads to the LLR updating function f_c expressed as follows [23]:

$$f_c(x) = \ln \frac{(1 - \hat{p}_e) \cdot \exp(x) + \hat{p}_e}{(1 - \hat{p}_e) + \hat{p}_e \cdot \exp(x)}. \tag{35}$$

In (35), x denotes the extrinsic LLRs of the information bits, obtained by D_1 and D_2, and the output of f_c are the updated LLRs by exploiting $\hat{p}_e$ as the correlation knowledge of the intra-link. The VI operations at the receiver can be expressed as:

$$L^u_{a,D_1} = f_c\left\{ \Pi_0^{-1}\left(L^u_{e,D_2} \right) \right\}, \tag{36}$$

$$L^u_{a,D_2} = f_c\left\{ \Pi_0\left(L^u_{e,D_1} \right) \right\}. \tag{37}$$

6 Numerical results

In this section, the numerical results of the theoretical outage probability calculation and the FER performance of the BICM-ID based Slepian-Wolf relay system obtained through simulations are presented. In the simulations for the BICM-ID based Slepian-Wolf relay system, we use the half rate non-recursive systematic convolutional code with generator polynomials of $(3,2)_8$ for both C_1 and C_2. Non-Gray quaternary-phase-shift-keying (QPSK) was used for both the Link 1 and Link 2 transmission[e]. Hence, the coefficients R_{ci} $(i = 1, 2)$ representing channel coding rate and modulation multiplicity is equal to one $(= \frac{1}{2} \times 2)$ in the theoretical calculations of the outage probability. The interleaver length is 4000 and the doping ratio P_{d1} and P_{d2} are set to five in the simulations. The LLR threshold for (33) was set to one, as in [6], to select the reliable LLRs output from D_1 and D_2.

Figure 4 shows the theoretical outage probabilities of the proposed Slepian-Wolf relay system, in the case $\rho = 0$

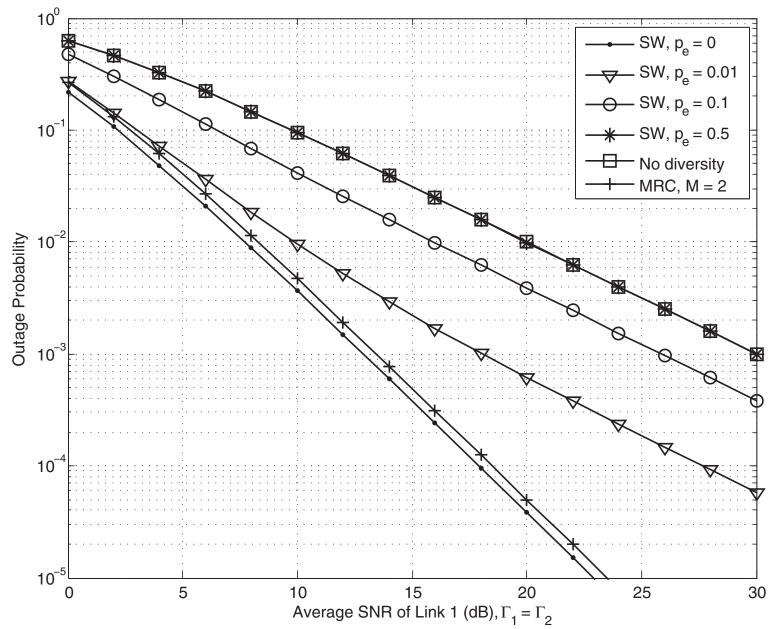

Figure 4 The theoretical outage probability of the proposed relay transmission model, $\Gamma_1 = \Gamma_2$, and $\rho = 0$, with p_e as a parameter. The 2nd order diversity can be achieved only if b_1 and b_2 are fully correlated ($p_e = 0$) with $\rho = 0$.

and average SNRs $\Gamma_1 = \Gamma_2$. It is found that, only when b_1 and b_2 are fully correlated ($p_e = 0$), the 2nd order diversity can be achieved, which is consistent to the asymptotic tendency analysis presented in Section 4.1. Moreover, it should be noticed that the Slepian-Wolf relay system can achieve slightly better outage performance than that with MRC, which is also consistent to the mathematical proof presented in Section 4.2. However, in the case when $p_e \neq 0$, the diversity order of the outage curves always plateaus at one as the average SNR increases. This asymptotic tendency agrees with the mathematical proof presented in Section 4.3. When b_1 and b_2 are completely independent ($p_e = 0.5$), obviously, the outage curves of the Slepian-Wolf relay is the same as that without diversity.

