Half-Duplex Relaying Strategy Suitable for a Relay with Mobility

Inho Hwang[1] and Jeong Woo Lee[2]
[1, 2] School of Electrical and Electonics Engineering,
Chung-Ang University
Seoul 156-756, Korea
[e-mail: [1] inodaman@gmail.com, [2] jwlee2@cau.ac.kr]
*Corresponding author: Jeong Woo Lee

Received May 23, 2014; revised October 23, 2014; revised November 13, 2014; accepted November 30, 2014; published January 31, 2015

Abstract

We propose a new time-division half-duplex estimate-and-forward (EF) relaying strategy suitable for a relay with mobility. We reconfigure EF relaying to guarantee a strong relay-destination link which is required to achieve a high rate using EF relaying. Based on the reconfigured model, we optimize the relaying strategy to attain a high rate irrespective of the relay position with preserving the total transmit bandwidth and energy. The proposed relaying strategy achieves high communication reliability for any relay position, which differs from conventional EF and decode-and-forward (DF) relaying schemes.

Keywords: Relay, estimate-and-forward relaying, time-division half-duplex relaying, achievable rate

This research was supported by the Chung-Ang University Excellent Student Scholarship, and supported by the MSIP (Ministry of Science, ICT and Future Planning), Korea, under the ITRC (Information Technology Research Center) support program (NIPA-2014-H0301-14-1015) supervised by the NIPA (National IT Industry Promotion Agency).

http://dx.doi.org/10.3837/tiis.2015.01.007 **ISSN : 1976-7277**

1. Introduction

Decode-and-forward (DF) and estimate-and-forward (EF) relaying protocols are two prominent relaying strategies for the three terminal relay channel composed of source, relay and destination nodes [1][2]. The performance of DF relaying is highly dependent on the relay position between the source and the destination [3]. The performance of EF relaying shows less dependency on the relay position under the condition of a strong relay-destination link [3][4][5][6]. In wireless communications, however, a strong relay-destination link is not feasible when the relay is not in close proximity to the destination. Thus, the performance of EF relaying is also highly dependent on the relay position. If the relay has mobility, as in the mobile relay and the nomadic relay systems [7][8], the relay can change its position randomly. Recently, a mobile relay for a LTE-Advanced system was investigated in [9]. A mobile relay equipped with amplify-and-forward (AF) protocol which utilizes minimum power was proposed in [10]. In fact, we need a new relaying strategy with sufficiently high resultant communication reliability, irrespective of the relay position. The new relaying strategy should not require bandwidth expansion and an energy increase for operation.

As a solution, we propose a new time-division half-duplex EF relaying strategy, where half-duplex relaying is preferred in practical cooperative communication systems due to the absence of a self-interference (echo) signal [11], and the time-division relaying strategy can be easily extended to frequency-division relaying. First, we reconfigure EF relaying such that the actual relay-destination channel is included in the newly defined relay unit in order to ensure that the resultant relay-destination link is always strong. Based on the reconfigured model, we manipulate equations associated with the achievable rate of relay channels, and propose a systematic way to optimize the relaying strategy to maximize the achievable rate. The proposed relaying strategy includes quantization at the relay as well as power allocation between the source and the relay. When optimizing the relaying strategy, we consider the actual relay-destination channel condition as well as the modulation order at the source node and the relay node with constraints on the transmit bandwidth and energy. With the same transmit bandwidth and energy, the proposed relaying strategy achieves higher communication reliability than direct communication and conventional EF relaying. The performance of the proposed relaying strategy is much less sensitive to the relay position than conventional EF and DF relaying. These observations show that the proposed relaying strategy is suitable for a relay with mobility.

2. System Model

We consider a time-division half-duplex relay channel composed of a source node (S), a relay node (R) and a destination node (D). Channels from S to R, from R to D and from S to D are called SR, RD and SD channels, respectively, each of which has the channel gain h_{sr}, h_{rd} and h_{sd}, respectively.

The relay channel operates in a broadcast (BC) mode during the first time fraction t and in a multiple-access (MAC) mode during the next time fraction $1-t$, where $0<t<1$, as depicted in **Fig. 1**. Suppose that S does not transmit a signal (silent) in MAC mode.

In BC mode, S transmits a symbol X, which is received as V at R after passing through the SR channel and is received as Z_1 at D after the SD channel. In MAC mode, R transmits a symbol W which is received as Z_2 at D after the RD channel. Note that W is formed at R by quantizing V as $W = Q_t(V)$, where Q_t denotes an L_q-bin quantization function. We consider a scalar quantization Q_t with low complexity because it does not result in remarkable information loss compared with an optimal vector quantization requiring a great deal of computation [12][13]. No additional channel coding is applied to W to avoid the resultant bandwidth expansion of the RD channel. Then, the relay channel is modeled as

$$\begin{aligned} V &= h_{sr} X + N_R \\ Z_1 &= h_{sd} X + N_{D_1} \\ Z_2 &= h_{rd} W + N_{D_2}, \end{aligned} \tag{1}$$

where N_R, N_{D_1} and N_{D_2} are zero-mean additive circular symmetric complex white Gaussian noises with the single-sided power spectral density of N_0. At D, log-likelihood ratios (LLR's) of bits mapped to X are computed from Z_1 in BC mode and from Z_2 in MAC mode, which are combined to use in the detection and decoding processes.

For simple analysis, we suppose that all nodes are aligned on a straight line with R located between S and D as shown in **Fig. 2**. The distance of R from S and from D is d and $1-d$, respectively, with $0 < d < 1$. Then, $|h_{sd}|^2 = 1$, $|h_{sr}|^2 = 1/d^{\alpha}$ and $|h_{rd}|^2 = 1/(1-d)^{\alpha}$, where α is a channel attenuation factor.

As a reference system, we consider a direct communication system in which the M_o-ary symbol is transmitted from S to D with the energy per symbol E_T. The relay system is constrained to utilize the same transmit energy and overall transmission bandwidth as those of a reference system. The energy constraint is expressed by

$$tE_S + (1-t)E_R = E_T, \tag{2}$$

where E_S and E_R denote the energy per symbol at S and at R, respectively. To satisfy the bandwidth constraint, the relay system must transmit the same number of symbols as the reference system. For this purpose, alphabet sizes of X and W must be $M = M_o^{1/t}$ and $L = L_q^{t/(1-t)}$, respectively, where $X \in \{x_0, \cdots, x_{M-1}\}$ and $W \in \{w_0, \cdots, w_{L-1}\}$. We consider M and L be powers of two. It follows that $t = \frac{1}{a}\log_2 M_o$ and $L_q = 2^{b(a/\log_2 M_o - 1)}$ with positive integers a and b.

