A Low-Complexity Practical Quantize-and-Forward Scheme for Two-hop Relay Systems

Duong T. Tran
School of Computer and Communication Sciences
École Polytechnique Fédérale de Lausanne
Lausanne 1015, Switzerland
Email: duong.tran@epfl.ch

Sumei Sun, Ernest Kurniawan
Modulation and Coding Department
Institute for Infocomm Research, A*STAR
1 Fusionopolis Way #21-01, Singapore 138632
Email: {sunsm,ekurniawan}@i2r.a-star.edu.sg

***Abstract*—We study a low-complexity practical quantize-and-forward (QF) scheme, a special case of the compress-and-forward (CF) transmission for half-duplex relay systems. By adjusting the number of quantization levels, we show that significant performance improvement can be achieved even though the relay node does not exploit any correlation information with the signal received at the destination. We demonstrate the performance of our scheme using 16QAM as the modulation and Turbo Code as the channel coding, and compare its performance against the decode-and-forward (DF) scheme. An approximately 2 dB gain is shown to be achievable at a target error rate of 10^{-4} in the scenario where the relay is close to destination.**

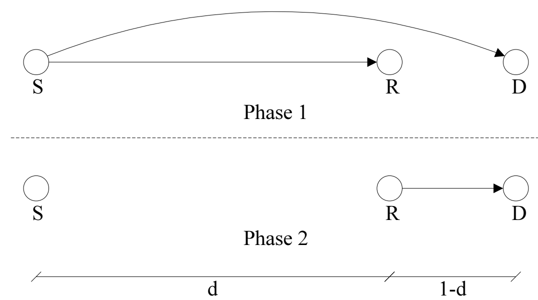

Fig. 1. The three-node relay channel

I. Introduction

Recently, relaying has been utilized as an efficient technique to provide cooperative diversity. The most fundamental model is the three-node cooperative relay channel which includes a source (S), a destination (D) and a relay (R). There are some foundation papers that focused on deriving the capacity bounds of three-node relay channel in full-duplex operating mode [1, 2]. Motivated by practical implementation, Madsen et. al. [3] studied half-duplex relaying and derived the capacity bounds when the relay node operates in a time-division manner. They proved the achievable rate for the two notable relay schemes: decode-and-forward (DF) and compress-and-forward (CF).

CF scheme is known to outperform DF scheme when the relay is close to the destination [3]. In this scenario, the S-R link is weak, the relay hence cannot decode the transmitted signal from the source efficiently. While the DF seems to be in vain, the relay node in CF scheme can forward some quantized/compressed knowledge of its received signal to the destination through the strong R-D link to enhance the decoding at the destination. In that way, CF does not suffer as much loss of information at the relay as DF.

The existing implementations of CF scheme can be divided into two categories, namely those which utilize the Wyner-Ziv coding [4] to quantize and compress the signal at the relay exploiting the correlation with the signal at the destination [5–7], and those which ignore this correlation to simplify the relay processing [8]. Our work will adopt the later approach and no side information from the destination is used to compress the estimate (quantized value) of the signal received at the relay $Y_{\mathrm{r}1}$. We show that as long as the estimation of $Y_{\mathrm{r}1}$ can be recovered reliably at the destination, the decoder of the quantize-and-forward (QF) scheme can significantly outperform the DF. Instead of a complicated Wyner-Ziv coding, the relay processing is therefore simplified to include only a low complexity quantizer, a source encoder and a channel encoder. No requirement for the correlation information between the received signals at the destination and the relay nodes has also eliminated the information exchange over the network, hence making the scheme more practically viable.

We demonstrate our proposed QF scheme using bandwidth-efficient 16QAM modulation (4 bits/2 dimensions) instead of BPSK modulation as in most of existing works, and apply the quantization on both in-phase (I) and quadrature (Q) components independently. Turbo Code is used as the channel code to get close to the theoretically achievable performance. Compared to other schemes such as the S $\rightarrow$ D direct transmission and the DF scheme with the same modulation and channel code, our QF scheme is shown to be superior in terms of the error rate performance.

The rest of the paper is organized as follows. Section II introduces the system model. Analysis of the achievable rate is described in Section III. The proposed scheme is presented in Section IV, and in Section V we give the details of the quantization and source coding process. The numerical results are given in Section VI, and finally, concluding remarks are drawn in Section VII.

