A Soft Information Delivery Scheme in Two-Way Relay Channels with Network Coding

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Abstract—**In this paper, we propose a practical 1-bit soft forwarding protocol for a network-coded two-way relay channel. Different from the conventional estimate-and-forward (EF) protocol, the proposed protocol forwards 1-bit soft information at the relay. We employ the joint trellis coded quantization/modulation (TCQ/M) to implement 1-bit transmission of the soft information. Also, the codebooks in the TCQ are designed to be adaptive to the source-to-relay channel conditions so that the system can achieve the full diversity gain over fading channels. Specifically, in the low source-to-relay channel SNR region, we apply the TCQ/M to the soft information based on the codebook generated by the Lloyd-Max quantizer. In the high source-to-relay channel SNR region, where the soft information is equivalent to its hard decision, we design the codebook by repeating the soft information. It has been shown that the proposed protocol outperforms both the amplify-and-forward (AF) and the decode-and-forward (DF) protocols over fading channels.**

I. INTRODUCTION

The recent emerging relay strategies have been shown significant advantages for most future wireless applications. Two of these relay strategies are the amplify-and-forward (AF) protocol [1] and the decode-and-forward (DF) protocol [2], which have been widely studied in the literature. In the AF protocol, the relay amplifies the incoming signal and forwards it to the destination, which suffers from the noise amplification at the relay. In the DF protocol, the relay decodes the received signal, re-encodes it and then forwards it to the destination. The drawback of the DF protocol is that it propagates the erroneous decisions to the destination. To solve these problems, soft information forwarding (SIF) [3] has been raised. One of the SIF based protocol is called estimate-and-forward (EF) [4]. It has been shown in [4] that the EF protocol outperforms the AF and DF protocols in the one-way relay channels. Recently, two-way relay channels (TWRC) have become increasingly appealing to both academia and industry. That is mainly because the network coding can be employed to achieve higher spectral efficiency. Quite a few relay strategies have been proposed in the TWRC, e.g., [5], [6].

In particular, the soft network coding protocol proposed for the TWRC in [5] has attracted a lot of attention. However, it was assumed in [5] that the relay-to-source channels have limitless bandwidth. Thus, the soft information can be transmitted to each source from the relay without quantization. In practice, due to the finite channel bandwidth, we need to quantize the soft information before transmission. However, even if we quantize the soft information into a limited number of bits, it still has a much lower spectrum efficiency than the DF protocol. Therefore, 1-bit soft forwarding is an attractive approach to achieving better performance than the DF with the same bandwidth. One of the quantization scheme that can realize 1-bit quantization with a good performance is the joint trellis coded quantization/modulation (TCQ/M) [7]–[10], because the quantization noise can be reduced without rate increase if a structured codebook with an expanded set of quantization levels is used. Although any modulation scheme can be used in conjunction with the TCQ, it is shown that a joint TCQ/M system ensures that the squared distance between the channel sequences is commensurate with the squared error in the quantization [8], [9].

In this work, we are interested in designing a practical 1-bit soft forwarding protocol based on the joint TCQ/M in the TWRC over fading. Also, we design adaptive codebooks in the TCQ based on different source-to-relay channel conditions. This is because the probability distribution of the soft information varies with different signal-to-noise ratio (SNR) values of the source-to-relay channels. Specifically, the probability density function (PDF) of the soft information presents approximately a Gaussian distribution in the low channel SNR region. On the other hand, the values of the soft information are equivalent to hard decisions in the high channel SNR region. This work applies the TCQ/M to the soft information by using codebooks generated from the Lloyd-Max quantizer in the low channel SNR region, which we define as the EF with TCQ scheme throughout the paper. In the high channel SNR region, where the soft information is equivalent to its hard decision, the codebook is designed by repeating the soft information, and the scheme is defined as the EF with TCQ codewords repeat scheme. It is shown in the simulation that the proposed protocol outperforms both the AF and the DF protocols over the fading channels. It also closely approximates the performance of the conventional EF protocol where the soft information is assumed to be transmitted without quantization.