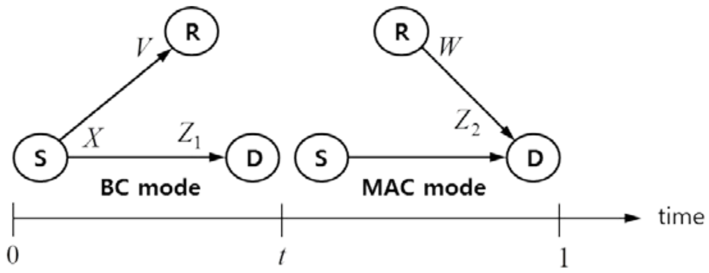

Fig. 1. Half-duplex relay channel operating in BC mode and MAC mode.

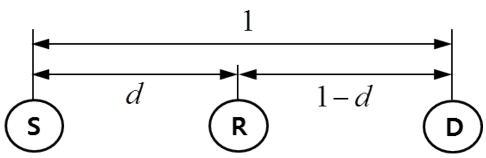

Fig. 2. Relay channel with all nodes aligned on a straight line.

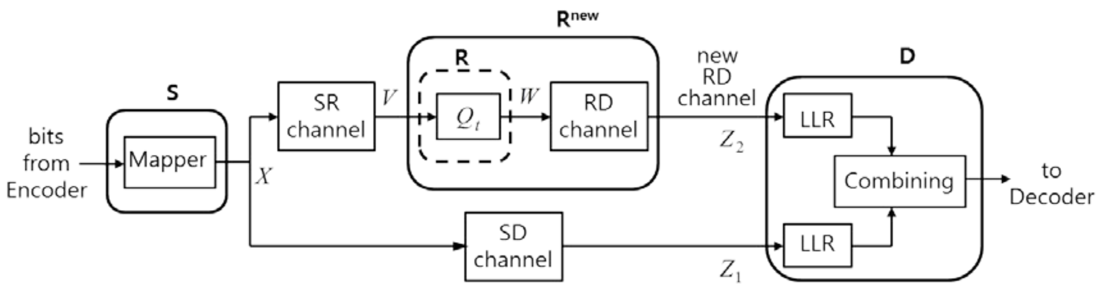

Fig. 3. The models of conventional and reconfigured EF relaying.

3. Relaying Strategy

3.1 Conventional EF Relaying

Let us consider a conventional configuration of the time-division half-duplex EF relaying as depicted in **Fig. 3**, where the relay unit (R) is represented by a dotted box. The achievable rate by this configuration is given by [11][12]

$$R_{EF} = \max_{0<t<1} \max_{p(x),p(w)} t\, I(X;Z_1,W) \tag{3}$$

subject to

$$t\, I(V;W \mid Z_1) \leq (1-t)R_{rd}\,, \tag{4}$$

where R_{rd} is the achievable rate over the RD channel in MAC mode, and $p(x)$ and $p(w)$ denote the distribution of X and W, respectively. This is obtained from [11][12] by assuming that S is silent in MAC mode. Suppose that V is quantized as W without exploiting the side information Z_1, which results in $I(V;W\,|\,Z_1)=I(V;W)$. Note that $I(V;W)=H(W)-H(W\,|\,V)=H(W)$ because W is a deterministic function of V, i.e., $W=Q_t(V)$. Thus, the constraint (4) is simplified as

$$H(W)\le\frac{1-t}{t}R_{rd}. \tag{5}$$

Note that $R_{rd}\le\log_2(1+|h_{rd}|^2\frac{E_R}{N_0})$. Suppose $t=0.5$, $d=0.2$, $\alpha=2$, $L_q\ge 4$ and $p(w_i)=1/L$ which is identical for all $i=0,\cdots,L-1$. Then, we have $2\le H(W)\le\frac{1-t}{t}\log_2(1+\frac{E_R}{N_0}\cdot\frac{1}{(1-d)^\alpha})$ and it follows that $(2^{\frac{2t}{1-t}}-1)(1-d)^\alpha\le\frac{E_R}{N_0}$. Since $\frac{E_T}{1-t}\ge E_R$ by (2), we obtain $\frac{E_T}{N_0}\ge(1-t)(2^{\frac{2t}{1-t}}-1)(1-d)^\alpha=-0.1773$ dB. This means that $\frac{E_T}{N_0}\ge-0.1773$ dB is required to satisfy constraint (4). If channel coded bits with the rate $R_c=1/2$ are to be transmitted by EF relaying, then $\frac{E_b}{N_0}\ge 2.833$dB is required to satisfy (4) because $\frac{E_T}{N_0}=R_c\frac{E_b}{N_0}$. In case of direct communication, reliable communication is available at E_b/N_0 much lower than 2.833dB by using the rate 1/2 turbo codes [14]. This analysis tells us that conventional EF relaying may result in poorer performance than direct communication with some operating parameters. To avoid this problem, R is placed near D when EF relaying is used. Consequently, a conventional EF relaying strategy is not suitable for a relay with mobility. To resolve this problem, we propose a new EF relaying strategy under a new framework working well for various d values, even at low SNR.

3.2 Proposed Relaying Strategy

The proposed relaying strategy operates in the same manner as introduced in Sec. 2. S broadcasts M-ary symbol $X\in\{x_0,\cdots,x_{M-1}\}$ in BC mode during the time fraction t, where X is received as V at R and as Z_1 at D. At R, V is quantized as L-ary symbol $W\in\{w_0,\cdots,w_{L-1}\}$ by $W=Q_t(V)$. At D, LLR's of bits mapped to X are computed from Z_1. In MAC mode during $1-t$, R transmits W which is received as Z_2 at D. Then, LLR's of bits mapped to X are computed from Z_2 and combined with LLR's obtained in BC mode. The SR channel can be represented by the transition probability $p(w_k\,|\,x_j)$, $j=0,\cdots,M-1$ and $k=0,\cdots,L-1$, defined by

$$p(w_k\,|\,x_j)=\frac{1}{\pi N_0}\int_{v\in\mathcal{V}_k}\exp\left\{-\frac{|v-h_{sr}x_j|^2}{N_0}\right\}dv, \tag{6}$$

where $\mathcal{V}_k$ denotes the quantization bin of V mapped to w_k. The quantization at R can also be conducted by using the matched filtered signal $\tilde{v}=h_{sr}^*v/|h_{sr}|=\tilde{v}_I+j\tilde{v}_Q$, by which (6) can be written in another form as

$$p(w_k \mid x_j) = \frac{1}{\pi N_0} \int_{\theta_I^k}^{\theta_I^{k+1}} \exp\left\{ -\frac{(\tilde{v}_I - |h_{sr}| \Re\{x_j\})^2}{N_0} \right\} d\tilde{v}_I \cdot \int_{\theta_Q^k}^{\theta_Q^{k+1}} \exp\left\{ -\frac{(\tilde{v}_Q - |h_{sr}| \Im\{x_j\})^2}{N_0} \right\} d\tilde{v}_Q , \tag{7}$$

where the bin bounded by $\theta_I^k \leq \tilde{v}_I < \theta_I^{k+1}$, $\theta_Q^k \leq \tilde{v}_Q < \theta_Q^{k+1}$ is mapped to w_k, and $\Re\{\cdot\}$ and $\Im\{\cdot\}$ denote the real part and the imaginary part, respectively. The RD channel can be represented by the transition probability $f(z_2 \mid w_k)$, $k = 0, \cdots, L-1$, defined by

$$f(z_2 \mid w_k) = \frac{1}{\pi N_0} \exp\left\{ -\frac{|z_2 - h_{rd} w_k|^2}{N_0} \right\}. \tag{8}$$