II. The System Model

We consider a three-node relay channel operating in half-duplex mode as in Fig. 1. In our work, we divide the time equally between the two phases so the ratio of either phase 1 or

978-1-4673-0990-5/12/$31.00 ©2012 IEEE

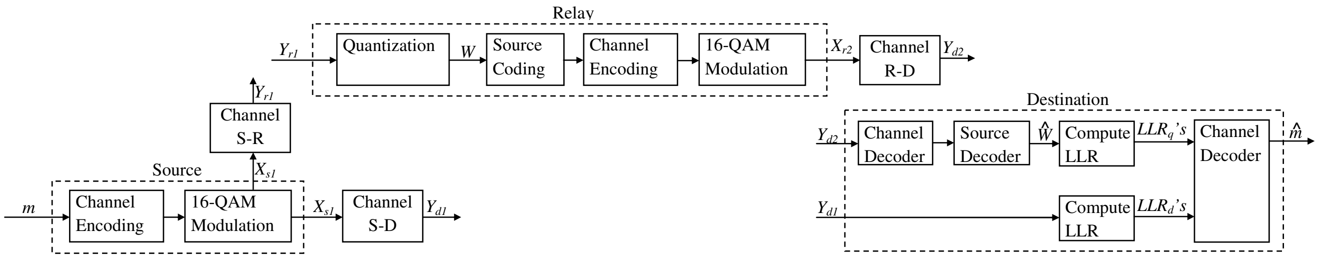

Fig. 2. System Block Diagram

2 duration to the entire transmission period is $\alpha = 1 - \alpha = \frac{1}{2}$. Fig. 2 illustrates the block diagram of our QF scheme. We will deal with the signal one by one similarly in term of each channel used, so we use the normal font (instead of bold font) to represent the signal. Denote X, Y, and N as the transmitted signal, received signal, and the noise respectively at any node, and use subscripts to represent the node and the phase index. For example X_{s1} represents the transmitted signal at the source in the first phase of time. In addition, suppose that the relay node is on the S-D line that the ratio of distances of S-R link and R-D link, to that of S-D link is d and $1-d$, respectively. Denote c_{sd}, c_{sr} and c_{rd} as the channel coefficient for the S-D, S-R, and R-D links, respectively.

In the first phase (the broadcast phase), the source transmits the signal to both the relay and the destination, whose received signals can be written as

$$Y_{\mathrm{r1}} = \sqrt{P_{\mathrm{s1}}} c_{\mathrm{sr}} X_{\mathrm{s1}} + N_{\mathrm{r1}}, \tag{1}$$
$$Y_{\mathrm{d1}} = \sqrt{P_{\mathrm{s1}}} c_{\mathrm{sd}} X_{\mathrm{s1}} + N_{\mathrm{d1}}, \tag{2}$$

where P_{s1} denotes the transmit power from S in Phase 1, and $\mathcal{E}\left\{|X_{\mathrm{s1}}|^2\right\} = 1$. Since Y_{r1} and Y_{d1} are two noisy versions of X_{s1}, they are correlated.

In the second phase, the relay will quantize and compress its received signal Y_{r1} into W, which will then be mapped into X_{r2}, the transmitted signal from the relay in phase 2. Assuming $\mathcal{E}\left\{|X_{\mathrm{r2}}|^2\right\} = 1$, and denoting the transmit power from R in phase 2 as P_{r2}, we have the signal received at the destination in this phase given as

$$Y_{\mathrm{d2}} = \sqrt{P_{\mathrm{r2}}} c_{\mathrm{rd}} X_{\mathrm{r2}} + N_{\mathrm{d2}}, \tag{3}$$

where we assume that only R transmits to D, while S remains idle.

The destination will decode Y_{d2} to get an estimation of compressed signal from the relay $\hat{W}$. After that, $\hat{W}$ and the side information Y_{d1} are combined to recover the original message. In our proposed scheme, we assume that the destination has the channel state information of the links between any two given nodes.

