

Performance Analysis for Lossy-Forwarding Relaying in Nakagami-m Fading Channels

Shen Qian*

騫 申

Abstract—Lossy decode-and-forward (DF) relaying, also known as lossy forwarding (LF), has attracted much attention since it can significantly enhance the transmission reliability and expand the communication coverage at a small increase on computational effort compared to its DF counterpart. Meanwhile, it can further simplify the operations at the relay node by removing the error-detecting operation, e.g., cyclic redundancy check, which is usually encompassed in the conventional DF. Due to these advantages, LF has been intensively investigated with the aim of its applications to various cooperative communication networks having different topologies. This paper offers a comprehensive analysis on the LF relaying strategy and makes comparisons between LF and DF. As expected, the performance enhancement of LF over DF has been demonstrated in the exemplifying scenario. LF has great potential to be applied in future 5G wireless communication networks, e.g., device-to-device, vehicle-to-vehicle, and machine-to-machine communications.

I. INTRODUCTION

A promising cooperative technique called lossy forwarding (LF) relaying [1] has gained a lot of attention recently, since it improves throughput efficiency and reduces the outage probability, compared to the conventional decode-and-forward (DF) relaying [2]. Unlike the conventional DF strategy [3], the decoded information sequence at the relay (R) is interleaved, re-encoded, and transmitted to destination (D), even though errors may be detected in the information sequence after decoding at R. Iterative processing between two decoders at the destination, one for decoding the signal received via the source (S)-D link and the other for that via the R-D link, with log-likelihood ratio (LLR) exchange via a LLR modification function improves decoding performance. The LF technique can be viewed as a distributed joint source-channel coding system with side information [4], [5]. It has been found that LF can achieve turbo-cliff-like bit error rate (BER) performance over additive white Gaussian noise (AWGN) channels [6].

In [7], the initial idea for LF is provided by utilizing Slepian-Wolf type cooperation for wireless communications. The coding algorithms are proposed for fading relay channel in [8] with the purpose of achieving the turbo processing gain. The key concept of the coding technique for LF is introduced in [1], where it assumes that the relay does not need to necessarily recover the information sent from S perfectly. In [9], a three-node LF relaying over Rayleigh fading channels is studied by identifying the relationship between the DF protocol and Slepian-Wolf coding [10]. However, a drawback of [1], [9] is that the admissible rate region is determined by the Slepian-Wolf theorem which does not perfectly match the problem

setup, since only the information of S needs to be recovered at the destination. Zhou *et al.* [2] eliminate the aforementioned drawback by utilizing the theorem of the source coding with side information in the network information theory. Based on [2], the technique is further extended to multiple access relay channel (MARC) [11], where a pair of correlated sources are transmitted to a destination with the aid of one relay. Furthermore, He *et al.* [12] and Qian *et al.* [13] apply the LF technique to multi-source multi-relay systems.

This paper discusses in detail the theoretical performance limits of LF relaying, including theoretical performance limits and comparisons among different relaying schemes. In the paper, we provide a general study of the state-of-the-art in LF cooperative relaying. More specifically, we start by introducing some information-theoretic preliminaries, e.g., distributed lossless source coding and distributed lossless source coding with a helper.

II. INFORMATION-THEORETIC PRELIMINARIES

In this section, we present some important information-theoretic preliminaries, which will be utilized in the performance limit analyses of LF. To be specific, we provide the achievable rate region for distributed lossless source coding and distributed lossless source coding with a helper. Also, we introduce Shannon's lossy source-channel separation theorem, which is used to measure the lower bound of distortion, occurred in the S-R links.

A. Distributed Lossless Source Coding

In this subsection, we introduce two important theories related to distributed lossless source coding. The first one considers the transmission of correlated sources, where all the sources need to be perfectly recovered at the destination. The second one considers the transmission of correlated sources with a helper. The difference in the two cases lies in that the helper does not need to be recovered in the second case. Its functionality is just to help the recovery of the correlated sources.

1) *Slepian-Wolf Coding*: Distributed lossless source coding system is depicted in Fig. 1. Let $\{X_1^i, X_2^i, \dots, X_N^i\}_{i=1}^{\infty}$ be a sequence of jointly independent and identically distributed (i.i.d) discrete random tuples generated by the sources X_1, X_2, \dots, X_N with a joint probability density function (pdf) $p(x_1, x_2, \dots, x_N)$. According to the source coding theorem, if all the sources are encoded together, a sum rate $H(X_1, X_2, \dots, X_N)$ is sufficient to achieve lossless decoding. However, if the sources are independently encoded with rates

*Assistant Professor, Dept. of of Information Systems Creation

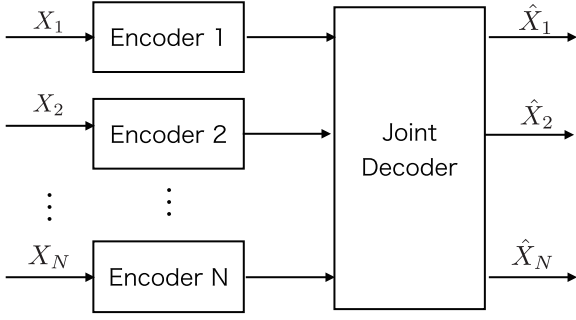


Fig. 1. Distributed lossless source coding.