Let b_ℓ be the ℓ-th bit in the bit stream mapped to X, then the LLR of b_ℓ is computed in BC mode as

$$L(b_\ell \mid z_1) = \log \frac{p(b_\ell = 0 \mid z_1)}{p(b_\ell = 1 \mid z_1)} = \log \frac{\sum_{j: x_j \in \chi_\ell^0} \exp\left\{ -|z_1 - x_j|^2 / N_0 \right\}}{\sum_{j: x_j \in \chi_\ell^1} \exp\left\{ -|z_1 - x_j|^2 / N_0 \right\}}, \tag{9}$$

where χ_ℓ^0 and χ_ℓ^1 denote the set of symbols X whose corresponding ℓ-th bit is 0 and 1, respectively. In MAC mode, the LLR of b_ℓ is computed as

$$L(b_\ell \mid z_2) = \log \frac{p(b_\ell = 0 \mid z_2)}{p(b_\ell = 1 \mid z_2)} = \log \frac{\sum_{j: x_j \in \chi_\ell^0} \sum_{k=0}^{L-1} p(w_k \mid x_j) f(z_2 \mid w_k)}{\sum_{j: x_j \in \chi_\ell^1} \sum_{k=0}^{L-1} p(w_k \mid x_j) f(z_2 \mid w_k)}. \tag{10}$$

The LLR's of each bit b_ℓ computed in BC mode and MAC mode are combined as $L(b_\ell) = L(b_\ell \mid z_1) + L(b_\ell \mid z_2)$ to be used in the detection and decoding processes.

Although the proposed relaying strategy and the conventional EF relaying scheme [12] operate in a similar manner, they differ in determining optimal parameters of relaying schemes. In the proposed relaying strategy, the modulation scheme of W and the actual RD channel condition are taken into account to optimize operating parameters. On the other hand, in the conventional EF relaying scheme, the RD channel is assumed error-free. For finding optimal parameters of the relaying strategy, let us reconfigure the time-division half-duplex EF relaying as depicted in **Fig. 3**, where the new relay unit is represented by a solid box with the label $\mathrm{R}^{\mathrm{new}}$. Note that $\mathrm{R}^{\mathrm{new}}$ includes the actual RD channel as well as R. The newly defined RD channel is free of additive noise and attenuation so that $R_{rd} \to \infty$ and the constraint (4) is not needed. Note that W is the output of R in the conventional configuration. Considering that Z_2 is the output of $\mathrm{R}^{\mathrm{new}}$, the optimization problem (3) with constraint (4) in the conventional configuration can be modified as

$$R_{EF} = \max_{0<t<1} \max_{p(x),p(w)} t\, I(X;Z_1,Z_2) \tag{11}$$

without a constraint in the new configuration. At low SNR, Z_1 and Z_2 are almost independent so $I(X;Z_1,Z_2) \approx I(X;Z_1) + I(X;Z_2)$. In addition, $I(X;Z_1)$ and $I(X;Z_2)$ are maximized when X is uniformly distributed. Thus, at low SNR, (11) is approximated by

$$R_{EF} \approx \max_{0<t<1} \max_{p(w):p(x)=\frac{1}{M}} t\,(I(X;Z_1) + I(X;Z_2)). \tag{12}$$

At low SNR, $I(X;Z_1)$ is upper-bounded by the capacity of *M*-ary input additive white Gaussian noise (AWGN) channel, denoted by $C_M(E_S/N_0)$, because X is modulated as an *M*-ary signal. For given d, E_T and N_0, $p(w)$ is determined by E_S and Q_t. Consequently, for given d and E_T, (12) can be written by

$$R_{EF} \approx \max_{0<t<1} \max_{E_S,Q_t:p(x)=\frac{1}{M}} t\,(C_M(E_S/N_0) + I(X;Z_2)). \tag{13}$$

With $p(x) = \frac{1}{M}$, we have

$$I(X;Z_2) = \log_2 M - \int f(z_2) H(X \mid z_2) dz_2, \tag{14}$$

where

$$H(X \mid z_2) = -\sum_{j=0}^{M-1} p(x_j \mid z_2) \log_2 p(x_j \mid z_2) \tag{15}$$

and

$$\begin{aligned} p(x_j \mid z_2) &= \sum_{k=0}^{L-1} p(x_j \mid w_k, z_2) p(w_k \mid z_2) = \sum_{k=0}^{L-1} p(w_k \mid z_2) \frac{p(x_j)}{p(w_k)} f(z_2 \mid w_k) \frac{p(w_k)}{f(z_2)} \\ &= \frac{\sum_{k=0}^{L-1} p(w_k \mid x_j) f(z_2 \mid w_k)}{\sum_{j=0}^{M-1} \sum_{k=0}^{L-1} p(w_k \mid x_j) f(z_2 \mid w_k)}. \end{aligned} \tag{16}$$

In the second equality of (16), $p(x_j \mid w_k, z_2) = p(x_j \mid w_k)$ is used because X, W and Z_2 form a Markov chain in this order as well as in the reverse order, and in the last equality,

$$f(z_2) = \sum_{j=0}^{M-1} \sum_{k=0}^{L-1} \frac{1}{M} p(w_k \mid x_j) f(z_2 \mid w_k) \tag{17}$$

is used. A closed form of $I(X;Z_2)$ is obtained by plugging (15)-(17) into (14) with the aid of (6)-(8). Then, by using the closed form of $I(X;Z_2)$, we can find numerically optimal values of t and E_S as well as the optimal quantizer Q_t that maximize $t(C_M(E_S/N_0)+I(X;Z_2))$ and we can evaluate the resultant achievable rate R_{EF} for given d, E_T and N_0.