Assuming unit variance for the AWGN noise, and considering only large-scale fading, we will have the SNR of the three links written as

$$\begin{aligned} \gamma_{\mathrm{sd}} &= c_{\mathrm{sd}}^2 P_{\mathrm{s1}} = 1 \times P_{\mathrm{s1}}, && (4)\\ \gamma_{\mathrm{sr}} &= c_{\mathrm{sr}}^2 P_{\mathrm{s1}} = P_{\mathrm{s1}}/d^{\lambda}, && (5)\\ \gamma_{\mathrm{rd}} &= c_{\mathrm{rd}}^2 P_{\mathrm{r2}} = P_{\mathrm{r1}}/(1-d)^{\lambda}, && (6) \end{aligned}$$

where λ is the path loss exponent. In this paper, we set $\lambda = 3$.

III. The achievable rate

The proposed QF scheme is designed with the objective of maximizing the end-to-end achievable rate. Consider a scalar quantizer of length V for Y_{r1}, where $\nabla = \{r_0 = -\infty, r_1, r_2, \ldots. r_{V-1}, r_V = +\infty\}$ are the corresponding quantization thresholds for $Y_{\mathrm{r1}}/(\sqrt{P_{\mathrm{s1}}} c_{\mathrm{sr}})$. $W = \{w_0, w_1, \ldots, w_{V-1}\}$ are the symbols specifying the corresponding quantization intervals designed by ∇. According to [3, 8], the rate of CF scheme in a half-duplex channel mode is

$$R = \sup_{0 \le \alpha \le 1, \nabla} \alpha I(X_{\mathrm{s1}}; W, Y_{\mathrm{d1}}) + (1-\alpha) R_{\mathrm{sd2}}, \tag{7}$$

subject to:

$$\alpha I(Y_{\mathrm{r1}}; W | Y_{\mathrm{d1}}) \le (1-\alpha) R_{\mathrm{rd2}},$$
$$R_{\mathrm{rd2}} \le I(X_{\mathrm{r2}}; Y_{\mathrm{d2}} | X_{\mathrm{s2}}), R_{\mathrm{sd2}} \le I(X_{\mathrm{s2}}; Y_{\mathrm{d2}} | X_{\mathrm{r2}}),$$
$$R_{\mathrm{sd2}} + R_{\mathrm{rd2}} \le I(X_{\mathrm{s2}}, X_{\mathrm{r2}}; Y_{\mathrm{d2}}).$$

Here α is the time sharing factor between the two phases. In this paper, we consider equal time sharing, i.e., $\alpha = \frac{1}{2}$. As S is idle in Phase 2, we have $R_{\mathrm{sd2}} = 0$. In addition, no side information from Y_{d1} is exploited to quantize/compress Y_{r1}. Therefore, the overall rate in (7) is simplified into

$$R = \sup_{\nabla} \frac{1}{2} I(X_{\mathrm{s1}}; W, Y_{\mathrm{d1}}), \tag{8}$$

subject to

$$I(Y_{\mathrm{r1}}; W) \le R_{\mathrm{rd2}}, \tag{9}$$
$$R_{\mathrm{rd2}} \le I(X_{\mathrm{r2}}; Y_{\mathrm{d2}}). \tag{10}$$

Denoting n_b as the number of bits used to quantize the signal at the relay, we have $R_{\mathrm{rd2}} \le n_b$. It is apparent that the constraint in (10) is less stringent than that in (9) as R is positioned close to D . Therefore, the terms can be simplified

TABLE I
CONSTELLATION OF 16QAM

b_0b_1	I	b_2b_3	Q
00	-3	00	-3
01	-1	01	-1
11	1	11	1
10	3	10	3

as [8]

$$\max_{\nabla, I(Y_{\mathrm{r1}};W)\leq R_{\mathrm{rd2}}} I(X_{\mathrm{s1}};Y_{\mathrm{d1}},W) = \max_{\nabla, I(Y_{\mathrm{r1}};W)\leq n_b} I(X_{\mathrm{s1}};Y_{\mathrm{d1}},W)$$
$$= \max_{\nabla, I(Y_{\mathrm{r1}};W)\leq n_b} I(X_{\mathrm{s1}};Y_{\mathrm{d1}}) + I(X_{\mathrm{s1}};W|Y_{\mathrm{d1}}),$$

which can be reduced as to find

$$\max_{\nabla, I(Y_{\mathrm{r1}};W)\leq n_b} I(X_{\mathrm{s1}};W|Y_{\mathrm{d1}}) \approx \max_{\nabla, I(Y_{\mathrm{r1}};W)\leq n_b} I(X_{\mathrm{s1}};W). \tag{11}$$

