Title	A Comparative Study of Different Relaying Strategies over One-Way Relay Networks
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Citation	Proceedings of European Wireless 2016; 22th European Wireless Conference: 241-246
Issue Date	2016
Type	Conference Paper
Text version	author
URL	http://hdl.handle.net/10119/14705
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Description	

A Comparative Study of Different Relaying Strategies over One-Way Relay Networks

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***Abstract*—We derive and compare the analytical outage probabilities of conventional decode-and-forward (DF), adaptive DF (ADF), compress-and-forward (CF), and lossy-forward (LF) relaying protocols over fading channels. A joint decoding is assumed at the destination to exploit the source-relay correlation for retrieving the original information of the source. With DF, only if the information sequence can be decoded with an arbitrary low error probability at the relay, it will be forwarded to the destination. With ADF, the source retransmits the information, if a failure of the transmission happens on the source-relay link. With CF, the relay performs the Wyner-Ziv compression and forwards the compressed version to the destination. With LF, the relay node always forwards decoded information sequence to the destination even if a decoding error is detected. The impact of line-of-sight component in the fading variations for transmission chain is taken into account. It is shown that the outage probability with the LF relaying is smaller than that with CF and DF relaying. ADF is superior to LF in terms of outage performance due to the feedback information.**

I. INTRODUCTION

Cooperative transmission, in which nodes cooperate with each other to communicate with destination, provides spatial diversity gain over fading channels in wireless networks. Internet of things (IoT) and machine to machine (M2M) communications are examples of the forthcoming fifth generation (5G) communication networks that accommodate massive number of devices. Therefore, it is important to find new cooperation techniques for further promoting the energy- and spectrum-efficiency while reducing the transmission latency.

In a widely studied conventional decode-and-forward (DF) protocol, if error is detected at the relay, the received information sequence will be discarded [1], [2]. However, even if error is detected at the relay, the information sequences transmitted from the source and relay are still correlated. The relationship between the DF relaying and Slepian-Wolf coding has been identified in [3]. The destination receives two sequences, one from the source and the other from the relay. Thereby, an iterative processing between two decoders for log-likelihood ratio (LLR) exchanging via a LLR modification function [4] reduces the decoding error probability. The technique is further extended to multiple access relay channel (MARC) [5], where the scheme has been referred to lossy-forward (LF) relaying. Furthermore, it has been found that analysing the exact rate region of LF falls into the category of source coding with side information [6], [7] in network information theory [8].

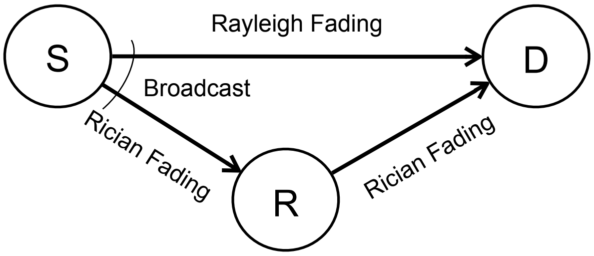


Fig. 1. One-way relaying transmission system.

In [9], a comparative study on the outage probabilities of DF and LF was conducted. It is concluded that the DF relaying with joint decoding and the DF relaying with maximum ratio combining perform comparably in terms of outage probabilities. The LF relaying always achieves better outage performance than the DF relaying. However, the comparison is based on an assumption that the relay is located at a fixed point between the source and the destination and therefore, the relationship between outage performance and relay position has not been addressed. Moreover, transmit phases and hence power efficiencies are not taken into account in the outage probability comparison.

In this paper, our focus is mainly on the performance comparison of relaying protocols with the half-duplex and orthogonal setting, i.e., LF, DF, adaptive DF (ADF), and compress-and-forward (CF). Joint decoding process is assumed at the destination for all the relaying schemes. With DF, the relay keeps silent if error is detected after decoding. With ADF, the source retransmits the information sequence to the destination if error is detected after decoding at the relay. With LF, the relay always forwards the information sequence to the destination. The system outage event is measured by using a spectral efficiency (information rate) threshold model.

The main contributions of this paper are summarized as follows: 1) We derive the mathematical expressions of the outage probability of the DF, ADF, and LF relaying over block fading channels, where the line-of-sight (LOS) component is taken in account. The outage probability of the CF relaying is also evaluated as a reference for the performance bound of CF scheme; 2) The outage probabilities of the DF, ADF, LF and CF relaying are compared with each other, with the geometric gain and fair comparison in terms of transmit phase are taken into account; 3) We find that the LF relaying achieves better outage performance than the DF and CF relaying, with or without the impact of LOS component. It is also found that LF performs better than DF and CF no matter where the relay is. Though the ADF outperforms LF in terms of outage probability, no feedback information is required from R to S in the LF relaying scheme.