4. Numerical Results

Consider BPSK and QPSK modulated direct communication schemes ($M_o = 2$ and $M_o = 4$) as reference systems. We suppose that d is known to all nodes, and let $\alpha = 2$ and $N_0 = 2$. Optimal values of t and E_S as well as the optimal quantizer Q_t in the proposed relaying strategy for given d and E_T are obtained as follows. We first find the candidate values of t satisfying $t = \frac{1}{a}$ with an arbitrary positive integer a, as introduced in Sec. 2, and fix the value of t as one of cadidates. Then, by varying the value of E_S, we do the following. For each E_S, we find threshold values of Q_t that maximize the value of $t(C_M(E_S/N_0)+I(X;Z_2))$ by using the closed form obtained in Sec. 3. The quantization at R is conducted for the matched filtered signal $\tilde{v} = h_{sr}^* v / |h_{sr}| = \tilde{v}_I + j\tilde{v}_Q$. Each phase component of $\tilde{v}$, i.e., $\tilde{v}_I$ and $\tilde{v}_Q$, is quantized independently based on the set of per-phase thresolds $\{\theta_k\}_{k=1}^{\sqrt{L_q}-1}$, by which L_q-level quantization is obtained. Then, we find the value of E_S and its corresponding $\{\theta_k\}_{k=1}^{\sqrt{L_q}-1}$ which results in the maximum value of $t(C_M(E_S/N_0)+I(X;Z_2))$ for a given t. By repeating the same procedure for all candidate values of t, we find the optimal combination of t, E_S and $\{\theta_k\}_{k=1}^{\sqrt{L_q}-1}$, and evaluate the achievable rate R_{EF}. The number of quantization bins L_q is sub-optimally chosen as the value above which the performance is not improved significantly by increasing L_q compared with the resultant growth of complexity. The values of per-phase thresholds are set as symmetric, i.e., $\theta_k = -\theta_{\sqrt{L_q}-k}$, $k = 1,\cdots,\sqrt{L_q}-1$.

First, consider the case that BPSK-modulated direct communication ($M_o = 2$) is a reference system. Through a numerical search, we determine $t = 0.5$ resulting in $M = 4$, and $L_q = L = 16$ as optimal values. The set of per-phase thresholds is in the form of $\{-\theta_1, 0, \theta_1\}$. We choose QPSK and 16-QAM as the modulation schemes for X and W, respectively. Let us consider $x_0 = -a - ja$ with $a = \sqrt{E_S/2}$, which is a point in the signal constellation for the QPSK symbol X. The transition probability $p(w_0 \mid x_0)$ is obtained by using (7) as

$$\begin{aligned} p(w_0 \mid x_0) &= \Pr\left\{\Re\{\tilde{V}\} < -\theta_1 \text{ and } \Im\{\tilde{V}\} < -\theta_1\right\} \\ &= Q\left(\theta_1 - |h_{sr}|a\right)\cdot Q\left(\theta_1 - |h_{sr}|a\right), \end{aligned} \tag{18}$$

where $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp(-\frac{u^2}{2})du$. All other transition probabilities $p(w_k \mid x_j)$ are obtained in a similar manner. Optimal parameters for some d and per-bit SNR, E_b/N_0, with $t = 0.5$ and $L_q = 16$ are listed in **Table 1** as samples.

Next, consider the case that QPSK-modulated direct communication ($M_o = 4$) is a reference system. We determine $t = 0.5$ resulting in $M = 16$, and $L_q = L = 256$ as optimal values. The set of per-phase thresholds is in the form of $\{-\theta_7, \cdots, -\theta_1, 0, \theta_1, \cdots, \theta_7\}$. We choose 16-QAM and 256-QAM as the modulation schemes for X and W, respectively. Transition probabilities $p(w_k \mid x_j)$, $j = 0, \cdots, 15$, $k = 0, \cdots, 255$, are obtained in a similar manner to the case of BPSK-modulated reference system as introduced above. Optimal parameters for some d and per-bit SNR, E_b / N_0, with $t = 0.5$ and $L_q = 256$ are listed in **Table 2** as samples.

Table 1. Optimal parameters of the proposed relaying strategy and resultant R_{EF} for some d and E_b/N_0 with t = 0.5, L_q = 16, α = 2 and N_0 = 2, where the reference system is BPSK-modulated direct communication. In numerical search, increments of E_S and θ_1 are 0.001.

d	E_b / N_0 [dB]	E_T	E_S	θ_1	R_{EF}
0.9	-1.3	0.494	0.912	0.537	0.513031
	-1.2	0.506	0.934	0.541	0.523905
	-1.1	0.517	0.956	0.544	0.534963
0.7	-1.1	0.517	0.830	0.241	0.503156
	-1.0	0.530	0.851	0.243	0.515141
	-0.9	0.542	0.872	0.245	0.527345
0.4	-1.1	0.517	0.657	0.163	0.517316
	-1.0	0.530	0.672	0.165	0.530058
	-0.9	0.542	0.687	0.167	0.543017
0.2	-1.6	0.461	0.386	0.131	0.498781
	-1.5	0.472	0.393	0.133	0.509411
	-1.4	0.483	0.399	0.134	0.520157

Table 2. Optimal parameters of the proposed relaying strategy and resultant R_{EF} for some d and E_b/N_0 with t = 0.5, L_q = 256, α = 2 and N_0 = 2, where the reference system is QPSK-modulated direct communication. In numerical search, increments of E_S and θ_k are 0.001.

d	E_b / N_0 [dB]	E_T	E_S	θ_1, θ_2, θ_3, θ_4, θ_5, θ_6, θ_7	R_{EF}
0.9	-0.8	0.665	1.238	0.205, 0.399, 0.576, 0.736, 0.882, 1.016, 1.141	0.902780
	-0.4	0.730	1.358	0.209, 0.410, 0.594, 0.763, 0.916, 1.057, 1.187	0.966217
	0.0	0.800	1.490	0.213, 0.419, 0.613, 0.790, 0.952, 1.100, 1.237	1.032273
0.7	-0.1	0.782	1.325	0.102, 0.204, 0.305, 0.406, 0.505 ,0.603, 0.699	0.972758
	0.1	0.819	1.388	0.108, 0.215, 0.322, 0.428, 0.532, 0.634, 0.733	1.006192
	0.3	0.857	1.453	0.114, 0.228, 0.341, 0.452, 0.561, 0.667, 0.769	1.040188
0.4	-0.1	0.782	1.091	0.067, 0.133, 0.200, 0.267, 0.335, 0.404, 0.473	0.951078
	0.1	0.819	1.143	0.070, 0.140, 0.210, 0.281, 0.353, 0.425, 0.499	0.983616
	0.3	0.857	1.198	0.074, 0.147, 0.221, 0.296, 0.372, 0.448, 0.526	1.016602
0.2	-0.7	0.681	0.824	0.039, 0.077, 0.116, 0.155, 0.194, 0.232, 0.271	0.864945
	-0.5	0.713	0.864	0.039, 0.079, 0.118, 0.157, 0.197, 0.236, 0.276	0.896919
	-0.3	0.747	0.907	0.040, 0.080, 0.120, 0.160, 0.200, 0.240, 0.280	0.929560