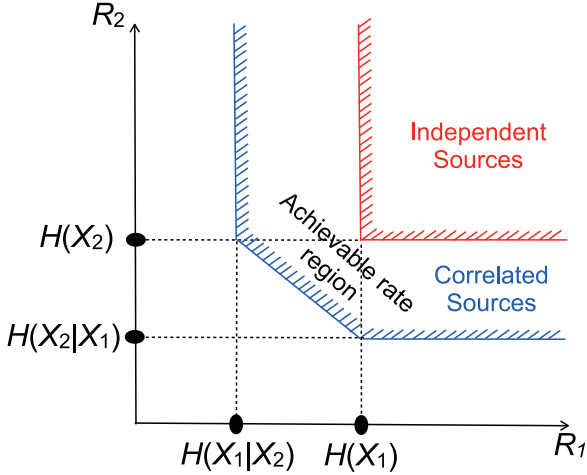


Fig. 2. The achievable Slepian-Wolf rate region for two sources.

R_1, R_2, \dots, R_N , we get the following achievable rate region originally introduced in [14]:

Theorem 1 (Slepian-Wolf Theorem): Let $H(X(\mathcal{S}))$ denotes the joint entropy of the tuple $(X_j : j \in \mathcal{S})$ and \mathcal{S}^c denotes the complement of the set \mathcal{S} . A sequence $\{X_1^i, X_2^i, \dots, X_N^i\}_{i=1}^\infty$ of discrete random tuples is drawn according to $(X_1, X_2, \dots, X_N) \sim p(x_1, x_2, \dots, x_N)$, where $X_n^i \in \mathcal{X}_n$, $n = 1, 2, \dots, N$. Then, for any rate tuples (R_1, R_2, \dots, R_N) that satisfy

$$\sum_{j \in \mathcal{S}} R_j \geq H(X(\mathcal{S})|X(\mathcal{S}^c)), \quad \forall \mathcal{S} \subseteq \{1, 2, \dots, N\}, \quad (1)$$

the error probability of joint decoding (JD) at the destination can be made arbitrarily small.

An achievable Slepian-Wolf rate region for two correlated sources, i.e., X_1 and X_2 , is illustrated in Fig. 2. It can be observed that the rate region achieved by applying JD is larger compared to independent decoding and the improvement depends on the correlation between the two sources.

2) *Distributed Lossless Source Coding with a Helper:* The Slepian-Wolf coding assumes that all the correlated sources need to be recovered at the destination. However, in cooperative relaying with the aim of higher diversity, relay(s) is

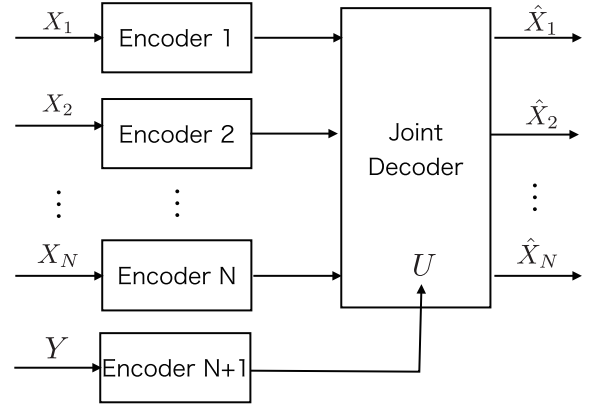


Fig. 3. Distributed lossless source coding of an arbitrary number of sources with a helper.

(are) only serving as helper(s), see Fig. 3, where the helper Y can be the network-coded version of the estimates of X_1, X_2, \dots, X_N in multiple access relay channel (MARC), for instance. In the presence of the helper, the achievable rate region will be further enlarged compared to that without any helpers by following the theorem of conditioning reduces entropy. More details on this are offered in the following theorem:

Theorem 2 (Distributed Lossless Source Coding with a Helper):

Let $\{X_1^i, X_2^i, \dots, X_N^i, Y^i\}_{i=1}^\infty$ be a sequence of jointly i.i.d discrete random tuples generated by the sources X_1, X_2, \dots, X_N, Y . The achievable rate region for the lossless recovery of (X_1, X_2, \dots, X_N) with a helper Y is the set of rate tuples $(R_1, R_2, \dots, R_{N+1})$ that satisfy

$$\begin{cases} \sum_{j \in \mathcal{S}} R_j \geq H(X(\mathcal{S})|U, X(\mathcal{S}^c)), \quad \forall \mathcal{S} \subseteq \{1, 2, \dots, N\}, \\ R_{N+1} \geq I(Y; U), \end{cases} \quad (2)$$

for some conditional probability mass function (pmf) $p(u|y)$ with $|\mathcal{U}| \leq |\mathcal{Y}| + 2^N - 1$.