We have

$$I(Y_{\mathrm{r1}};W) = H(W) - H(W|Y_{\mathrm{r1}}) = H(W),$$

with $H(W|Y_{\mathrm{r1}})$ being equal to 0 since W is a deterministic function of Y_{r1}. Then

$$\max_{\nabla, I(Y_{\mathrm{r1}};W)\leq n_b} I(X_{\mathrm{s1}};W) = \max_{\nabla, H(W)\leq n_b} I(X_{\mathrm{s1}};W)$$
$$= \max_{\nabla, H(W)\leq n_b} H(W) - H(W|X_{\mathrm{s1}}). \tag{12}$$

In general, getting the achievable rate is equivalent to finding the mutual information between the signal at the source and its quantized version at the relay. This criteria will be used to adjust the quantization thresholds ∇ later.

IV. THE RELAY AND DESTINATION PROCESSING

We consider 16QAM as the modulation format for X_{s1}, with the constellation mapping given in table I. A scaling factor $\frac{1}{\sqrt{10}}$ is applied to the signal so as to normalize the symbol energy into unity.

The information signal and its modulation at the source are given as follows

$$\mathbf{X}_m = \{s\} = \{x_1x_2\} = \{00, 01, 11, 10\},$$
$$\mathbf{X}_{\mathrm{s1}} = \{x_{\mathrm{s1}}\} = \{-3, -1, 1, 3\}/\sqrt{10},$$
$$\mathbf{P}_{X_m} = \begin{bmatrix} p_{00} & p_{01} & p_{11} & p_{10} \end{bmatrix} = \begin{bmatrix} \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \end{bmatrix}.$$

16QAM can be simply interpreted as two 4PAM modulation of the in-phase (I) and quadrature (Q) components. Therefore in the following we will just describe the processing based on the I component, while that for the the Q component is exactly the same.

A. Quantization Processing at the Relay

Without considering the side information from Y_{d1} for the quantization of Y_{r1}, the transition probability from X_{s1} to W is as follows

$$p(W=w|X_{\mathrm{s1}}=x_{\mathrm{s1}}) = \int_{\sqrt{P_{\mathrm{s1}}}c_{\mathrm{sr}}r_i}^{\sqrt{P_{\mathrm{s1}}}c_{\mathrm{sr}}r_{i+1}} p(y|X_{\mathrm{s1}}=x_{\mathrm{s1}})dy$$
$$= \frac{1}{\sqrt{2\pi}} \int_{\sqrt{P_{\mathrm{s1}}}c_{\mathrm{sr}}r_i}^{\sqrt{P_{\mathrm{s1}}}c_{\mathrm{sr}}r_{i+1}} (e^{\frac{-(y-\sqrt{P_{\mathrm{s1}}}c_{\mathrm{sr}}x_{\mathrm{s1}})^2}{2}})dy, \tag{13}$$

where (r_i, r_{i+1}) is the interval that w specifies. Note that X_m and X_{s1} can be written interchangeably. We have

$$p(W=w) = \sum_{x_1x_2} p(X_m = x_1x_2)p(W=w|X_m=x_1x_2)$$
$$= \frac{1}{4}(P(w|00) + P(w|01) + P(w|11) + P(w|10)). \tag{14}$$

The quantization thresholds are determined based on

$$\max_{\nabla, H(W)\leq n_b} I(X_{\mathrm{s1}};W) = \max_{\nabla, H(W)\leq n_b} H(W) - H(W|X_{\mathrm{s1}}), \tag{15}$$

with

$$H(W) = H(p(w_0), p(w_1), ...p(w_{V-1})), \tag{16}$$
$$H(W|X_{\mathrm{s1}}) = \sum_{x_{\mathrm{s1}}} P(X_{\mathrm{s1}}=x_{\mathrm{s1}})H(W|X_{\mathrm{s1}}=x_{\mathrm{s1}}), \tag{17}$$
$$H(W|X_{\mathrm{s1}}=x_{\mathrm{s1}}) = H(p(w_0|x_{\mathrm{s1}}), ...p(w_{V-1}|x_{\mathrm{s1}})). \tag{18}$$

W is then mapped into its binary representation using a lossless source encoder such as Huffman code. Once the source code has been applied to both I and Q components, channel encoder (Turbo Code) and 16QAM modulation is applied, before the signal is finally transmitted to the destination.