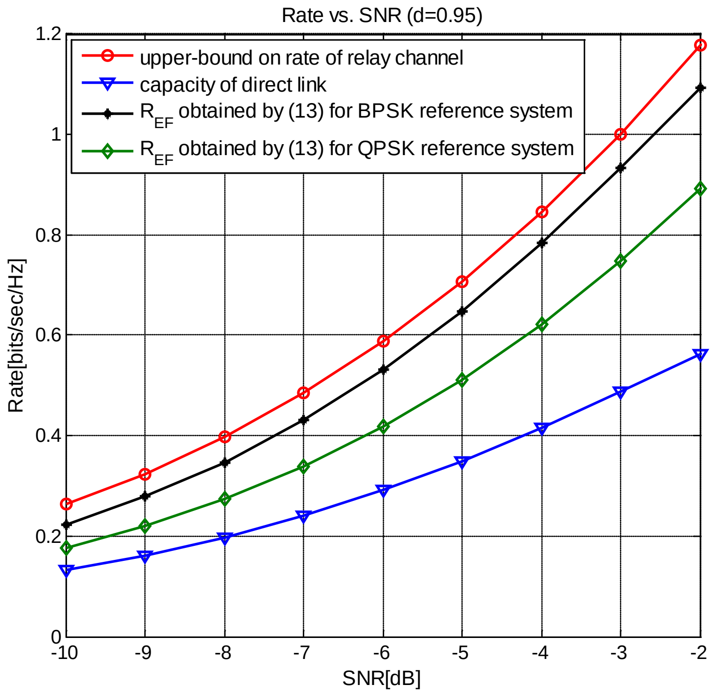

Fig. 4. Achievable rate of the proposed relaying strategy, the direct link capacity and the upper bound on the achievable rate of a relay channel, where the relay position $d = 0.95$.

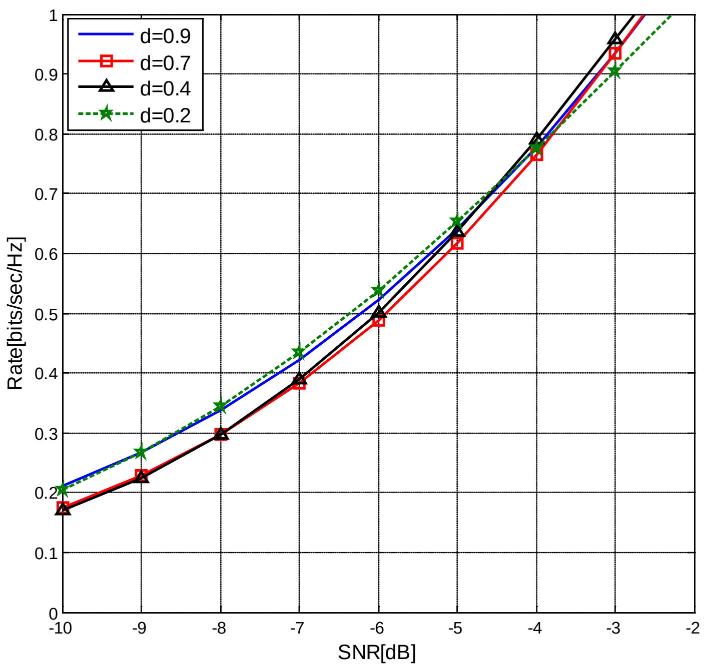

Fig. 5. Achievable rates of the proposed relaying strategy for different relay positions d, where the reference system is BPSK-modulated direct communication.

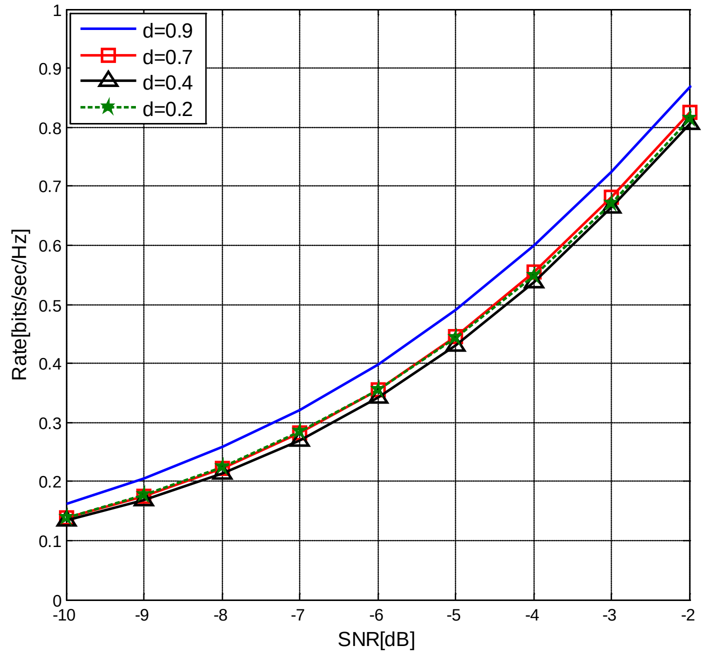

Fig. 6. Achievable rates of the proposed relaying strategy for different relay positions d, where the reference system is QPSK-modulated direct communication.

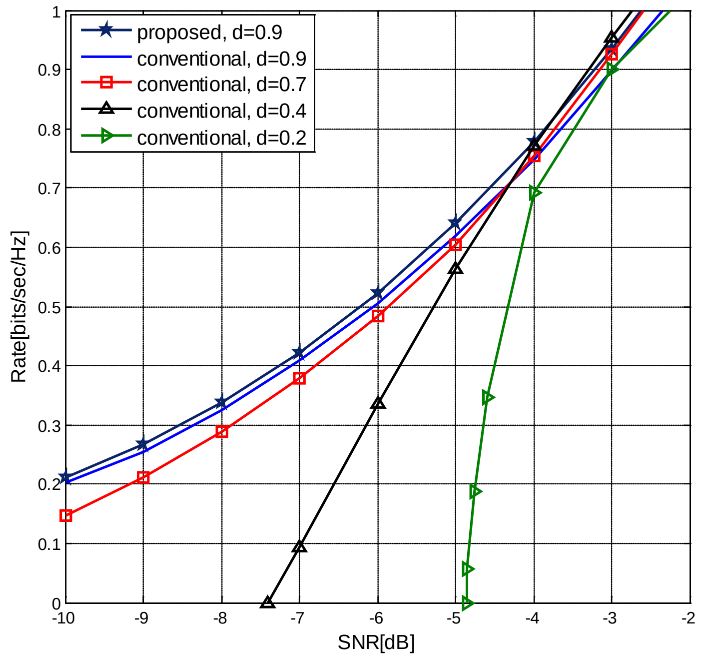

Fig. 7. Achievable rates of the conventional EF relaying strategy for different relay positions d in case that the reference system is BPSK-modulated direct communication, where the achievable rate of the proposed relaying scheme for $d = 0.9$ is also plotted.