II. SYSTEM MODEL

As shown in Fig. 1, in the TWRC, the two sources transmit or receive information at different time slots. At the first time slot, S_1 transmits its own signals to both the relay and S_2. At the second time slot, S_2 transmits its own signals to both the relay and S_1. The received signal at the relay from each source and the received signal from the direct link can be respectively

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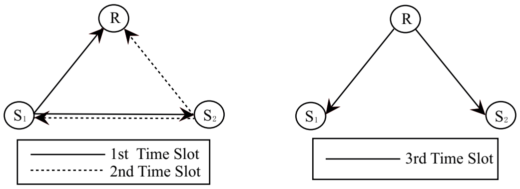

Fig. 1. a two-way relay network.

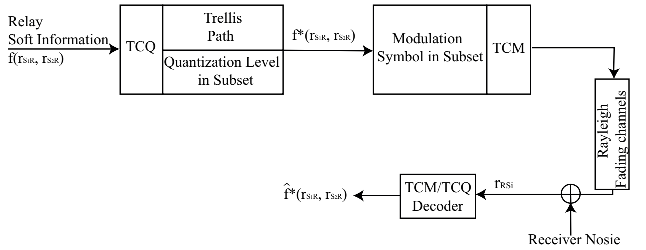

Fig. 2. joint TCQ/M system.

calculated by

$$\begin{aligned} r_{S_iR} &= \sqrt{E_S}h_{S_iR}x_{S_i} + n_{S_iR}, \\ r_{S_iS_j} &= \sqrt{E_S}h_{S_iS_j}x_{S_i} + n_{S_iS_j}, \end{aligned} \tag{1}$$

where x_{S_i} represents signals transmitted from either of the two sources S_i, binary phase shift keying (BPSK) modulated, E_S is defined as the transmission power at both sources, $h_{S_iS_j}$ and h_{S_iR} represent the channel coefficient between two sources, and the channel coefficient between each source S_i and the relay, respectively. $n_{S_iS_j}$ and n_{S_iR} are the noise sample at the source and the relay, which are both defined as Gaussian distributed with zero mean value and variance σ^2. r_{S_iR} and $r_{S_iS_j}$ represent the signal received at the relay and the other source from one source, respectively. As for the SNR of the source-to-relay channel, it can be defined by $\rho_{S_iR} \triangleq h^2_{S_iR}E_S/\sigma^2$.

At the third time slot, the relay processes the received signals and then broadcasts the processed signal to both S_1 and S_2. In this stage, we apply the TCQ to the soft network coded symbols defined in [5]. At first, the network coded symbol is defined as $x_R \triangleq x_{S_1}x_{S_2}$. Afterwards, the minimum mean squared error (MMSE) estimation of x_R is calculated, namely the conditional expectation of $x_{S_1}x_{S_2}$ based on r_{S_1R} and r_{S_2R}: $\mathrm{E}\left(x_{S_1}x_{S_2}|r_{S_1R}, r_{S_2R}\right)$. Due to the independence of the received r_{S_1R} and r_{S_2R}, the MMSE estimation at the relay is given by

$$\begin{aligned} \mathrm{E}\left(x_{S_1}x_{S_2}|r_{S_1R}, r_{S_2R}\right) &= \mathrm{E}\left(x_{S_1}|r_{S_1R}\right)\mathrm{E}\left(x_{S_2}|r_{S_2R}\right) \\ &= \tanh\left(\frac{LLR_{x_{S_1,R}}}{2}\right)\tanh\left(\frac{LLR_{x_{S_2,R}}}{2}\right), \end{aligned} \tag{2}$$

where $LLR_{x_{S_i},R}$ represents the log-likelihood ratio (LLR) of r_{S_iR} at the relay, which is calculated as $LLR_{x_{S_i},R} = \ln\frac{p\left(x_{S_i}=1|h_{S_iR}, r_{S_iR}\right)}{p\left(x_{S_i}=-1|h_{S_iR}, r_{S_iR}\right)} = \frac{2\sqrt{E_S}h_{S_iR}r_{S_iR}}{\sigma^2}$. $f(r_{S_1R}, r_{S_2R})$ is defined as

$$\begin{aligned} &f(r_{S_1R}, r_{S_2R}) \\ &= \frac{\tanh\left(\frac{LLR_{x_{S_1,R}}}{2}\right)\tanh\left(\frac{LLR_{x_{S_2,R}}}{2}\right)}{\sqrt{\mathrm{E}\left[\left|\tanh\left(\frac{LLR_{x_{S_1,R}}}{2}\right)\tanh\left(\frac{LLR_{x_{S_2,R}}}{2}\right)\right|^2\right]}}, \end{aligned} \tag{3}$$

which is power-normalized relay function in the EF protocol.