The rest of this paper is organized as follows: the system and channel models used in outage probability analysis are described in Section II. The outage probability definition and derivation of the DF, ADF, CF, and LF relaying are presented in Section III. Section IV shows the numerical results by comparing the performances of the considered relaying strategies. Finally, Section V concludes this paper.

II. SYSTEM AND CHANNEL MODEL

We consider a simple, three nodes relaying transmission model in a time-division channel allocation, as shown in Fig. 1. A source (S) broadcasts the information sequence b_{S} to a relay (R) and a destination (D) at the first time slot. In the second time slot, either S or R, or neither of them, transmits the message b_{S} or b_{R} to D. Four relaying strategies are considered: 1) LF relaying: R decodes, re-encodes the information and forwards the received information sequence to D no matter whether the S-R link error is detected or not; 2) conventional DF relaying: R keeps silent if error is detected after decoding; 3) ADF relaying: S retransmits if error is detected after decoding at R; 4) CF relaying: R performs the Wyner-Ziv coding to compress the received information sequence and forwards it to D.

The received signals y_1 via the S-D link and y_2 via the R-D link both at D, and the received signal y_3 via the S-R link at R are expressed as

$$y_1 = \sqrt{G_{\mathrm{SD}}} h_{\mathrm{SD}} x_1 + n_{\mathrm{SD}}, \tag{1}$$

$$y_2 = \sqrt{G_{\mathrm{RD}}} h_{\mathrm{RD}} x_2 + n_{\mathrm{RD}}, \tag{2}$$

$$y_3 = \sqrt{G_{\mathrm{SR}}} h_{\mathrm{SR}} x_1 + n_{\mathrm{SR}}, \tag{3}$$

respectively, where G_{ij} ($ij = \mathrm{SD}, \mathrm{RD}, \mathrm{SR}$) are the gains related to the distance of each link. h_{ij} and n_{ij} denote the complex channel gains and zero-mean white additive Gaussian noise (AWGN) with variance of $N_0/2$ per dimension, respectively. It is assumed that h_{ij} is constant over one block duration due to the block fading assumption. x_1 and x_2 denote the modulated symbols corresponding to the coded and interleaved information sequences, transmitted from S and R, respectively.

The S-D link is assumed to suffer from frequency non-selective block Rayleigh fading which only has non-line-of-sight (NLOS) components. The S-R and R-D links are assumed to experience block Rician fading having both NLOS and LOS components. In Rician fading model, K factor denotes the ratio of the LOS component power to NLOS components average power. With $K = 0$, Rician fading reduces to Rayleigh fading. With $K = \infty$, channel is equivalent to static AWGN channel. The S-D, S-R, and R-D links are mutually independent with each other.

Let d_{SD}, d_{RD} and d_{SR} denote the distances between S and D, R and D, and S and R, respectively. The geometric gains of the S-R and R-D links, G_{SR} and G_{RD}, respectively, can be defined as

$$G_{\mathrm{SR}} = \left(\frac{d_{\mathrm{SD}}}{d_{\mathrm{SR}}}\right)^{\alpha}, G_{\mathrm{RD}} = \left(\frac{d_{\mathrm{SD}}}{d_{\mathrm{RD}}}\right)^{\alpha}, \tag{4}$$

where α is the path loss exponent. The gain G_{SD} of the S-D link is normalized to unity.

III. OUTAGE PROBABILITY ANALYSIS

In this section, the expressions of outage probability for various relaying protocols are derived. The outage is defined as that the information rate exceeds the capacity at corresponding signal-to-noise ratio (SNR). The outage probabilities of non-cooperative transmissions, i.e., direct transmission (DT) and 2-hop (2H) transmission, are also provided as references. Let T_R and C_{ij} denote the threshold information rate and channel capacity of the ij link with Gaussian codebook assumption, respectively.

*A. Direct Transmission (*DT*)*

In direct transmission, there is no cooperation among nodes. S sends message to D without the help of R. The outage probability of the direct transmission can be defined as

$$P_{\mathrm{out}}^{\mathrm{DT}} = \Pr\left\{2T_R > C_{\mathrm{SD}}(\gamma_{\mathrm{SD}})\right\}, \tag{5}$$

where γ_{SD} is the instantaneous SNR of S-D link. Note that the threshold information rate R is double since there is only one time slot transmission from S to D.

The outage probability expression of direct transmission can be obtained by an integral with respect to the probability density function (pdf) of the instantaneous SNR, as

$$P_{\mathrm{out}}^{\mathrm{DT}} = 1 - Q_1\left(\sqrt{2K_{\mathrm{SD}}}, \sqrt{\frac{2(1+K_{\mathrm{SD}})(2^{2T_R}-1)}{\Gamma_{\mathrm{SD}}}}\right), \tag{6}$$

with Rician fading is assumed in the S-D link. $Q_1(\cdot,\cdot)$ is the Marcum Q-Function.