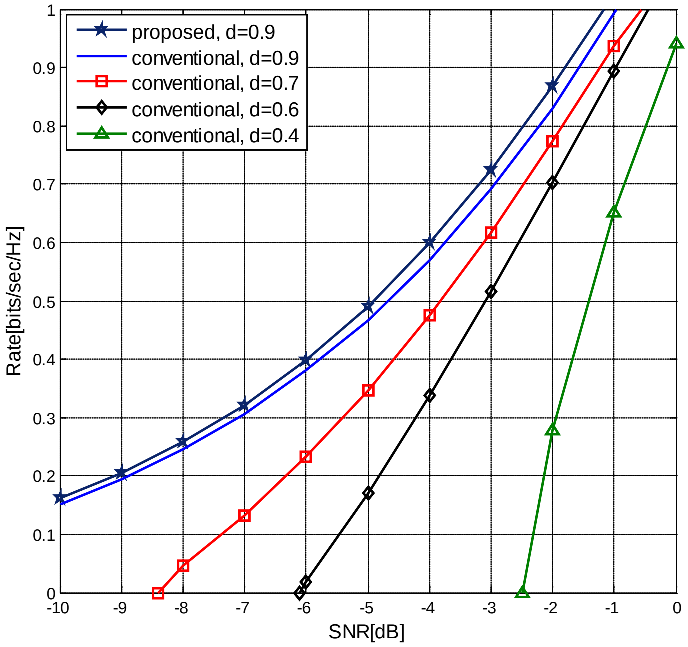

Fig. 8. Achievable rates of the conventional EF relaying strategy for different relay positions d in case that the reference system is QPSK-modulated direct communication, where the achievable rate of the proposed relaying scheme for $d = 0.9$ is also plotted.

The achievable rates evaluated by (13) with optimally chosen parameters for $d = 0.95$ are plotted in **Fig. 4** for the cases that the reference system is BPSK and QPSK modulated direct communications. The capacity of the reference system (direct link) and the upper bound on the achievable rate of relay channel are also plotted. For fair comparison, the same transmit bandwidth and energy are considered for all schemes. The upper bound on the achievable rate of relay channel corresponds to the capacity of 1×2 SIMO (single-input multiple-output) AWGN channel under the assumption that the RD channel is perfect and S remains silent in MAC mode. It is observed from **Fig. 4** that the achievable rate of the proposed scheme approaches the upper bound of the relay channel at low SNR especially when the reference system is BPSK-modulated direct communication. Achievable rates of the proposed relaying strategy for various relay positions are plotted in **Fig. 5** and **Fig. 6.** Achievable rates of the conventional EF relaying are also plotted for various relay positions in **Fig. 7** and **Fig. 8.** It is observed that the achievable rate of the proposed relaying strategy is insensitive to the relay position. On the other hand, the conventional EF relaying scheme shows high dependency on the relay position in terms of the achievable rate, and may not provide a reliable communication link when d is small, i.e., R is far from D. It is also observed that the proposed relaying strategy results in a higher rate than the conventional EF relaying scheme when d is not close to 1.

We plot the simulated bit error rate (BER) performances of the proposed relaying, conventional EF relaying and DF relaying strategies in **Fig. 9** - **Fig. 12**. In simulations, 16200-bit irregular low-density parity check (LDPC) codes [15][16] with 50 iterations of message passing decoding are used. For simulations associated with BPSK-modulated reference system, we use rate 1/3 irregular LDPC codes whose degree distribution polynomials are defined by $\lambda(x) = 0.4x + 0.2x^2 + 0.4x^{11}$ and $\rho(x) = x^4$. For simulations associated with QPSK-modulated reference system, we use rate 1/5 irregular LDPC codes whose degree distribution polynomials are defined by $\lambda(x) = 0.5333x + 0.1111x^2 + 0.3556x^{11}$ and $\rho(x) = 0.2x^2 + 0.8x^3$. Degree distribution polynomials of irregular LDPC codes are chosen to show sufficiently good BER performances over a direct link. In conventional EF relaying [12], no data loss over the RD channel is assumed, i.e., $z_2 = w_k$. Since there is, in fact, signal attenuation and additive noise over the RD channel, we first demodulate z_2 as $\hat{w}_k$, $k = 0, \cdots, L-1$, and compute $L(b_\ell \mid z_2)$ by modifying (10) as

$$L(b_\ell \mid z_2) = \log \frac{\sum_{j:x_j \in \chi_\ell^0} p(\hat{w}_k \mid x_j)}{\sum_{j:x_j \in \chi_\ell^1} p(\hat{w}_k \mid x_j)} \quad (19)$$

for MAC mode simulations of conventional EF relaying, where $\hat{w}_k$ is the demodulated symbol of z_2. When optimizing the conventional EF relaying scheme given by (3) and (4), a L-ary input AWGN channel capacity is used as R_{rd}. In DF relaying, V is decoded, re-encoded and mapped to M-ary symbols W at R, where the same channel codes are used at S and R, and the transmit power is allocated between S and R to achieve the maximum rate [1][3].

It is observed that the proposed relaying strategy achieves a BER performance gain over the reference system for all d values with satisfying bandwidth and energy constraints. The proposed relaying scheme shows good BER performances, irrespective of d, which is different from conventional EF relaying [12]. The performance of conventional EF relaying gets poorer as d decreases. It is also observed that DF relaying shows poorer BER performance than the proposed scheme for large and small d values, where the performance of DF relaying is highly dependent on d.

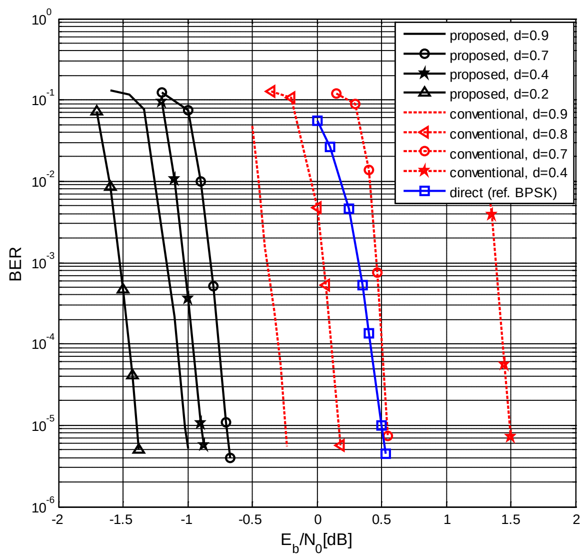

Fig. 9. BER performances of the proposed relaying and conventional EF relaying strategies, where the reference system is BPSK-modulated direct communication and the code rate is 1/3.