Figure 5 demonstrates the FER performance of the BICM-ID based Slepian-Wolf relay system ($\rho = 0$), where the theoretical outage curve is also plotted for comparison. It is found that the FER and the theoretical outage curves exhibit the same decay, however, there is a 2–3 dB gap in average SNR between them. This is because the BICM-ID technique used in this example does not achieve close-capacity performance. This indicates that there is a possibility that the gap can further be reduced by using very close-capacity achieving techniques [21,24].

Figure 6 shows the impact of the relay location on the outage probability as a function of the distance ratio d_2/d_1, by assuming that the relay location is in a line between source and destination nodes. According to (1), $\Gamma_2 = \Gamma_1 + 10\log_{10}\left[(d_1/d_2)^{3.52}\right]$ (dB). Because of the very stable intra-link assumption that we made in the theoretical analysis, in the simulation for the impact evaluation of the relay location, we assume an AWGN source-relay link[f]. The received average SNR at the relay is denoted by Γ_R, and $\Gamma_R = \Gamma_1 + 10\log_{10}\left[(d_1/(d_1 - d_2))^{3.52}\right]$ (dB). Furthermore, we assume the Slepian-Wolf relaying technique presented in [25], where the coding and modulation parameters are exactly the same as that described in the previous section. The only difference from the technique presented in the previous section is that in [25], the intra-link signal detection process is also included, where instead of performing fully iterative decoding at the relay, only systematic part is extracted (no decoding for C_1 is performed after viterbi decoding of DACC). This significantly reduces the computational complexity of the relay [25].

We first obtained the bit error rate (BER) curve of the intra-link transmission via simulations[g]. The SNR values were calculated at different locations using the equation shown above, and then converted into p_e referring to the simulation result. With the fixed p_e value, obtained via the methodology described above, we evaluated the FER performance via simulations, where Link 1 and Link 2 were assumed to suffer from statistically independent block Rayleigh fading. The FER curves are shown in Figure 6 for $\Gamma_1 = 3$ dB, together with the theoretical outage curve.

Interestingly, it is found that there is an optimal relay location. If the relay location is too close to the source, the FER performance is worse than that at the optimal

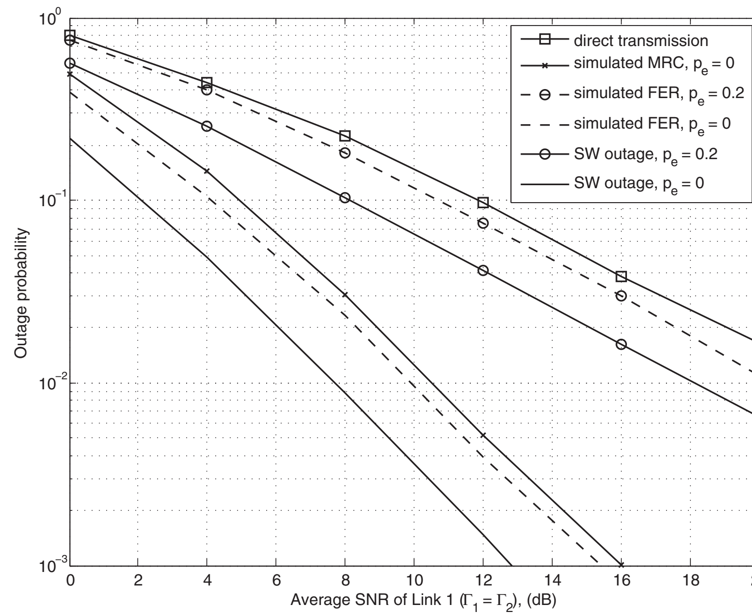

Figure 5 Comparison of the theoretical outage probability and the FER of the BICM-ID based Slepian-Wolf relay system. The performance tendencies of the theoretical outage probability and the FER of the BICM-ID based relay system are consistent with each other.