*B. 2-hop Transmission (*2H*)*

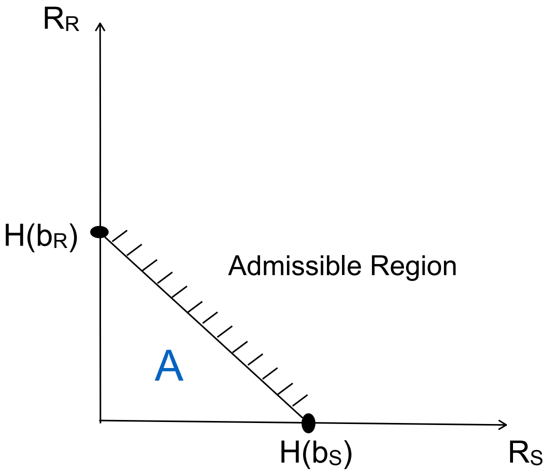
In 2H transmission, S transmits the information sequence to R at the first time slot. R decodes and forwards the information sequence to D during the second time slot. No direct link exists between S and D. Therefore, D only retrieve the original information from R. In the 2H transmission, the outage event occur when either the S-R transmission or R-D transmission fails. Therefore, the outage probability is defined as

$$P_{\mathrm{out}}^{\mathrm{2H}} = \Pr\left\{T_R > C_{\mathrm{SR}}(\gamma_{\mathrm{SR}}) || T_R > C_{\mathrm{RD}}(\gamma_{\mathrm{RD}})\right\}. \tag{7}$$

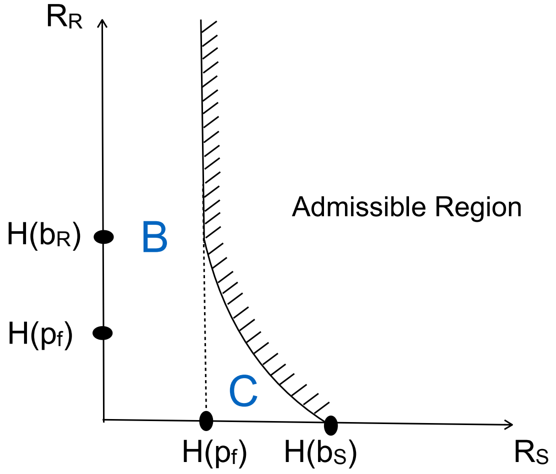
where γ_{SR} is the instantaneous SNR of S-R link.

Similar to (6), the outage probability expression of 2H transmission is expressed as,

$$\begin{aligned} P_{\mathrm{out}}^{\mathrm{2H}} = 1 - Q_1&\left(\sqrt{2K_{\mathrm{SR}}}, \sqrt{\frac{2(1+K_{\mathrm{SR}})(2^{T_R}-1)}{\Gamma_{\mathrm{SR}}}}\right) \\ &\cdot Q_1\left(\sqrt{2K_{\mathrm{RD}}}, \sqrt{\frac{2(1+K_{\mathrm{RD}})(2^{T_R}-1)}{\Gamma_{\mathrm{RD}}}}\right). \end{aligned} \tag{8}$$



(a) Rate region for S and R when $p_f = 0$



(b) Rate region for S and R when $p_f \neq 0$

Fig. 2. Rate region for LF relaying.

*C. Lossy-Forward (*LF*)*

The information sequence, obtained as the result of decoding at R, is interleaved, re-encoded and transmitted to D, even if decoding error is detected. The correlation knowledge between the information sequences transmitted from S and R is utilized in the iterative joint decoding process at D. The outage probability is defined as the probability that the source coding rate pair of S and R ($R_{\rm S}$, $R_{\rm R}$) falls into the inadmissible area A in Fig. 2(a), or B or C in Fig. 2(b). p_f represents the bit flipping probability between the information sequence obtained after decoding at R and the original sequence sent from S [8], [10].

Let $P_{\rm A}$, $P_{\rm B}$, and $P_{\rm C}$ denote the probabilities that ($R_{\rm S}$, $R_{\rm R}$) falls into the inadmissible areas A, B, and C, respectively. According to the source coding with side information theorem [6, Section15.8], [7, Section10.4], the outage probability of the LF relaying can be written as

$$\begin{aligned}P_{\rm out}^{\rm LF} =&P_{\rm A}+P_{\rm B}+P_{\rm C}\\ =&{\rm Pr}[p_f=0, 0\leq R_{\rm S}<1, 0\leq R_{\rm R}<H(p'_f)],\\ &+{\rm Pr}[0<p_f\leq 0.5, 0\leq R_{\rm S}<H(p_f), R_{\rm R}\geq 0],\\ &+{\rm Pr}[0<p_f\leq 0.5, H(p_f)\leq R_{\rm S}<1,\\ &\ 0\leq R_{\rm R}<H(p_f*p'_f)].\end{aligned} \tag{9}$$

where p'_f represent the crossover probability of the R-D link.