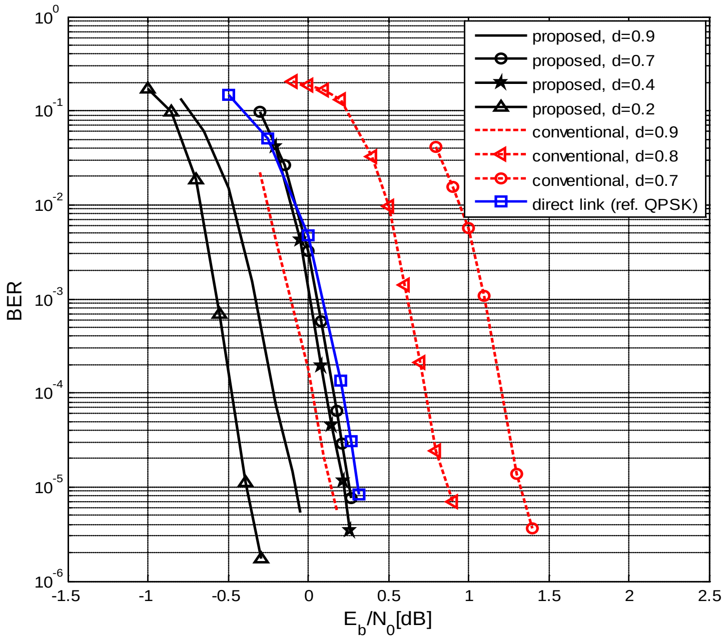

Fig. 10. BER performances of the proposed relaying and conventional EF relaying strategies, where the reference system is QPSK-modulated direct communication and the code rate is 1/5.

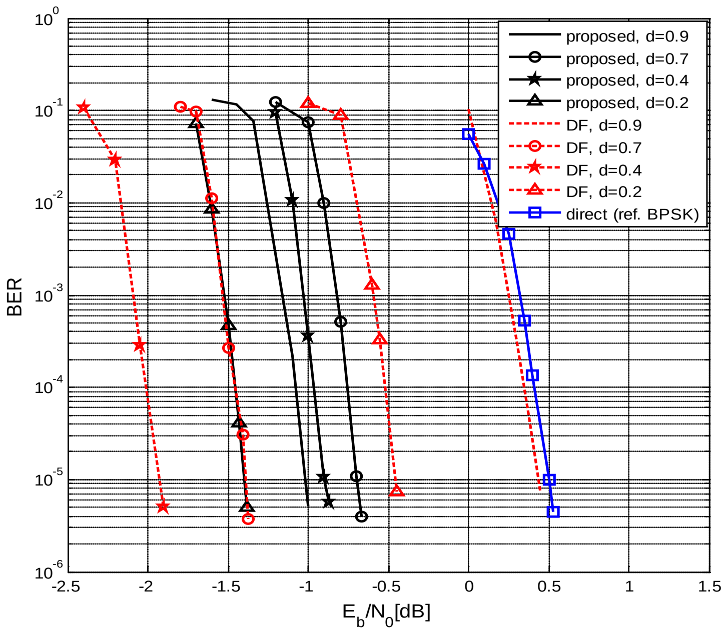

Fig. 11. BER performances of the proposed relaying and DF relaying strategies, where the reference system is BPSK-modulated direct communication and the code rate is 1/3.

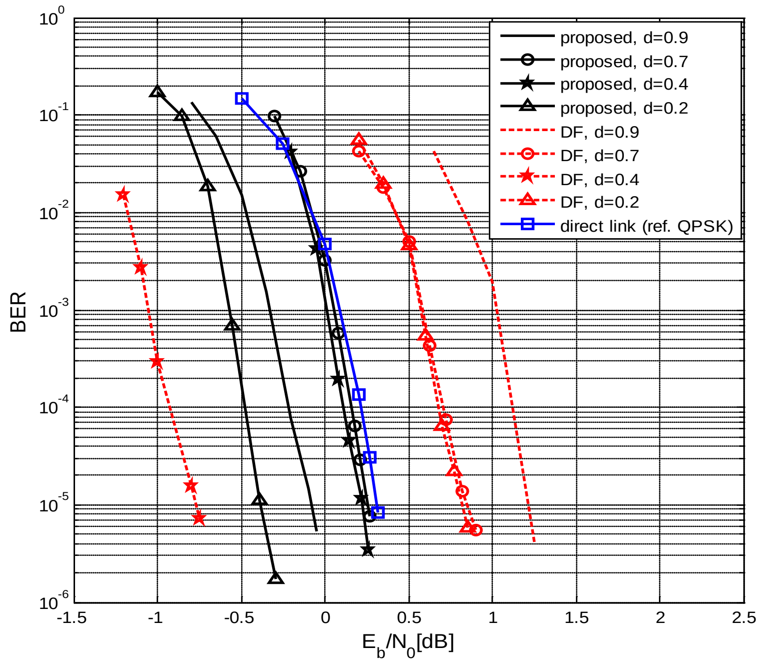

Fig. 12. BER performances of the proposed relaying and DF relaying strategies, where the reference system is QPSK-modulated direct communication and the code rate is 1/5.

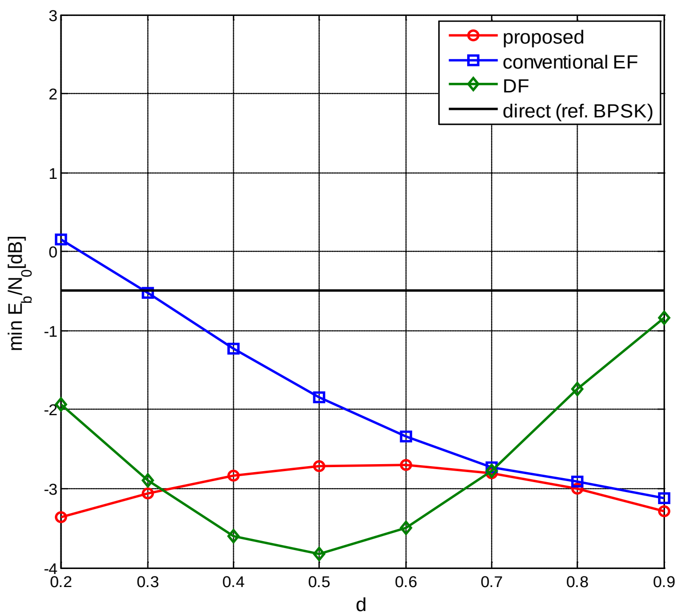

Fig. 13. Minimum values of E_b / N_0 required by the proposed relaying, conventional EF relaying and DF relaying strategies to achieve the rate 1/3 with various relay positions, where the reference system is BPSK-modulated direct communication.

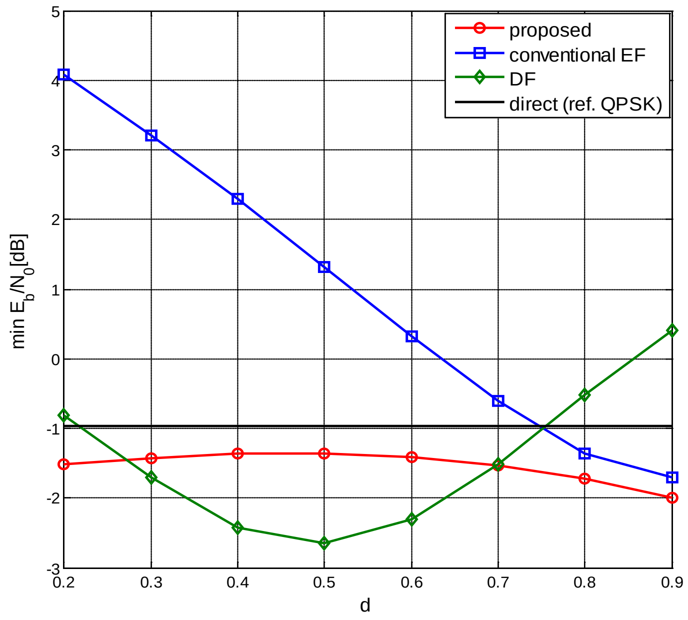

Fig. 14. Minimum values of E_b / N_0 required by the proposed relaying, conventional EF relaying and DF relaying strategies to achieve the rate 1/5 with various relay positions, where the reference system is QPSK-modulated direct communication.