location. This tendency is consistent to the theoretical outage curve also shown in Figure 6. In fact, there are two factors that improve the FER/outage performance: one is the correlation exploitation, and the other is the energy of each link. Let the distance between the source and the optimal location be denoted by d_{opt}. At d_{opt}, the combined effect is maximized, while the contribution of Link 2 energy tends to be smaller when $d_1 - d_2 < d_{\text{opt}}$ (In this case, the p_e value is already very small and hence the contribution of correlation is fully exploited). It is also found that there is a gap between the FER simulation result and theoretical outage curve, because the

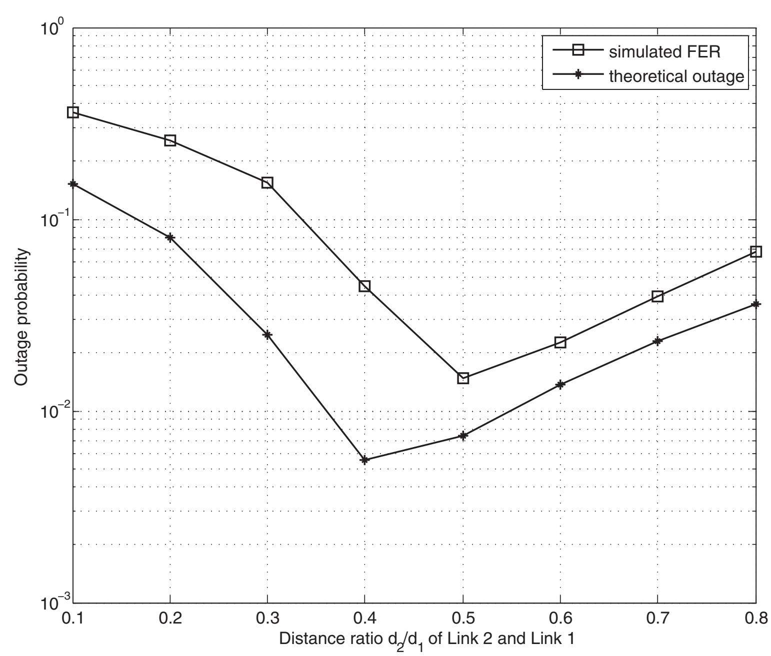

Figure 6 Outage probability versus the distance ratio. The p_e value follows the distribution of the BER of the intra-link..

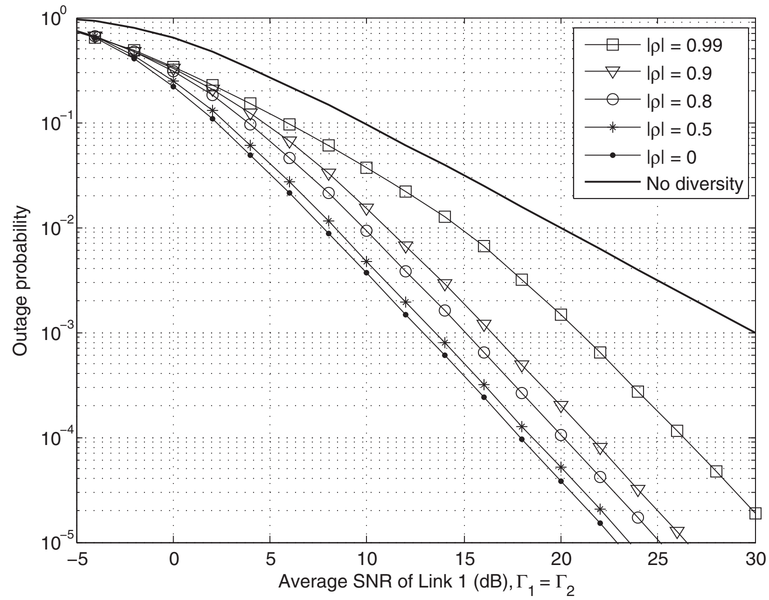

Figure 7 The theoretical outage probability when fading of the two links is correlated and $p_e = 0$. When b_1 and b_2 are fully correlated, the 2nd order diversity can still be achieved if $|\rho| < 1$.