The achievable rate region for lossless source coding of one source with a helper is shown in Fig. 4. It can be seen that the achievable rate region is larger than that of Slepian-Wolf coding (referring to Fig. 2) because there is no need to recover Y . The achievable rate region for distributed lossless source coding with more than one helper is unknown in general even in the case of single source.

B. Shannon's Lossy Source-Channel Separation Theorem

The concept of LF allows intra-link errors in the network. The information transmission in the source-to-relay (S-R) and relay-to-destination (R-D) links can therefore be modeled by Shannon's lossy source-channel separation theorem. The theorem states that the transmission of a message from a transmitter to a receiver with a distortion D , needs to satisfy

$$R_c R(D) \leq C(\gamma), \quad (3)$$

where R_c is the spectral efficiency including the channel code rate and modulation order, $R(D)$ is the rate-distortion function,

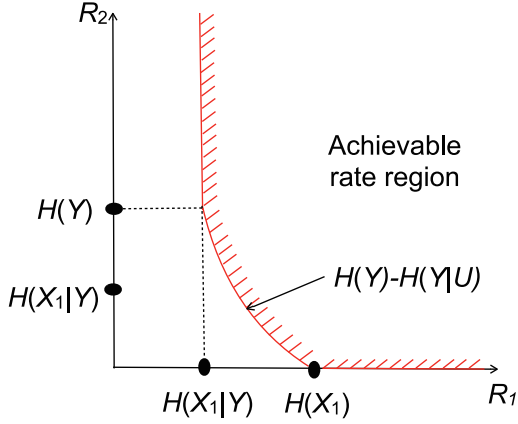


Fig. 4. The achievable rate region for lossless source coding of one source with a helper.

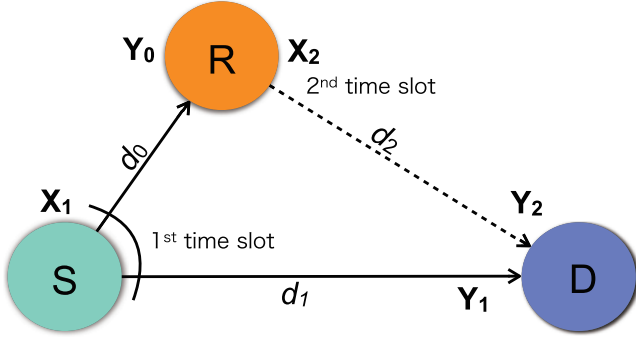


Fig. 5. The block diagram of the three-node one-way relay system.

and $C(\gamma)$ denotes the channel capacity (Gaussian capacity or constellation constrained capacity) as a function of receive SNR γ .

In LF, we focus on discrete binary sources and therefore, the distortion is expressed as:

$$R(D) = 1 - H_2(D), \quad (4)$$

where $H_2(D) = -D \log_2(D) - (1 - D) \log_2(1 - D)$ is the binary entropy function. With the help of (3) and (4), we can derive the relationship between the distortion and receive SNR:

$$D_{min} = \begin{cases} H_2^{-1}(1 - C(\gamma)/R_c), & \text{for } 0 \leq \gamma < \gamma^* \\ 0, & \text{for } \gamma \geq \gamma^*, \end{cases} \quad (5)$$

where γ^* is the minimum SNR required for zero distortion.

III. ONE-WAY RELAY NETWORK

In this section, we focus on the theoretical performance limits of the three-node LF relaying system, as shown in Fig. 5.

A. System Model

1) *LF System*: In the three-node one-way half-duplex relay system, the source S and relay R cooperatively transmit a message to the destination D, as shown in Fig. 5. To allow transmission orthogonality, we assume that a time-division channel allocation is considered. Therefore, two time slots are needed for one transmission round. During the first time slot, S first performs channel coding and modulation, denoted as $\mathcal{E}_1(\cdot)$, on the original information sequence \mathbf{u}_1 . The coded and modulated signal $\mathbf{x}_1 = \mathcal{E}_1(\mathbf{u}_1)$ is then broadcast to both R and D. During the second time slot, R first conducts signal demodulation and decoding, denoted as $\mathcal{D}_1(\cdot)$, on the received signal \mathbf{y}_0 . The estimate of \mathbf{u}_1 , i.e., $\mathbf{u}_2 = \mathcal{D}_1(\mathbf{y}_0)$, is then interleaved, re-encoded, and modulated to signal \mathbf{x}_2 . According to principle of LF relaying, the coded and modulated signal \mathbf{x}_2 is always transmitted to D, no matter whether \mathbf{u}_2 contains decoding errors (such errors are referred to as intra-link errors) or not. It should be noted that the decoder output at R is correlated with the original information sequence sent from S, which is referred to as *source-relay correlation* and represented by bit-flipping model (equivalent to binary symmetric channel (BSC)).