We use the TCQ to implement the quantization of the power-normalized relay function, namely $f(r_{S_1R}, r_{S_2R})$, and denote $f^*(r_{S_1R}, r_{S_2R})$ as the quantized relay function. A joint TCQ/M system follows after the power-normalized relay function is calculated, as shown in Fig. 2. For the TCQ/M at rate 1, quadrature phase-shift keying (QPSK) is employed as the modulation technique. Then the signal received by each source from the relay can be given by $r_{RS_i} = \sqrt{E_R}h_{RS_i}f^*(r_{S_1R}, r_{S_2R}) + n_{RS_i}$. h_{RS_i} represents the channel coefficient between the relay and the source, which is modeled as an independent zero mean Gaussian random variable with unit variance. n_{RS_i} is the noise sample at each source, which is the complex additive white Gaussian noise (AWGN) sample with per-dimension mean value zero and variance $\sigma^2/2$. As shown in Fig. 2, the received quantized signal at the output of the TCQ/M decoder is denoted by

$$\hat{f}^*(r_{S_1R}, r_{S_2R}) = f(r_{S_1R}, r_{S_2R}) + n_{equiv\_RS_i}, \tag{4}$$

where $\hat{f}^*(r_{S_1R}, r_{S_2R})$ denotes the received quantized signal, and $n_{equiv\_RS_i}$ is regarded as the quantization noise.

In the joint TCQ/M system, the encoding rate for the TCQ and the transmission rate for the TCM are the same. They both use the identical trellis to ensure the consistent labeling in the trellis diagram, which can guarantee that likely channel error events will only lead to small additional TCQ distortion [8]. The TCQ and the TCM both use the Viterbi algorithm, which is used to find the appropriate sequence path of quantization levels or modulation symbols which has the shortest Euclidean distance to the corresponding input. Consider two sequences of length m: the input sequence of the source encoder $\mathbf{x}$, and the corresponding output sequence $\hat{\mathbf{x}}$, the Euclidean distance between the two sequences is given by

$$\mathrm{d}\left(\mathbf{x}, \hat{\mathbf{x}}\right) = \sqrt{\sum_{i=1}^{m}\left(x_i - \hat{x}_i\right)^2}, \tag{5}$$

and the Viterbi algorithm is used to find the output sequence which minimizes $\mathrm{d}\left(\mathbf{x}, \hat{\mathbf{x}}\right)$. Equivalently it can be viewed as minimizing the mean squared error (MSE) of the two sequences, namely $\rho_m\left(\mathbf{x}, \hat{\mathbf{x}}\right) = \mathrm{d}^2\left(\mathbf{x}, \hat{\mathbf{x}}\right)/m$; thus, the variance of $n_{equiv\_RS_i}$ in (4) can be expressed as $\rho_m\left(f\left(r_{S_1R}, r_{S_2R}\right), \hat{f}^*\left(r_{S_1R}, r_{S_2R}\right)\right)$.

The TCQ/M system functions as follows. At an encoding rate R, for each incoming sample, the TCQ maps it into one of the 2^{R+1} reproduction levels (codewords), defined by a finite length of alphabets regarded as the codebook. This codebook is partitioned into 4 subsets, used as labels on a trellis with

2 branches entering and leaving each trellis state. Usually the TCQ uses a rate $R/(R+1)$ convolutional encoder to define the structure of the trellis, and the Viterbi algorithm is used to search all possible paths in the trellis and select the minimum distortion path. It takes 1 bit to specify the sequence of the trellis branches and $(R-1)$ bits to specify the corresponding codewords in each subset. Combined with the TCM, the single bit used in the TCQ is then taken as the input to the TCM convolutional encoder, and the rest $(R-1)$ bits are used to specify the modulation symbol in the TCM subset. Fig. 2 shows the joint TCQ/M system, as the TCQ generates a sequence consisting of the 2^{R+1} reproduction levels from the defined codebook. These levels are mapped to the symbols made up of the 2^{R+1}-point TCM alphabets [7]–[9].