BICM-ID relay in this article does not achieve close-capacity performance as stated before.

Figure 7 shows the theoretical outage curves in the presence of fading correlation ρ between Link 1 and Link 2 while the source bits b_1 and b_2 are fully correlated ($p_e = 0$). Obviously, the larger the correlation of the fading variation, the larger the outage probability. This is consistent to the theoretical result provided in Section 4.4 that the 2nd order diversity can finally be achieved with arbitrary value of $|\rho| \neq 1$, by increasing the average SNRs.

7 Conclusions

In this study, we have theoretically analyzed the outage probability and its asymptotic properties of a simple one-way relay transmission system allowing intra-link errors, where the source-relay correlation can be exploited in the joint decoding process at the destination, based on the Slepian-Wolf theorem. The outage probability can be calculated by a set of double integrals of the admissible rate region with respect to the *pdf* of the instantaneous SNRs of the transmission links, identified by the Slepian-Wolf theorem. It has been found through the asymptotic tendency analysis that the 2nd order diversity can be achieved only when the information bit streams at the source and the relay are fully correlated. Otherwise, it converges into one as the average SNRs of the source-destination and/or relay-destination links increase. Interestingly, the Slepian-Wolf relay system's outage probability is found to be smaller than the case where the signals received via the two links are maximum-ratio-combined before decoding. We have provided a mathematical proof of this discovery. However, this proof has been given to only the case where the two links suffer from independent block Rayleigh fading with the same average SNR. Hence, whether or not this discovery commonly holds for the arbitrary distance ratio d_2/d_1, and/or for correlated fading variation, is still an open hypothesis. The correlation ρ of the fading variation [15] of the source-destination and relay-destination links were also taken into account, in addition to the source-relay information correlation $\mu = \langle (2b_1 - 1)(2b_2 - 1) \rangle$. Interestingly, it has been found that the diversity order is only determined by the information correlation and is independent of the link variation correlation, so far as $|\rho| < 1$. It has to be noted that the intra-link transmission is parameterized by a bit-flipping probability p_e in this article. This is because p_e is the bit error probability of the information part after decoding at the relay, which depends on a lot of parameters related to the intra-link transmission. If the probability density function (*pdf*) of p_e is known, obviously it is possible to calculate the outage probability in the case that the three links are all time-varying. However, this is left as a future study.

This article also compared the FER of a BICM-ID based Slepian-Wolf relay system, as an example of our proposed technique, with the theoretical outage probability for $\rho = 0$. The decay of the FER and outage curves are consistent with each other, however, with a 2–3 dB gap in average SNR between them. This is because the BICM-ID technique used in this example does not achieve close-capacity performance, and there is a probability that the gap can be reduced by utilizing very close-capacity achieving code.

Endnotes

[a]A Gaussian codebook is assumed for channel coding.
[b]Even without the interleaver Π_0 at the relay node, a serious error propagation is expected in the case of MRC, if $p_e \neq 0$, due to the use of DACC. Hence, performing MRC at the destination by ignoring the intra-link errors even degrades the performance. However, without DACC, HI cannot reach a point in the extrinsic information transfer (EXIT) chart close enough to the (1,1) mutual information point. The terminologies "DACC" and "HI" are introduced in Section 5.
[c]This indicates that in the simulations, we did not perform actual decoding and demapping processes at the relay.
[d]Equation (32) holds both for Link 1 and Link 2. Therefore, for the sake of simplicity, we omitted the link index from the variables.
[e]Through the EXIT chart analysis conducted as a preliminary study, the demapper and the decoder's EXIT curves are found to be well matched with the transmission chain parameters described above, even though the codes used are very simple and easy to decode.
[f]The p_e value is a parameter which follows the distribution of the bit error rate of the intra-link.
[g]It should be noted that according to the assumption that the intra-link is a static AWGN channel, the instantaneous fading channel gain were ignored.

Competing interests
The authors declare that they have no completing interests.

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