For calculating the outage probability, the relationships between $\gamma_{\rm SD}$ and $R_{\rm S}$, and that between the instantaneous channel SNR of the R-D link $\gamma_{\rm RD}$ and $R_{\rm R}$ are established as

$$\gamma_{ij}\geq \Theta(R_k)=\left(2^{2R_k}-1\right), (k={\rm S},{\rm R}), \tag{10}$$

according to Shannon's lossless source channel separation theorem.

The relationship between p_f and $\gamma_{\rm SR}$ can be established as

$$p_f=\Lambda(\gamma_{\rm SR})=H_2^{-1}\left(1-\log_2\left(1+\gamma_{\rm SR}\right)\right), \tag{11}$$

with the Hamming distortion measure. $H_2^{-1}(\cdot)$ denoting the inverse function of the binary entropy.

Then the outage probability of the LF relaying can be expressed as

$$\begin{aligned}P_{\rm A} =&\frac{1}{\overline{\gamma}_{\rm SD}}Q_1\left(\sqrt{2K_{\rm SR}},\sqrt{\frac{2(1+K_{\rm SR})}{\overline{\gamma}_{\rm SR}}}\right)\\ &\cdot\int_{\gamma_{\rm SD}=\Theta(0)}^{\Theta(1)}\exp\left(-\frac{\gamma_{\rm SD}}{\overline{\gamma}_{\rm SD}}\right)\left[1-Q_1\left(\sqrt{2K_{\rm RD}},\right.\right.\\ &\left.\left.\sqrt{2\left(1+K_{\rm RD}\right)\frac{\Theta(1-\Theta(\gamma_{\rm SD}))}{\overline{\gamma}_{\rm RD}}}\right)\right]d\gamma_{\rm SD},\end{aligned} \tag{12}$$

$$\begin{aligned}P_{\rm B} =&\int_{\gamma_{\rm SR}=\Theta(0)}^{\Theta(1)}\exp\left(-\frac{(1+K_{\rm SR})\gamma_{\rm SR}}{\overline{\gamma}_{\rm SR}}\right)\\ &\cdot\left(\frac{\left(1+K_{\rm SR}\right)e^{-K_{\rm SR}}}{\overline{\gamma}_{\rm SR}}\right)I_0\left(2\sqrt{\frac{K_{\rm SR}\left(1+K_{\rm SR}\right)\gamma_{\rm SR}}{\overline{\gamma}_{\rm SR}}}\right)\\ &\cdot\left[1-\exp\left(-\frac{\Theta(1-\Lambda(\gamma_{\rm SR}))}{\overline{\gamma}_{\rm SD}}\right)\right]d\gamma_{\rm SR},\end{aligned} \tag{13}$$

and

$$\begin{aligned}P_{\rm C} =&\frac{1}{\overline{\gamma}_{\rm SD}}\left(\frac{\left(1+K_{\rm SR}\right)e^{-K_{\rm SR}}}{\overline{\gamma}_{\rm SR}}\right)\int_{\gamma_{\rm SD}=\Theta(1-\Lambda(\gamma_{\rm SR}))}^{\Theta(1)}\\ &\cdot\int_{\gamma_{\rm SR}=\Theta(0)}^{\Theta(1)}\exp\left(\frac{-\gamma_{\rm SD}}{\overline{\gamma}_{\rm SD}}\right)\exp\left(-\frac{(1+K_{SR})\gamma_{\rm SR}}{\overline{\gamma}_{\rm SR}}\right)\\ &\cdot I_0\left(2\sqrt{\frac{K_{\rm SR}\left(1+K_{\rm SR}\right)\gamma_{\rm SR}}{\overline{\gamma}_{\rm SR}}}\right)\left[1-Q_1\left(\sqrt{2K_{\rm RD}},\right.\right.\\ &\left.\left.\sqrt{2\left(1+K_{\rm RD}\right)\frac{\Theta[\xi(\gamma_{\rm SD},\gamma_{\rm SR})]}{\overline{\gamma}_{\rm RD}}}\right)\right]d\gamma_{\rm SD}d\gamma_{\rm SR},\end{aligned} \tag{14}$$

where $\xi(\gamma_{\rm SD},\gamma_{\rm SR}) = H\{H^{-1}[1-\Theta(\gamma_{\rm SD})]*H^{-1}[1-\Lambda(\gamma_{\rm SR})]\}$.