At the receiver, the decoding is accomplished by first using the Viterbi algorithm to find the path which has the MMSE to the received signals, and then mapping the selected path back into the TCQ levels. The received quantized signal $\hat{f}^*(r_{S_1R}, r_{S_2R})$ at S_i from the relay is multiplied with x_{S_i} to cancel the source's own signal, which is then combined with $r_{S_jS_i}$ to make a hard decision on x_{S_j}.

III. SOFT INFORMATION QUANTIZATION

In order to compete with the DF protocol whose transmission rate is 1 at the relay, we utilize the TCQ at rate 1 to implement the quantization. We assume that channels between all terminals experience independent slow Rayleigh fading. In other words, channel coefficients keep constant during an m-symbol block but change independently to the next block. Due to the slow fading, it is possible for receivers to accurately estimate the channel-state-information (CSI) at all receivers. Besides, the codebook for the TCQ should be synchronized at both the relay and receivers. This can be achieved by presetting different codebooks for the TCQ according to different source-to-relay channel SNRs. The source-to-relay CSI is known to the relay, and the destination also knows the source-to-relay CSI; thus, the synchronization can be achieved.

In this work, we employ the Lloyd-Max quantizer [11], [12] to determine the codebook for each block in the TCQ when the source-to-relay channel SNR is low. Similar systems can be established based on other quantization methods, such as the equiprobable output quantizer [13]. The Lloyd-Max quantizer can be an insight for other methods. For a quantizer with Q reproduction levels, the Lloyd algorithm is applied to minimize the mean squared error distortion, which is given by

$$D_Q = \mathrm{E}\left\{\left(f(r_{S_1R}, r_{S_2R}) - f^*(r_{S_1R}, r_{S_2R})\right)^2\right\} = \sum_{i=1}^{Q} \int_{b_i}^{b_{i+1}} (l - c_i)^2 p(l) dl, \quad (6)$$

where b_i denotes the decision boundary, c_i represents the ith reproduction level, and $p(l)$ is the PDF of the signal that shall be quantized. The optimization can be solved iteratively by employing the Lloyd algorithm. In each iteration, the optimized decision boundary lies in the middle of two successive reproduction levels, i.e. $b_i = \frac{c_{i-1}+c_i}{2}$; the reproduction level is optimized by the centroid of the decision intervals, i.e. $c_i = \frac{\int_{b_i}^{b_{i+1}} lp(l)dl}{\int_{b_i}^{b_{i+1}} p(l)dl}$. For the network coded soft information $\mathrm{E}\left(x_{S_1}x_{S_2}|r_{S_1R}, r_{S_2R}\right)$ defined in (2), its PDF is given by

$$p_{\mathrm{E}\left(x_{S_1}x_{S_2}|r_{S_1R},r_{S_2R}\right)}(z) = \int \frac{1}{|y|} p_{\mathrm{E}\left(x_{S_2}|r_{S_2R}\right)}(y)\, p_{\mathrm{E}\left(x_{S_1}|r_{S_1R}\right)}\left(\frac{z}{y}\right) dy, \quad (7)$$

in which, the PDF of $\mathrm{E}\left(x_{S_i}|r_{S_iR}\right)$ can be expressed as

$$p_{\mathrm{E}\left(x_{S_i}|r_{S_iR}\right)}(t) = \frac{1}{2}\Big[p_{\mathrm{E}\left(x_{S_i}|r_{S_iR}\right)|x_{S_i}}(t|x=1) + p_{\mathrm{E}\left(x_{S_i}|r_{S_iR}\right)|x_{S_i}}(t|x=-1)\Big]. \quad (8)$$