2) *Channel Model*: The S-R, S-D, and R-D links are assumed to suffer from independent Rayleigh block fading or Nakagami- m block fading. Therefore, the channel gains keep constant within one transmission block but vary transmission-by-transmission. The received signals at R and D can be expressed as

$$\mathbf{y}_0 = \sqrt{G_0} \cdot h_0 \cdot \mathbf{x}_1 + \mathbf{n}_0, \quad (6)$$

$$\mathbf{y}_1 = \sqrt{G_1} \cdot h_1 \cdot \mathbf{x}_1 + \mathbf{n}_1, \quad (7)$$

$$\mathbf{y}_2 = \sqrt{G_2} \cdot h_2 \cdot \mathbf{x}_2 + \mathbf{n}_2, \quad (8)$$

where h_i and \mathbf{n}_i denote the complex channel gain and the zero-mean AWGN vector with the variance σ_i^2 per dimension, with $i \in \{0, 1, 2\}$ denotes the S-R, S-D, and R-D links, respectively. Without loss of generality, it is assumed that $\sigma_0^2 = \sigma_1^2 = \sigma_2^2 = N_0/2$. We also take into consideration of the geometric gain of each link, which is denoted by G_i . With d_i denoting the distance of the corresponding link (referring to Fig. 5) and G_1 being normalized to the unity, G_0 and G_2 can be defined as $G_0 = (d_1/d_0)^l$ and $G_2 = (d_1/d_2)^l$, respectively, where l is the pathloss exponent and empirically set to 3.52. The geometric gain between two nodes with distance d is written as $G = (\frac{1}{d})^l$. Note that we assume the transmit power per symbol at S and R is the equal, denoted as E_s .

With the definitions introduced above, the instantaneous and average receive SNRs of S-D link are expressed as $\gamma_1 = G_1 |h_1|^2 E_s / N_0$ and $\bar{\gamma}_1 = G_1 E_s / N_0$, respectively. Similar definitions apply to $\gamma_0, \bar{\gamma}_0, \gamma_2$ and $\bar{\gamma}_2$.

B. Achievable Rate Region Analysis

Similar to the channel gain in block fading, the intra-link error probability p stays constant over one transmission block, but varies transmission-by-transmission. The relationship between p and the instantaneous intra-link SNR can be found in (5). The correlation between \mathbf{u}_1 and \mathbf{u}_2 is purely

characterized by p , where $p = 0$ indicates perfect decoding at R, and $0 < p \leq 0.5$ indicates that intra-link errors appear. Assuming that \mathbf{u}_1 and \mathbf{u}_2 are described with rates R_1 and R_2 , respectively, the evolution of the achievable rate region for R_1 and R_2 is provided in Fig. 6.

1) *Exact Rate Region:* According to Theorem 2, successful recovery of \mathbf{u}_1 via JD at D can be achieved if R_1 and R_2 satisfies

$$\begin{cases} R_1 \geq H(\mathbf{u}_1|\hat{\mathbf{u}}_2), \\ R_2 \geq I(\mathbf{u}_2;\hat{\mathbf{u}}_2), \end{cases} \quad (9)$$

where $\hat{\mathbf{u}}_2$ is the estimate of \mathbf{u}_2 at D. Let $H(\mathbf{u}_1|\hat{\mathbf{u}}_2)$ and $I(\mathbf{u}_2;\hat{\mathbf{u}}_2)$ denote the entropy of \mathbf{u}_1 conditioned on $\hat{\mathbf{u}}_2$ and the mutual information between \mathbf{u}_2 and $\hat{\mathbf{u}}_2$, respectively. The relationship between \mathbf{u}_2 and $\hat{\mathbf{u}}_2$ can also be expressed as a bit-flipping model with a error probability α , where $\alpha \in [0, 0.5]$. It is easily found that $H(\mathbf{u}_1|\hat{\mathbf{u}}_2) = H_2(\alpha * p)$ and $I(\mathbf{u}_2;\hat{\mathbf{u}}_2) = H(\hat{\mathbf{u}}_2) - H(\hat{\mathbf{u}}_2|\mathbf{u}_2) = 1 - H_2(\alpha)$, where $\alpha * p = (1 - \alpha)p + \alpha(1 - p)$ is the binary convolution of α and p .