*D. Conventional Decode-and-Forward with Joint Decoder (*DF-JD*)*

In the DF-JD relaying, S broadcasts the coded information sequence to D and R at the first time slot. If the transmitted information is successfully recovered at R, the information sequence is forwarded to D at the second time slot. R keeps silent if error is detected after decoding at R. A joint decoding process is performed to combine the signals received from S and R. The outage probability of the DF-JD relaying is defined as

$$\begin{aligned} P_{\text{out}}^{\text{DF-JD}} =& \Pr\left\{T_R > C_{\text{SD}}(\gamma_{\text{SD}}) | T_R > C_{\text{SR}}(\gamma_{\text{SR}})\right\} \\ & \cdot \Pr\left\{T_R > C_{\text{SR}}(\gamma_{\text{SR}})\right\} + P_{\text{A}}. \end{aligned} \tag{15}$$

The outage probability can be calculated as

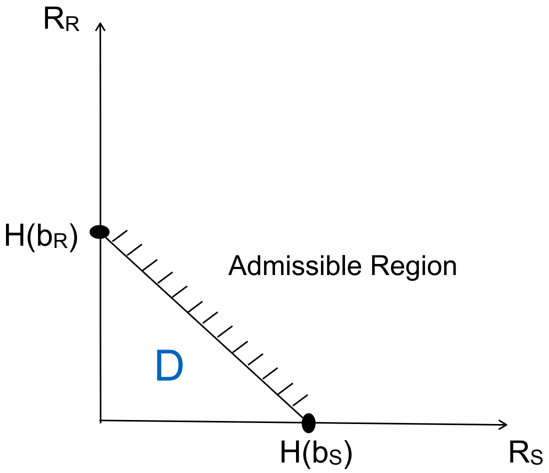
$$\begin{aligned} P_{\text{out}}^{\text{DF-JD}} =& \left(1 - Q_1\left(\sqrt{2K_{\text{SR}}}, \sqrt{\frac{2(1+K_{\text{SR}})(2^{T_R}-1)}{\Gamma_{\text{SR}}}}\right)\right) \\ & \cdot \left(1 - \exp\left(-\frac{2^{T_R}-1}{\Gamma_{\text{SD}}}\right)\right) \\ & + \frac{1}{\overline{\gamma}_{\text{SD}}} Q_1\left(\sqrt{2K_{\text{SR}}}, \sqrt{\frac{2(1+K_{\text{SR}})}{\overline{\gamma}_{\text{SR}}}}\right) \\ & \cdot \int_{\gamma_{\text{SD}}=\Theta(0)}^{\Theta(1)} \exp\left(-\frac{\gamma_{\text{SD}}}{\overline{\gamma}_{\text{SD}}}\right) \Bigg[1 - Q_1\Bigg(\sqrt{2K_{\text{RD}}}, \\ & \sqrt{2\left(1+K_{\text{RD}}\right)\frac{\Theta(1-\Theta(\gamma_{\text{SD}}))}{\overline{\gamma}_{\text{RD}}}}\Bigg)\Bigg] d\gamma_{\text{SD}}. \end{aligned} \tag{16}$$

*E. Adaptive DF with Joint Decoder (*ADF-JD*)*

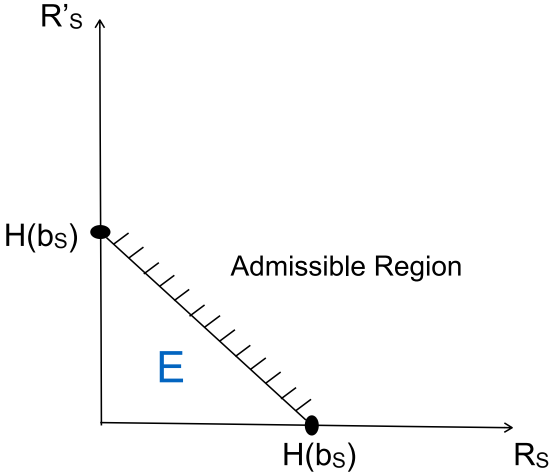
In ADF-JD transmission, S broadcasts the coded information sequence to D and R at the first time slot. If the transmitted information is successfully recovered at R, the information sequence is forwarded to D at the second time slot. The difference compared to DF-JD is that if the S-R transmission fails, S retransmits to D. D performs joint decoding to retrieve the original message of S. The information sequence is interleaved before forwarding to D from R when S-R transmission is successful, and also interleaved before retransmission from S when S-R retransmission fails. The rate region of ADF-JD is shown in Fig. 3(a) and Fig. 3(b). Similar as the case of LF, the outage probability is defined as the probability that the source coding rate pairs of S and R (R_{S}, R_{R}) and (R_{S}, R'_{S}) fall into the inadmissible area D or E shown in Fig. 3(a) and Fig. 3(b), respectively. R'_{S} is the rate of retransmitted information sequence from S.