B. Decoder at the Destination

At the destination, after channel decoding and source decoding (Huffman decoding) to reconstruct $\hat{W}$, maximal ratio combining (MRC) is applied to Y_{d1} and $\hat{W}$ to recover the original information signal. The log-likelihood ratio (LLR) values that are used as input to the decoder at this step are calculated as follows

$$\mathrm{LLR} = \mathrm{LLR}_{\mathrm{d}} + \mathrm{LLR}_{\mathrm{q}},$$

with $\mathrm{LLR}_{\mathrm{d}}$ and $\mathrm{LLR}_{\mathrm{q}}$ as LLRs calculated from Y_{d1} and $\hat{W}$, respectively.

The calculation of $\mathrm{LLR}_{\mathrm{q}}$ is based on the intervals instead of the specified reconstruction levels. This will significantly improve the decoding performance, as demonstrated in our simulation results given in Section VI. We will describe in detail the $\mathrm{LLR}_{\mathrm{q}}$ calculation in the next section.

V. THE QF SCHEME WITH DIFFERENT NUMBER OF QUANTIZATION LEVELS

In this section, we investigate the number of quantization levels in the QF scheme. Three cases are considered, namely, the QF with four, eight, and ten quantization levels. The calculation of probabilities of Y_{r1} falling into each quantization intervals, the corresponding source coder implementation, and the associated LLR computation of $\mathrm{LLR}_{\mathrm{q}}$ are given in detail.

A. QF with 4 Quantization Levels

If we use 4 levels to quantize the received signal at the relay node, then a maximum of 2 bits (equal to the number of bits for 4PAM) are needed to represent Y_{r1}. With $\nabla = \{-\infty, -2, 0, 2, +\infty\}/\sqrt{10}$, this is equivalent to the demodulation of $Y_{\mathrm{r1}}/(\sqrt{P_{\mathrm{s1}}}c_{\mathrm{sr}})$. One might think in this case, QF must be worse than DF. However, lossless source coding can help reduce the total number of bits needed; more importantly, calculation of $\mathrm{LLR_q}$ at the destination based on the quantization intervals instead of the specified reconstruction levels will help improve the performance significantly. Denoting $W = \{w_0, w_1, w_2, w_3\}$ with the binary representation of {00,01,11,10}, we will derive the $\mathrm{LLR_q}$ computation in the following.

Transition probabilities: For the probability in equation (13), if $x_{\mathrm{s1}} = \frac{-3}{\sqrt{10}}$ and w specify the interval $(-\infty, \frac{-2}{\sqrt{10}})$, combining with (5), we have

$$\begin{aligned} &p(W = w_0|X_{\mathrm{s1}} = \frac{-3}{\sqrt{10}}) \\ &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\sqrt{\gamma_{\mathrm{sr}}}\frac{-2}{\sqrt{10}}} e^{\frac{-(y-\sqrt{\gamma_{\mathrm{sr}}}\frac{-3}{\sqrt{10}})^2}{2}} dy \\ &= 1 - Q(\sqrt{\frac{2}{10}\gamma_{\mathrm{sr}}}). \end{aligned} \tag{19}$$

Using the same method, we can calculate all the transition probabilities for X_{s1} and W. Note that in this QF, the thresholds are fixed, so H(W) and the overall rate are fixed.

$\mathrm{LLR_d}$: The $\mathrm{LLR_{d1}}$ and $\mathrm{LLR_{d2}}$ corresponding to two binary bits x_1 and x_2 can be obtained as

$$\mathrm{LLR_{d1}} = \log\frac{p(x_1 = 0|y_{\mathrm{d1}})}{p(x_1 = 1|y_{\mathrm{d1}})}; \mathrm{LLR_{d2}} = \log\frac{p(x_2 = 0|y_{\mathrm{d1}})}{p(x_2 = 1|y_{\mathrm{d1}})}, \tag{20}$$