Let \mathcal{R}_{LF} denotes the achievable rate region defined by (9). For the purpose of better illustration, we divide the entire rate region into five sub-regions, $\mathcal{R}_a, \mathcal{R}_b, \mathcal{R}_c, \mathcal{R}_d$ and \mathcal{R}_e , as shown in Fig. 7. From this figure, we have $\mathcal{R}_{LF} = \mathcal{R}_c \cup \mathcal{R}_d \cup \mathcal{R}_e$. According to the discussions presented above, \mathcal{R}_{LF} can be expressed even in an explicit way as

$$R_1 \geq \begin{cases} H_2(p), & \text{for } R_2 \geq 1, \\ H_2[H_2^{-1}(1 - R_2) * p], & \text{for } 0 \leq R_2 \leq 1. \end{cases} \quad (10)$$

C. Outage Probability Analysis

1) *Relationship Between R_1, R_2 and Their Corresponding Instantaneous Channel SNRs:* Following Shannon's source-channel separation theorem, if the *total* information transmission rates satisfy

$$\begin{cases} R_1 R_{c,1} \leq C(\gamma_1), \\ R_2 R_{c,2} \leq C(\gamma_2), \end{cases} \quad (11)$$

the error probability over S-D and R-D links can be made arbitrarily small.

In the theoretical analysis, we only consider the equality of (11). The relationship between rate R_i and its corresponding instantaneous SNR γ_i is given by $R_i = \Phi_i(\gamma_i) = \frac{C(\gamma_i)}{R_{c,i}}$, with its inverse function $\gamma_i = \Phi_i^{-1}(R_i) = C^{-1}(R_i R_{c,i})$, where $i = 1, 2$ and $C^{-1}(\cdot)$ denotes the inverse function of channel capacity.

2) *Outage Probability Calculation:* Based on the exact achievable rate regions, the exact outage probability can be

defined as

$$\begin{aligned} P_{\text{out}}^{LF} &= \Pr\{0 \leq p \leq 0.5, (R_1, R_2) \notin \mathcal{R}_{LF}(p)\} \\ &= \Pr\{p = 0, (R_1, R_2) \in \mathcal{R}_a \cup \mathcal{R}_b\} \\ &\quad + \Pr\{0 < p \leq 0.5, (R_1, R_2) \in \mathcal{R}_a \cup \mathcal{R}_b\} \\ &= \underbrace{\Pr\{p = 0, (R_1, R_2) \in \mathcal{R}_a\}}_{P_{1,a}} + \underbrace{\Pr\{p = 0, (R_1, R_2) \in \mathcal{R}_b\}}_{P_{1,b}} \\ &\quad + \underbrace{\Pr\{0 < p \leq 0.5, (R_1, R_2) \in \mathcal{R}_a\}}_{P_{2,a}} \\ &\quad + \underbrace{\Pr\{0 < p \leq 0.5, (R_1, R_2) \in \mathcal{R}_b\}}_{P_{2,b}}, \end{aligned} \quad (12)$$

$P_{1,a}, P_{1,b}, P_{2,a}, P_{2,b}, P_{1,ab'}, P_{1,b''c}, P_{2,ab'}$ and $P_{2,b''c}$ can be further expressed as

$$P_{1,a} = 0, \quad (13)$$

$$\begin{aligned} P_{1,b} &= \frac{1}{\bar{\gamma}_2} \exp\left[-\frac{\Phi_1^{-1}(1)}{\bar{\gamma}_0}\right] \int_0^{\Phi_1^{-1}(1)} \exp\left(-\frac{\gamma_2}{\bar{\gamma}_2}\right) \\ &\quad \times \left[1 - \exp\left(-\frac{\Phi_1^{-1}[1 - \Phi_2(\gamma_2)]}{\bar{\gamma}_1}\right)\right] d\gamma_2, \end{aligned} \quad (14)$$

$$\begin{aligned} P_{2,a} &= \frac{1}{\bar{\gamma}_0} \exp\left[-\frac{\Phi_2^{-1}(1)}{\bar{\gamma}_2}\right] \int_0^{\Phi_2^{-1}(1)} \exp\left(-\frac{\gamma_0}{\bar{\gamma}_0}\right) \\ &\quad \times \left[1 - \exp\left(-\frac{\Phi_1^{-1}[1 - \Phi_1(\gamma_0)]}{\bar{\gamma}_1}\right)\right] d\gamma_0, \end{aligned} \quad (15)$$