Let P_{D} and P_{E} denote the probabilities that (R_{S}, R_{R}) and (R_{S}, R'_{S}) falls into the inadmissible areas D and E, respectively. The outage probability of ADF-JD can be defined as

$$\begin{aligned} P_{\text{out}}^{\text{ADF-JD}} =& P_{\text{D}} + P_{\text{E}} \\ =& \Pr[p_f = 0, 0 \le R_{\text{S}} < 1, 0 \le R_{\text{R}} < H(p_f)], \\ & + \Pr[0 < p_f \le 0.5, 0 \le R_{\text{S}} < 1, 0 \le R'_{\text{S}} < H(p_f)]. \end{aligned} \tag{17}$$



(a) Rate region for S and R when $p_f = 0$



(b) Rate region for S and S' when $p_f \neq 0$

Fig. 3. Rate region for adaptive DF with joint decoder (ADF-JD).

Then, the outage probability can be calculated as

$$\begin{aligned} P_{\text{out}}^{\text{ADF-JD}} =& \frac{1}{\overline{\gamma}_{\text{SD}}}\left(1 - Q_1\left(\sqrt{2K_{\text{SR}}}, \sqrt{\frac{2(1+K_{\text{SR}})}{\overline{\gamma}_{\text{SR}}}}\right)\right) \\ & \cdot \int_{\gamma_{\text{SD}}=\Theta(0)}^{\Theta(1)} \exp\left(-\frac{\gamma_{\text{SD}}}{\overline{\gamma}_{\text{SD}}}\right) \Bigg[1 - Q_1\Bigg(\sqrt{2K_{\text{RD}}}, \\ & \sqrt{2\left(1+K_{\text{RD}}\right)\frac{\Theta(1-\Theta(\gamma_{\text{SD}}))}{\overline{\gamma}_{\text{RD}}}}\Bigg)\Bigg] d\gamma_{\text{SD}}, \\ & + \int_{\gamma_{\text{SD}}=\Theta(0)}^{\Theta(1)} \frac{1}{\overline{\gamma}_{\text{SD}}}\left(1 - Q_1\left(\sqrt{2K_{\text{SR}}}, \sqrt{\frac{2(1+K_{\text{SR}})}{\overline{\gamma}_{\text{SR}}}}\right)\right) \\ & \cdot \exp\left(-\frac{\gamma_{\text{SD}}}{\overline{\gamma}_{\text{SD}}}\right)\left[1 - \exp\left(-\frac{\Theta(1-\Theta(\gamma_{\text{SD}}))}{\overline{\gamma}_{\text{SD}}}\right)\right] d\gamma_{\text{SD}}. \end{aligned} \tag{18}$$

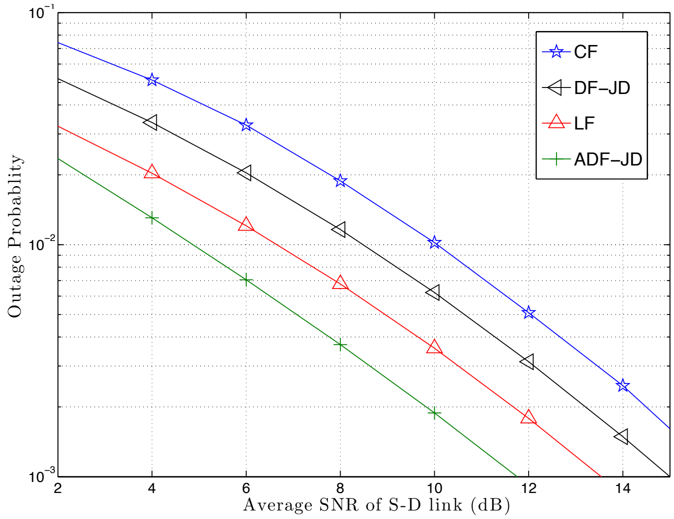


Fig. 4. Comparison of the outage probability of different relaying strategies, where S-D, S-R and R-D links are Rayleigh fading.