which can be simplified to

$$\mathrm{LLR_{d1}} = \log\frac{e^{\frac{-(y_{\mathrm{d1}}-\sqrt{\gamma_{\mathrm{sd}}}\frac{-3}{\sqrt{10}})^2}{2}} + e^{\frac{-(y_{\mathrm{d1}}-\sqrt{\gamma_{\mathrm{sd}}}\frac{-1}{\sqrt{10}})^2}{2}}}{e^{\frac{-(y_{\mathrm{d1}}-\sqrt{\gamma_{\mathrm{sd}}}\frac{+1}{\sqrt{10}})^2}{2}} + e^{\frac{-(y_{\mathrm{d1}}-\sqrt{\gamma_{\mathrm{sd}}}\frac{+3}{\sqrt{10}})^2}{2}}}, \tag{21}$$

and

$$\mathrm{LLR_{d2}} = \log\frac{e^{\frac{-(y_{\mathrm{d1}}-\sqrt{\gamma_{\mathrm{sd}}}\frac{-3}{\sqrt{10}})^2}{2}} + e^{\frac{-(y_{\mathrm{d1}}-\sqrt{\gamma_{\mathrm{sd}}}\frac{+3}{\sqrt{10}})^2}{2}}}{e^{\frac{-(y_{\mathrm{d1}}-\sqrt{\gamma_{\mathrm{sd}}}\frac{-1}{\sqrt{10}})^2}{2}} + e^{\frac{-(y_{\mathrm{d1}}-\sqrt{\gamma_{\mathrm{sd}}}\frac{+1}{\sqrt{10}})^2}{2}}}, \tag{22}$$

by applying Bayes' rule.

$\mathrm{LLR_q}$:

$$\begin{aligned} \mathrm{LLR_{q1}} &= \log\frac{p(w|x_1 = 0)}{p(w|x_1 = 1)} \\ &= \log\frac{\int_{\sqrt{\gamma_{\mathrm{sr}}}r_i}^{\sqrt{\gamma_{\mathrm{sr}}}r_{i+1}} (p(y|s = 00) + p(y|s = 01))dy}{\int_{\sqrt{\gamma_{\mathrm{sr}}}r_i}^{\sqrt{\gamma_{\mathrm{sr}}}r_{i+1}} (p(y|s = 10) + p(y|s = 11))dy}, \end{aligned} \tag{23}$$

$$\begin{aligned} \mathrm{LLR_{q2}} &= \log\frac{p(w|x_2 = 0)}{p(w|x_2 = 1)} \\ &= \log\frac{\int_{\sqrt{\gamma_{\mathrm{sr}}}r_i}^{\sqrt{\gamma_{\mathrm{sr}}}r_{i+1}} (p(y|s = 00) + p(y|s = 10))dy}{\int_{\sqrt{\gamma_{\mathrm{sr}}}r_i}^{\sqrt{\gamma_{\mathrm{sr}}}r_{i+1}} (p(y|s = 01) + p(y|s = 11)dy}, \end{aligned} \tag{24}$$

where (r_i, r_{i+1}) is the interval that w specifies. For each possible w recovered, we can use the Q-function to calculate the $\mathrm{LLR_q}$'s above in the same way as in (19). For example, if w specify the interval $(-\infty, \frac{-2}{\sqrt{10}})$, we would have

$$\log\frac{p(w|x_1 = 0)}{p(w|x_1 = 1)} = \log\frac{1}{Q(3\sqrt{\frac{2}{10}\gamma_{\mathrm{sr}}}) + Q(5\sqrt{\frac{2}{10}\gamma_{\mathrm{sr}}})}. \tag{25}$$

Following the same approach, we can have the LLRs for all the quantization intervals.

B. QF with 8 Quantization Levels

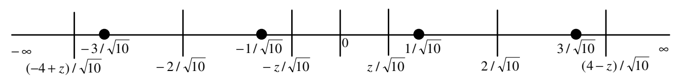

Fig. 3. 8 quantization intervals

At the relay, if we use 8 intervals to quantize Y_{r1}, the 9 quantization thresholds for $Y_{\mathrm{r1}}/(\sqrt{P_{\mathrm{s1}}}c_{\mathrm{sr}})$ will be $\{-\infty, -4+z, -2, -z, 0, z, 2, 4-z, +\infty\}/\sqrt{10}$, as illlustrated in Fig. 3, where $0 < z < 2$. For simplicity, we keep $\{-\infty, -2, 0, 2, +\infty\}/\sqrt{10}$ and insert the additional thresholds in-between these values. We need to point out that this choice of quantization threshold is simple yet suboptimal in general.