$$\begin{aligned} P_{2,b} &= \frac{1}{\bar{\gamma}_0 \bar{\gamma}_2} \int_0^{\Phi_1^{-1}(1)} \int_0^{\Phi_2^{-1}(1)} \exp\left(-\frac{\gamma_0}{\bar{\gamma}_0} - \frac{\gamma_2}{\bar{\gamma}_2}\right) \\ &\quad \times \left\{1 - \exp\left[-\frac{\Phi_1^{-1}[\Psi(\gamma_0, \gamma_2)]}{\bar{\gamma}_1}\right]\right\} d\gamma_0 d\gamma_2, \end{aligned} \quad (16)$$

$$P_{1,ab'} = 0, \quad (17)$$

$$\begin{aligned} P_{1,b''c} &= \frac{1}{\bar{\gamma}_1} \exp\left[-\frac{\Phi_1^{-1}(1)}{\bar{\gamma}_0}\right] \int_0^{\Phi_1^{-1}(1)} \exp\left(-\frac{\gamma_1}{\bar{\gamma}_1}\right) \\ &\quad \times \left[1 - \exp\left(-\frac{\Phi_2^{-1}[1 - \Phi_1(\gamma_1)]}{\bar{\gamma}_2}\right)\right] d\gamma_1, \end{aligned} \quad (18)$$

$$\begin{aligned} P_{2,ab'} &= \frac{1}{\bar{\gamma}_0} \int_0^{\Phi_1^{-1}(1)} \exp\left(-\frac{\gamma_0}{\bar{\gamma}_0}\right) \\ &\quad \times \left[1 - \exp\left(-\frac{\Phi_1^{-1}[1 - \Phi_1(\gamma_0)]}{\bar{\gamma}_1}\right)\right] d\gamma_0, \end{aligned} \quad (19)$$

and

$$\begin{aligned} P_{2,b''c} &= \frac{1}{\bar{\gamma}_0 \bar{\gamma}_1} \int_0^{\Phi_1^{-1}(1)} \int_0^{\Phi_1^{-1}(1)} \exp\left(-\frac{\gamma_0}{\bar{\gamma}_0} - \frac{\gamma_1}{\bar{\gamma}_1}\right) \\ &\quad \times \left[1 - \exp\left(-\frac{\Phi_2^{-1}[2 - \Phi_1(\gamma_0) - \Phi_1(\gamma_1)]}{\bar{\gamma}_2}\right)\right] d\gamma_1 d\gamma_0. \end{aligned} \quad (20)$$

respectively, with $\Psi(\gamma_0, \gamma_2) = H_2\{H_2^{-1}[1 - \Phi_1(\gamma_0)] * H_2^{-1}[1 - \Phi_2(\gamma_2)]\}$.

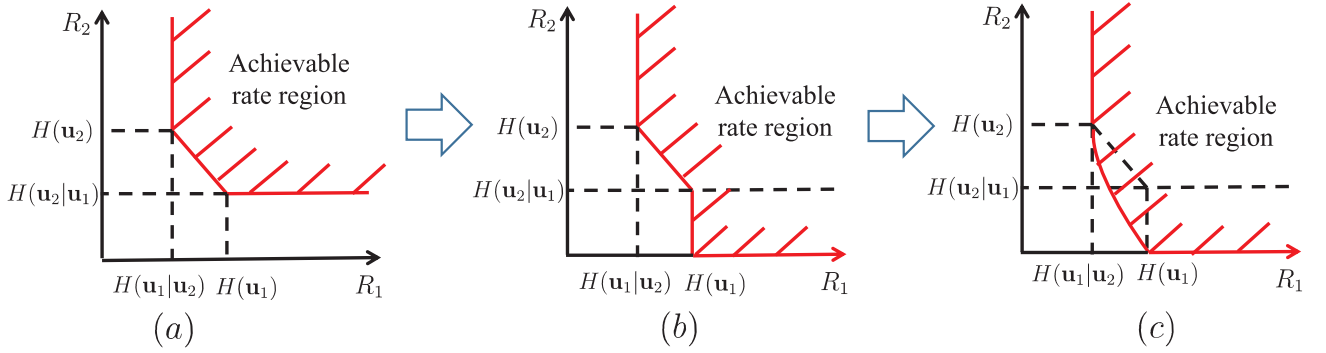


Fig. 6. The evolution of achievable rate region: (a) Slepian-Wolf rate region, (b) Extended Slepian-Wolf rate region, and (c) rate region of source coding with a helper.

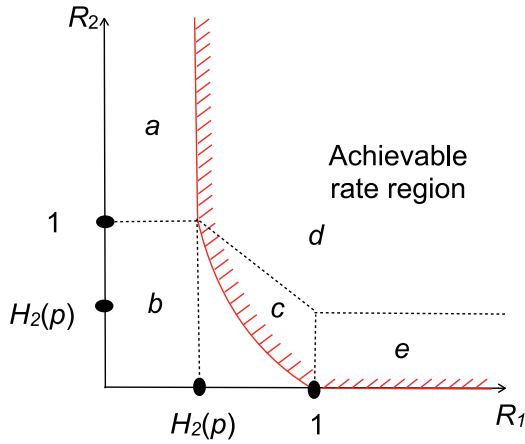


Fig. 7. The achievable rate region for S and R, divided into five sub-regions.