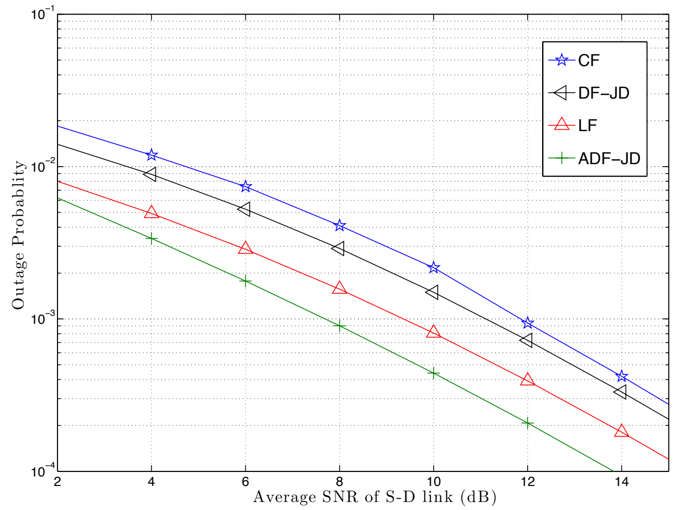


Fig. 5. Comparison of the outage probability of different relaying strategies, where S-D and S-R links are Rayleigh fading and R-D link is Rician fading.

F. Compress-and-Forward (CF)

With CF relaying, R performs the Wyner-Ziv coding to compress the received information sequence and forwards it to D. D estimates compressed information sequence by utilizing the information sequence transmitted from S as side information. The outage probability of CF relaying can be written as [11]

$$\begin{aligned} \mathrm{P}_{\mathrm{out}}^{\mathrm{CF}} = & \Pr\left\{T_R > I_{\mathrm{CF}} | T_R \le C_{\mathrm{RD}}(\gamma_{\mathrm{RD}}), T_R \ge T_{\mathrm{C}}\right\} \\ & \cdot \Pr\left\{T_R \le C_{\mathrm{RD}}(\gamma_{\mathrm{RD}})\right\} \cdot \Pr\left\{T_R \ge T_{\mathrm{C}}\right\} \\ & + \Pr\left\{T_R > C_{\mathrm{SD}}(\gamma_{\mathrm{SD}}) | T_R > C_{\mathrm{RD}}(\gamma_{\mathrm{RD}})\right\} \\ & \cdot \Pr\left\{T_R > C_{\mathrm{RD}}(\gamma_{\mathrm{RD}})\right\} \\ & + \Pr\left\{T_R > C_{\mathrm{SD}}(\gamma_{\mathrm{SD}}) | T_R < T_C\right\} \\ & \cdot \Pr\left\{T_R < T_C\right\}, \end{aligned} \tag{19}$$

where $T_C = \log_2\left(1 + \frac{1}{V_n} + \frac{\gamma_{\mathrm{SR}}}{(1+\gamma_{\mathrm{SD}})V_n}\right)$, and $I_{\mathrm{CF}} = \log_2\left(1 + \gamma_{\mathrm{SD}} + \frac{\gamma_{\mathrm{SR}}}{(1+V_n)}\right)$. $V_n = \frac{\gamma_{\mathrm{SR}}+\gamma_{\mathrm{SD}}+1}{\gamma_{\mathrm{RD}}}$ is the quantization noise variance [12], [13]. The outage probability of the CF relaying has no closed-form expression. However, it can be numerically calculated by Monte Carlo simulations.

IV. NUMERICAL RESULTS AND DISCUSSION

We compare the outage probability of the relaying strategies analysed in the previous section. The threshold rate are set to $T_R = 1$ and, the path loss exponent is set to $\alpha = 3.52$ in the case $K = 0$ as in [14], and $\alpha = 2$ in the case $K > 0$ as in [15].

Fig. 4 plots the theoretical outage probability versus average SNR of the S-D link, with the Rician factor K of each link being $K = 1$. In other words, all the links are suffering from Rayleigh fading. The relay is at the midpoint between the source and the destination. It is found that the 2nd order diversity can be achieved by all the relaying strategies. LF is about 1.5 dB better than DF-JD and 1.5 dB worse than ADF, respectively, at a outage probability of 0.01. This gap remains the same at the entire range of the average SNR. The analytical results are very useful for evaluating the performance of practical code design for difference protocols. The reason for ADF outperforming LF is that ADF has feedback information from R to tell S to retransmit when S-R transmission is failed. The admissible rate region of ADF in Fig. 3(b) is increased compared to that of LF in Fig. 2(b), which decreases the outage probability.

In Fig. 5 the theoretical outage probability versus average SNR is presented. The difference from Fig. 4 is the impact of the (LOS) component is considered in R-D link. As expected, the outage curves exhibit the tendency that the larger the K values, the smaller the outage probability. However, the decay of outage curves remains the same. The outage curves can achieve sharper decay than that with 2nd order diversity, only when the LOS component ratios of both the S-R and R-D links increase simultaneously.