As the BPSK modulation is applied in the source-to-relay channel and the additive Gaussian white noise (AWGN) is considered at the relay, the conditional PDF of $\mathrm{E}\left(x_{S_i}|r_{S_iR}\right)$ based on x_{S_i} in (8) is calculated as

$$p_{\mathrm{E}\left(x_{S_i}|r_{S_iR}\right)|x_{S_i}}(t|x) = \frac{\sigma^2}{h_{S_iR}(1-t^2)} \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{-\frac{1}{2\sigma^2}\left[\frac{\sigma^2}{2h_{S_iR}}\ln\left(\frac{1+t}{1-t}\right) - h_{S_iR}x\right]^2\right\}. \quad (9)$$

According to (7), (8) and (9), the reproduction levels are evaluated by numerical integration in the simulation. When the source-to-relay channel SNR is high, however, the use of the codebook generated by the Lloyd algorithm may lead to erroneous mapping in the trellis diagram. The reason is explained as follows. Based on the analysis of (3), there may still exist very few small numbers in large blocks, even though the relay function $f(r_{S_1R}, r_{S_2R})$ approaches 1 or -1. This is due to the occasional big noise at the receiver and random fading channel. By employing the Lloyd algorithm, such small numbers will appear in the codebook. As long as the structure of the convolutional encoder is set—the branch labeling in the trellis is set—such codebooks and the mapping principle given in (5) may map 1 or -1 into the small numbers, which decreases the reliability of the real values.

As the bad performance of the TCQ results from the unreasonable selection of the codebook when the source-to-relay channel SNR is high, we may refine the codebook in order to prevent mapping errors from occurring under the high channel SNR region. Motivated by (5), instead of selecting the path which minimizes the MSE between the two m-symbol sequences, we decide to minimize the MSE between each symbol and the corresponding reproduction level. This process can be treated as minimizing the following equation

$$\mathrm{d}(\mathbf{x}, \hat{\mathbf{x}}) = \sum_{i=1}^{m} \mathrm{d}_i(x_i, \hat{x}_i),$$

where

$$\mathrm{d}_i(x_i, \hat{x}_i) = \sqrt{(x_i - \hat{x}_i)^2} = |x_i - \hat{x}_i|. \quad (10)$$

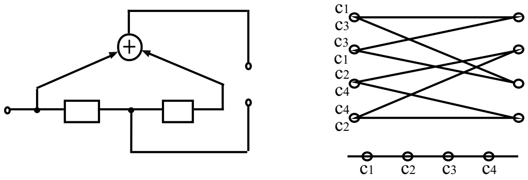

Fig. 3. A rate-1/2 convolutional encoder and corresponding trellis branch labeling.

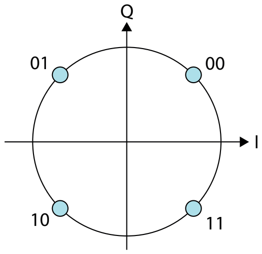

Fig. 4. Constellation diagram for QPSK with natural mapping.

Alternatively, (10) requires that for each state in the trellis, the branches entering or leaving the state should represent all possible codewords. And this can be simply achieved by repeating codewords in the codebook. The explanation is given by a rate-$1/2$ convolutional encoder shown in the left side of Fig. 3. The corresponding branch labeling is shown in the right side with reproduction levels c_i, $i = \{1, 2, 3, 4\}$. With such an encoder, for an integral encoding rate 1, the size of the codebook is $2^{1+1} = 4$. To guarantee correct mapping under the high source-to-relay channel SNR region where the soft information is equivalent to hard decision, codewords need to be repeated. Hence in the codebook of length four, only two different codewords can exist, namely 1 and -1. Then, the codebook consists of four codewords, i.e. -1, -1, 1, and 1. There are several ways to sort the four codewords in a codebook which can guarantee the accurate quantization, provided that TCM symbols mapping is consistent with the order of the codebook. For instance, if the QPSK with natural mapping shown in Fig. 4 is used as the modulation technique, and the branch labeling is depicted on the right side of Fig. 3, one possible codebook can be [-1 1 1 -1] corresponding to the modulation symbols [00 01 10 11]. As can be seen from Fig. 4, when -1 is mapped to both 00 and 11 symbols, and 1 is mapped to both 01 and 10 symbols, the overall QPSK constellation can be regarded as the BPSK constellation which expands the distance between different codewords.