In **Fig. 13** and **Fig. 14**, we plot the minimum values of E_b / N_0 required by the proposed relaying, conventional EF relaying and DF relaying strategies to achieve the target rate with various relay positions, where minimum E_b / N_0 required by direct communication is also plotted for comparison. For cases whose reference systems are BPSK and QPSK-modulated direct communications, the target rates are set as 1/3 and 1/5, respectively. Although the minimum E_b / N_0 is achieved by an infinite-length optimal coding scheme, this performance index provides enough insight on the BER performances of coded relaying schemes under comparison. The minimum E_b / N_0 requirement of the proposed relaying strategy is insensitive to the relay position, which differs from conventional EF relaying and DF relaying schemes. In case of conventional EF relaying, a higher value of minimum E_b / N_0 is required as d gets smaller. For great or small d , the proposed relaying strategy requires lower minimum E_b / N_0 than DF relaying.

Through various analyses, it is observed that the performance of the proposed relaying strategy is insensitive to the relay position. Consequently, the proposed relaying strategy is suitable for the relay system with mobility in which a relay position varies randomly.

5. Conclusion

We proposed a new time-division half-duplex EF relaying strategy resulting in reliable communication for all relay positions. We reconfigured EF relaying such that the channel between the relay and the destination is perfect, which is the basic requirement for EF relaying to achieve a high rate. From the reconfigured model, we manipulated equations associated with an achievable rate and found a systematic way to optimize an EF relaying strategy to maximize the achievable rate. The proposed EF relaying strategy enables reliable communication for all relay positions without bandwidth expansion and energy increase for transmission. Consequently, the proposed relaying scheme is suitable for a relay system with mobility.

References

[1] T. Cover and A. El Gamal, “Capacity theorems for the relay channel,” *IEEE Trans. Inf. Theory*, vol. 25, no. 5, pp. 572-584, Sept. 1979. Article (CrossRef Link)

[2] E. C. van der Meulen, “Three-terminal communication channels,” *Advanced Applied Probability*, vol. 3, pp. 120-154, 1971. Article (CrossRef Link)

[3] G. Kramer, M. Gastpar, and P. Gupta, “Cooperative strategies and capacity theorems for relay networks,” *IEEE Trans. Inf. Theory*, vol. 51, no. 9, pp. 3037-3063, Sept. 2005. Article (CrossRef Link)

[4] A. El Gamal, M. Mohseni, and S. Zahedi, “Bounds on capacity and minimum energy-per-bit for AWGN relay channels,” *IEEE Trans. Inf. Theory*, vol. 52, pp. 1545-1561, Apr. 2006. Article (CrossRef Link)

[5] M. Khojastepour, “Distributed cooperative communications in wireless networks,” Ph.D. thesis, 2004.

[6] C. Ng, N. Jindal, A. Goldsmith, and U. Mitra, “Capacity gain from two-transmitter and two-receiver cooperation,” *IEEE Trans. Inf. Theory*, vol. 53, pp. 3822-3827, Oct. 2007. Article (CrossRef Link)

[7] IEEE Std 802.16m-2011, IEEE standard for local and metropolitan area networks, Part 16: air interface for broadband wireless access systems, Amendment 3: advanced air interface. Article (CrossRef Link)

[8] IEEE Std 802.16j-2009, IEEE standard for local and metropolitan area networks, Part 16: air interface for broadband wireless access systems, Amendment 1: multihop relay specification. Article (CrossRef Link)

[9] L. Chen, Y. Huang, F. Xie, Y. Gao, L. Chu, H. He, Y. Li, F. Liang, and Y. Yuan, “Mobile relay in LTE-advanced systems,” *IEEE Commun. Mag*., vol. 51, no. 11, pp. 144-151, Nov. 2013. Article (CrossRef Link)

[10] H. Chang, M. Ku, K. Singh, J. Lin, “Low complexity amplify and forward mobile relay networks without source to relay CSI,” in *Proc. of IEEE VTC* Fall, Las Vegas, NV, Sept. 2013, pp. 1-5. Article (CrossRef Link)

[11] A. Host-Madsen and J. Zhang, “Capacity bounds and power allocation for wireless relay channels,” *IEEE Trans. Inf. Theory*, vol. 51, no. 6, pp. 2020-2040, June 2005. Article (CrossRef Link)

[12] A. Chakrabarti, A. Sabharwal, and B. Aazhang, “Practical quantizer design for half-duplex estimate and forward relaying,” *IEEE Trans. Commun.*, vol. 59, no. 1, pp.74-82, Jan. 2011. Article (CrossRef Link)

[13] D. Marco and D. L. Neuhoff, "Performance of low rate entropy constrained scalar quantizers,” in *Proc. of ISIT*, June 2004. Article (CrossRef Link)

[14] C. Berrou and A. Glavieux, “Near optimum error correction coding and decoding: turbo-codes,” *IEEE Trans. Commun.*, vol. 44, no. 10, pp. 1261-1271, Oct. 1996. Article (CrossRef Link)

[15] D. J. C. MacKay, “Good error correcting codes based on very sparse matrices,” *IEEE Trans. Inf. Theory*, vol. 45, no. 2, pp. 399-431, Mar. 1999. Article (CrossRef Link)

[16] T. Richardson, A. Shokrollahi, R. Urbanke, "Design of capacity-approaching irregular low-density parity-check codes," *IEEE Trans. Inf. Theory*, vol. 47, no. 2, pp. 619-637, Feb. 2001. Article (CrossRef Link)

Inho Hwang received B.S. and M.S. degrees in electrical engineering from Chung-Ang University, Seoul, Korea, in 2008 and 2010, respectively. He is currently pursuing Ph.D. degree at Chung-Ang University, Seoul, Korea. His research interests include cooperative communications and coding theory

.

Jeong Woo Lee is an associate professor in the School of Electrical and Electronics Engineering, Chung-Ang University, Seoul, Korea. He received B.S. and M.S. degrees from Seoul National University, Seoul, Korea in 1994 and 1996, respectively, and Ph.D. degree from the University of Illinois at Urbana-Champaign, IL, USA in 2003, all in electrical engineering. His current research interests include cooperative communications, mobile relay system and coding theory.