D. Nakagami- m Fading Channels

In this subsection, we investigate the outage performance of the three-node LF relaying network over independent Nakagami- m block fading channels. The outage probability of LF relaying with Gaussian codebook capacity over Nakagami- m block fading channels can be calculated in the same way as in the Rayleigh block fading case only by replacing the Rayleigh distribution with Nakagami- m distribution.

Fig. 8 presents the outage performances of LF relaying based on Gaussian codebook capacity and constellation constrained capacity, denoted by “ $P_{\text{out}}^{\text{LF}}$, GCC” and “ $P_{\text{out}}^{\text{LF}}$, CCC” in the legend, respectively. The Monte Carlo simulation results well match the theoretical outage probabilities. The gap between the curves of “ $P_{\text{out}}^{\text{LF}}$, GCC” and “ $P_{\text{out}}^{\text{LF}}$, CCC” is minimal. This is because that, in the low SNR region, the difference between Gaussian codebook capacity and constellation constrained capacity is negligible. Moreover, in the high SNR regime, even though the difference between Gaussian codebook capacity and constellation constrained capacity increases,

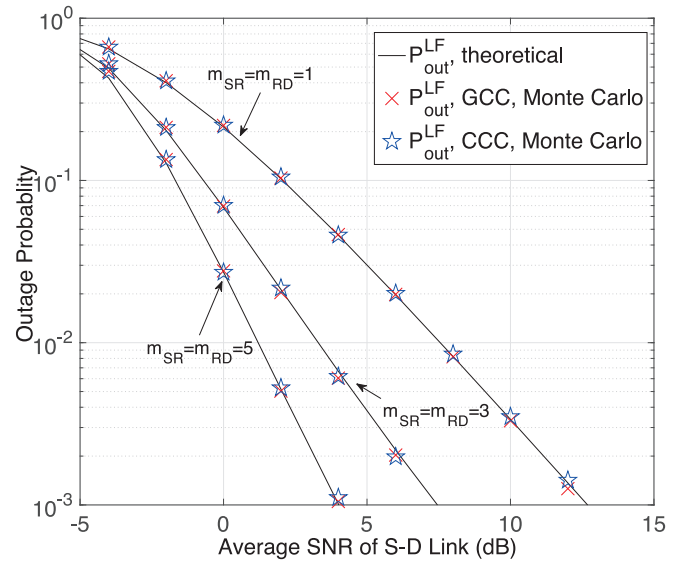


Fig. 8. Comparison between the Gaussian codebook capacity and quaternary constellation constrained capacity based outage probability of the LF relaying, where $m_0 = m_2$, $m_1 = 1$, and $G_0 = G_1 = G_2$.

the S-R link error probability p approaches 0, resulting in lossless transmission over the S-R link.

1) *Optimal Relay Location*: Fig. 9 shows the impact of the location of the relay on the outage performance, where $\bar{\gamma}_1 = 1$ dB. R is assumed to be located in a line parallel to the S-D link. R moves between $x = 0$ and $x = 1$, as shown in Fig. 9. The distance between the relay and the line connecting S and D is set at $\frac{1}{10}$ of the length of the S-D link. It is found that when R is closer to S, LF and DF show the same performance. This is because it is less likely that errors happen in reliable S-R transmission. Therefore, R becomes active in DF relaying in almost all the transmission rounds, which makes DF and LF relaying exhibit almost the same outage performance.

On the contrary, when R moves closer to D, the probability that error occur during S-R transmission increases with

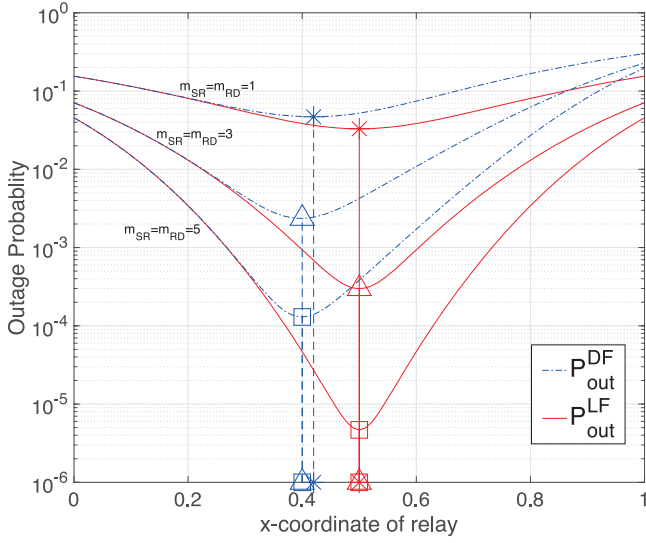


Fig. 9. The optimal relay positions of the LF and DF relaying where $m_1 = 1$. The vertical lines indicate the points where the outage probabilities are smallest.

degraded S-R link quality. In this case, R keeps silence in DF relaying with a high probability, which results in better performance of LF relaying over DF relaying. With LF, so long as $m_0 = m_2$, the midpoint is optimal for R (R has the same distance to S and D) in terms of outage probability.