Because z can be varied between (0,2), the distributions of intervals are not the same. Therefore, we use source encoding such as Huffman code to encode the intervals **W**

$$W = \{w_0, w_1, w_2, w_3, w_4, w_5, w_6, w_7\}$$

Using the same process as in the case of 4 quantization levels, we can calculate all the transition probabilities and LLRs. Here $n_b = \log_2 8 = 3$. By adjusting z, we can maximize the overall rate as

$$\begin{aligned} &\max_{\nabla, H(W)\le n_b} I(X_{\mathrm{s1}}; W) = \max_{z, H(W)\le n_b} H(W) - H(W|X_{\mathrm{s1}}) \\ &= H(p(w_0), p(w_1), ...p(w_7)) \\ &- \frac{1}{4}(H(p(w_0|00), p(w_1|00), ...p(w_7|00)) \\ &- \frac{1}{4}(H(p(w_0|01), p(w_1|01), ...p(w_7|01)) \\ &- \frac{1}{4}(H(p(w_0|11), p(w_1|11), ...p(w_7|11)) \\ &- \frac{1}{4}(H(p(w_0|10), p(w_1|10), ...p(w_7|10)). \end{aligned} \tag{26}$$

For example, if we use $\gamma_{\mathrm{sr}} = 3$dB, realization of $H(W)$ and $I(X_{\mathrm{s1}}; W)$ are shown in Fig. 4. After getting the optimal z, we calculate $\mathrm{LLR_q}$ the same way as in the case of 4 quantization levels above.

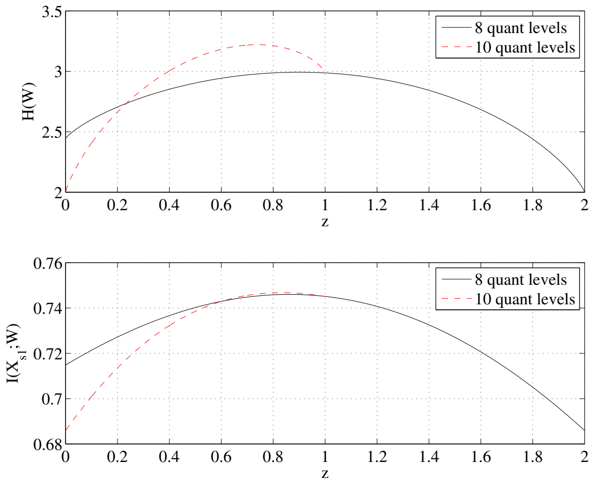

Fig. 4. Behavior of $H(W)$ and $I(X_{\rm s1}; W)$ when $\gamma_{\rm sr}$ = $3dB$

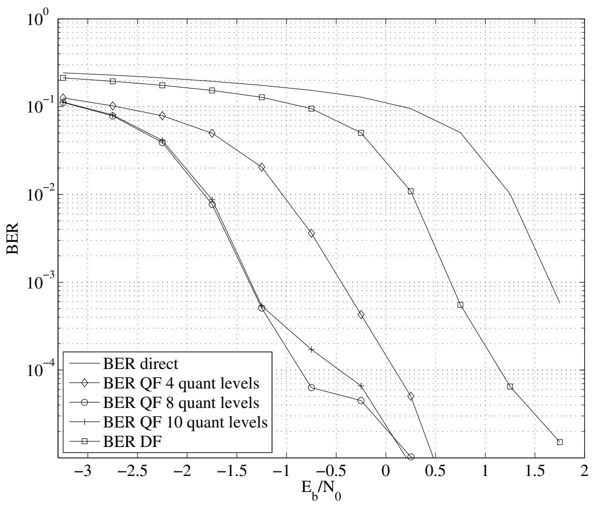

Fig. 5. BERs for AWGN with $\gamma_{\rm sr} = \gamma_{\rm sd} + 1dB$ and $\gamma_{\rm rd} = \gamma_{\rm sd} + 13dB$.

C. QF with 10 Quantization Levels

The process is identical to the case of 8 quantization levels. The 11 thresholds for $Y_{\rm r1}/(\sqrt{P_{\rm s1}}c_{\rm sr})$ are $\{-\infty, -2-z, -2, -2+z, -z, 0, z, 2-z, 2, 2+z, +\infty\}/\sqrt{10}$ with $0 < z < 1$. Here $n_b = \log_2 10$. The behavior of $H(W)$ and $I(X_{\rm s1}; W)$ are shown in Fig. 4.