Fig. 6 illustrates the outage probability as a function of relay location by assuming that the average SNR of S-D link is kept at 3 dB. All the links experience Rayleigh fading ($K = 0$). The outage performance of LF relaying is superior to that of DF-JD and CF relaying and inferior to that of ADF relaying. It is also found that the CF relaying achieves lower outage probability than DF-JD when R is close to S. Whereas in the case that R is close to D, DF-JD achieves better outage performance. This is because when R approaches S, the S-R link can support reliable S-R transmission, resulting in better performance of the DF-JD scheme; on the other hand, CF provides higher achievable rates when the S-R link transmission is not reliable enough.

The outage probabilities of relaying protocols are shown in Fig. 7, with both S-R and R-D links having LOS component ($K_{\mathrm{SR}} = K_{\mathrm{RD}} = 3$). We find that lower outage probability can be achieved compared to the case that all the links undergo Rayleigh fading. The LF relaying still achieves the lowest outage probability among the schemes without feedback. This observation indicates that as the ratio of LOS component increases (bigger K value), lower outage probability can be achieved. However, the outage performances of the different

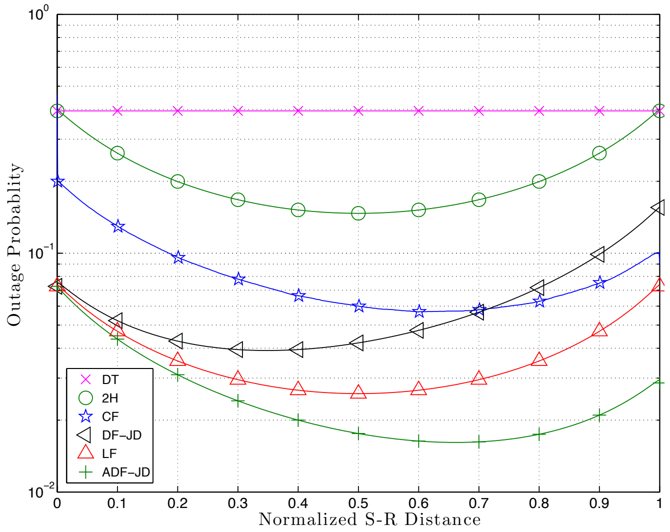


Fig. 6. Outage probability vs. normalized S-R distance, where S-D, S-R and R-D links are Rayleigh fading.

relaying schemes show the same tendencies with or without the impact of LOS component.

V. CONCLUSION

In this paper, we investigated and compared the outage probabilities of the CF, DF-JD, ADF-JD and LF relaying protocols. The analytical expressions for the outage probabilities were derived where the impact of the LOS component is taken into account. It has been shown that the LF relaying achieves lower outage probability than the CF and DF-JD relaying systems with or without the presence of the LOS components. The ADF-JD has shown superior outage performance over the LF relaying because of the contribution of feedback information. However, the LF relaying has the advantage in real-time (delay-critical) applications due to the feature of no feedback requirement, leading to higher overall spectral efficiency and capacity compared to ADF-JD.

For a fair comparison, only the joint decoding process was assumed at the destination to recover the original information. The investigation for optimum combining of different relaying strategies and decoding schemes is beyond the scope of this paper, but it will be treated as an important further study item.

ACKNOWLEDGMENT

This research was supported in part by European Union's FP7 project, ICT-619555 RESCUE, in part by Academy of Finland NETCOBRA project, in part by JAIST Doctoral Research Fellow program, and also in part by NEC C&C Grants for Non-Japanese Researchers.

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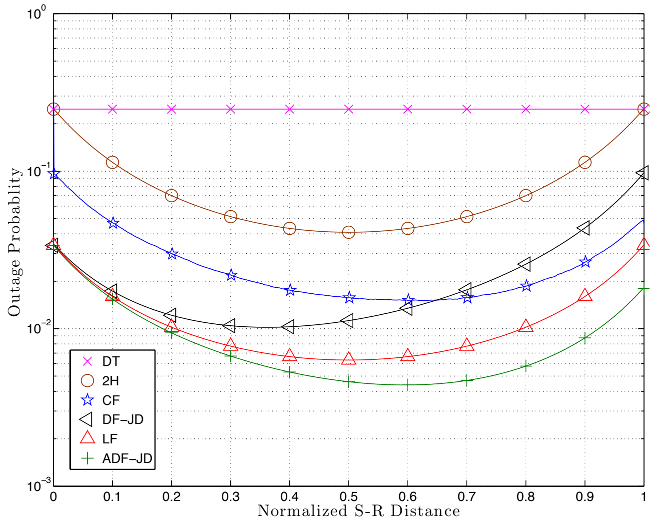

Fig. 7. Outage probability vs. normalized S-R distance, where S-D is Rayleigh fading, and S-R and R-D links are Rician fading.

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