From Fig. 9, it also can be found that, with LF relaying, the outage curves are symmetric to the midpoint between S and D. Since the errors happened in the S-R transmission can be corrected at D with JD, the quality of the S-R and R-D links becomes equally important, which results in the midpoint for R being the optimal. Moreover, for guaranteeing the same outage performance, LF relaying can search for (or locate) a relay in a larger range than DF relaying. This is a significant advantage especially in natural disaster situations.

IV. CONCLUDING REMARKS

In the paper, we have provided a comprehensive study on the achievable rate regions and outage analyses, where LF is adopted at the relay nodes. We have exploited the theorem of source coding with a helper to determine the achievable rate region of the three-node network while we have leveraged Slepian-Wolf theorem as an approximation. Source coding with multiple helpers remains a challenging problem in the performance limit analysis for multi-relay scenario. The simulation results has demonstrated that LF outperforms DF in general regarding the outage probability at the sacrifice of slightly more power consumption.

REFERENCES

[1] K. Anwar and T. Matsumoto, "Accumulator-assisted distributed turbo codes for relay systems exploiting source-relay correlation," *IEEE Commun. Lett.*, vol. 16, no. 7, pp. 1114–1117, July 2012.

[2] X. Zhou, M. Cheng, X. He, and T. Matsumoto, "Exact and approximated outage probability analyses for decode-and-forward relaying system allowing intra-link errors," *IEEE Trans. Wireless Commun.*, vol. 13, no. 12, pp. 7062–7071, Dec. 2014.

[3] J. Laneman, D. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inform. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec 2004.

[4] S. Qian, X. Zhou, X. He, J. He, M. Juntti, and T. Matsumoto, "Performance analysis for lossy-forward relaying over nakagami- m fading channels," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 11, pp. 10035–10043, Nov 2017.

[5] I. Shahid and P. Yahampath, "Distributed joint source-channel coding using unequal error protection LDPC codes," *IEEE Commun. Lett.*, vol. 61, no. 8, pp. 3472–3482, August 2013.

[6] A. J. Aljohani, S. X. Ng, and L. Hanzo, "Distributed source coding and its applications in relaying-based transmission," *IEEE Trans. Adv. Packag.*, vol. 4, pp. 1940–1970, 2016.

[7] R. Hu and J. Li, "Exploiting Slepian-Wolf codes in wireless user cooperation," in *Proc. IEEE Works. on Sign. Proc. Adv. in Wirel. Comms.*, June 2005, pp. 275–279.

[8] B. Zhao and M. C. Valenti, "Distributed turbo coded diversity for relay channel," *Electronics Letters*, vol. 39, no. 10, pp. 786–787, May 2003.

[9] M. Cheng, K. Anwar, and T. Matsumoto, "Outage probability of a relay strategy allowing intra-link errors utilizing Slepian-Wolf theorem," *EURASIP Journal on Advances in Signal Processing*, vol. 2013, no. 1, p. 34, 2013.

[10] D. Slepian and J. Wolf, "Noiseless coding of correlated information sources," *IEEE Trans. Inform. Theory*, vol. 19, no. 4, pp. 471–480, Jul 1973.

[11] P.-S. Lu, X. Zhou, and T. Matsumoto, "Outage probabilities of orthogonal multiple-access relaying techniques with imperfect source-relay links," *IEEE Trans. Wireless Commun.*, vol. 14, no. 4, pp. 2269–2280, Apr. 2015.

[12] J. He, I. Hussain, M. Juntti, and T. Matsumoto, "End-to-end outage probability analysis for multi-source multi-relay systems," in *Proc. of IEEE International Conference on Communications (ICC)*, May 2016, pp. 1–6.

[13] S. Qian, J. He, M. Juntti, and T. Matsumoto, "Performance analysis for multi-source multi-relay transmission over kappa-mu fading channels," in *Proc. Annual Asilomar Conf. Signals, Syst., Comp.*, May 2016, pp. 1–6.

[14] D. Slepian and J. Wolf, "Noiseless coding of correlated information sources," *IEEE Trans. Inform. Theory*, vol. 19, no. 4, pp. 471–480, Jul. 1973.