VI. Numerical Results

We present the performance of the proposed QF schemes by comparing the the Bit Error Rate (BER) vs E_b/N_0 performance with direct transmission and the DF scheme. We focus on the scenarios when the relay is close to the destination, such that $\gamma_{\rm sd}$ is only slightly smaller than $\gamma_{\rm sr}$, but much smaller than $\gamma_{\rm rd}$.

We employ Turbo Code comprising of two parallel identical recursive systematic convolutional encoder separated by an interleaver with overall code rate of $\frac{1}{3}$. The BERs vs. E_b/N_0 of different schemes are shown in Fig. 5 when $\gamma_{\rm sr} = \gamma_{\rm sd} + 1dB$ and $\gamma_{\rm rd} = \gamma_{\rm sd} + 13dB$.

From the figure, we can clearly see that the DF cannot perform as well as the proposed QF scheme. This is because DF considered here decodes the signal at the relay and then channel encodes the decoded sequence again and transmits to the destination. Due to the poor $\rm S \rightarrow D$ link, DF loses information by decoding the signal at the relay, such that we cannot get the 3dB gain at the destination even though MRC combining is performed on $Y_{\rm d1}$ and $Y_{\rm d2}$. With QF, as we do not decode at the relay, the signal does not suffer from the loss of hard decision. Furthermore, the $\rm LLR_q$'s are calculated using the entire quantization intervals, hence can help improve the performance.

From the figure, we can also observe that QF with 10 quantization levels has about the same performance as that with 8 levels, and they are both much better than the 4 level-case. We can predict the trend that by using more quantization levels, we can obtain better performance. However, this is achieved at the cost of higher computational complexity and slightly higher number of channel uses in the second phase.

VII. Conclusion

In this paper, a practical quantize-and-forward half-duplex relay scheme has been proposed. In this QF scheme, the received signal at the relay is quantized without considering the side information at the destination, hence a lower complexity is incurred than the Wyner-Ziv-aspired compress-and-forward schemes. The log-likelihood ratio calculation at the destination has taken into account the whole quantization intervals, hence leads to significant performance improvement. Simulation results demonstrated superior performance over the decode-and-forward and direct transmission schemes when the relay is close to the destination. At a later time, we will compare this method with the amplify-and-forward and other existing relay schemes. For a more pragmatic realization, we will also consider applying the scheme to fading channel and/or using higher level of modulation other than 16QAM as a future work.

References

[1] T. M. Cover and A. A. El Gamal, "Capacity theorems for the relay channel," *IEEE Trans. Inf. Theory*, vol. 25, pp. 572-584, Sep. 1979.

[2] G. Kramer, M. Gastpar, and P. Gupta, "Cooperative Strategies and Capacity Theorems for Relay Networks," *IEEE Trans. Inf. Theory*, vol. 51, pp. 3037-3063 , Sep. 2005.

[3] A. Host-Madsen and J. Zhang, "Capacity bounds and power allocation for wireless relay channels," *IEEE Trans. Inf. Theory*, vol. 51, pp. 2020-2040, June 2005.

[4] A. Wyner and J. Ziv, "The rate-distortion function for source coding with side information at the decoder," *IEEE Trans. Inf. Theory*, vol. 22, pp. 1-10, Jan. 1976.

[5] M. Uppal, Z. Liu, V. Stankovic, and Z. Xiong, "Compress-forward coding with BPSK modulation for the half-duplex Gaussian relay channel," *IEEE Trans. Signal Process*, vol. 57, pp. 4467-4481, Nov. 2009.

[6] R. Blasco-Serrano, R. Thobaben, and M. Skoglund, "Compress-and-forward relaying based on symbol-wise joint source-channel coding," *IEEE Int. Conf. on Communications*, June 2010.

[7] Y. Qi, R. Hoshyar, and R. Tafazolli, "A Novel Quantization Scheme in Compress-and-Forward Relay System," *IEEE Vehicular Tech. Conf. Spring 2009*, Apr. 2009.

[8] A. Chakrabarti, A. de Baynast, A. Sabharwal, and B. Aazhang, "Practical Quantizer Design for Half-Duplex Estimate-and-Forward Relaying," *IEEE Trans. on Communications*, Vol.59, pp. 74-83, Jan. 2011.