IV. PERFORMANCE ANALYSIS

We first study the threshold for the selection of the codebooks. Then, we analyze the process of canceling each source's own signal from the received network coded signal.

A. Set a threshold

As the probability distribution of the soft information at the relay is varied according to the source-to-relay channel SNR, we force the relay to evaluate the quality of the received signals by checking whether the received signals satisfy the preset requirement. When the TCQ codewords are repeated, the only codewords 1 and -1 are just the BPSK symbols of the DF protocol. To prevent erroneous decisions in the DF protocol from propagating to the receivers, we set a threshold based on the instantaneous bit error rate (BER) of each received block; it is computed as

$$P_{e-S_iR} = Q\left(\sqrt{E_S h_{S_iR}^2/\sigma^2}\right), \tag{11}$$

where $Q(\cdot)$ is a Q-function [14, (4.1)], and the content inside the Q-function denotes the SNR of the source-to-relay channel.

In this work, we predetermine a BER threshold at the relay, so as to switch between different transmission schemes. If the instantaneous BER is smaller than the predetermined BER threshold, P_{th}, the source-to-relay transmission is deemed to be highly reliable and the soft information centralizes on 1 and -1. In the TWRC, according to (2), the network coded symbols are equivalent to 1 and -1 as long as both received blocks from the two sources are highly reliable. So we use the EF with TCQ codewords repeat scheme when both P_{e-S_1R} and P_{e-S_2R} are smaller than P_{th}. Otherwise, the EF with TCQ scheme using codebooks generated from the Lloyd algorithm is utilized. That is,

$$\begin{aligned}&\text{Relay Strategy} =\\ &\begin{cases}\text{EF with TCQ codewords repeat} & \text{if } P_{e-S_iR} < P_{th}\\ \qquad\text{EF with TCQ} & \text{Otherwise}\end{cases}.\end{aligned}$$

Setting the certain BER as a threshold is equivalent to setting the corresponding source-to-relay channel SNR as a threshold according to (11). In practice, the threshold can be eliminated because codebooks are predetermined at both the relay and receivers based on the different source-to-relay channel SNRs.

B. Cancel the source's own signal

The received quantized signal at each receiver has been defined in (4), which is then multiplied with x_{S_i} so as to cancel x_{S_i}. We follow the method for the EF protocol in [4], the estimated symbol of x_{S_i} is defined as $\hat{x}_{S_i} = \psi_i\left(x_{S_i} + e_{S_i}\right)$, where e_{S_i} denotes the uncorrelated soft noise, and ψ_i represents the scalar factor which makes the soft noise e_{S_i} uncorrelated to the information symbol x_{S_i}, namely, $\mathrm{E}\left(e_{S_i}x_{S_i}\right) = 0$, and $\psi_i = \frac{\mathrm{E}\left(x_{S_i}\hat{x}_{S_i}\right)}{\mathrm{E}\left(x_{S_i}^2\right)}$. Besides, we define $\beta = \sqrt{E_R/\mathrm{E}\left(\left|\tanh\left(\frac{LLR_{x_{S_1,R}}}{2}\right)\tanh\left(\frac{LLR_{x_{S_2,R}}}{2}\right)\right|^2\right)}$, hence the canceling process can be expressed as

$$\begin{aligned}x_{S_i}\hat{f}^*(r_{S_1R}, r_{S_2R}) &= \beta\hat{x}_{S_1}\hat{x}_{S_2}x_{S_i} + n_{equiv\_RS_i}x_{S_i}\\ &= \beta\psi_1\psi_2 x_{S_j} + \beta\psi_1\psi_2\left(e_{S_j} + x_{S_i}x_{S_j}e_{S_i} + x_{S_i}e_{S_i}e_{S_j}\right)\\ &\quad + n_{equiv\_RS_i}x_{S_i}, \end{aligned} \tag{12}$$

where we define the noise item, i.e. $N_{S_i} \triangleq \beta\psi_1\psi_2\left(e_{S_j} + x_{S_i}x_{S_j}e_{S_i} + x_{S_i}e_{S_i}e_{S_j}\right) + n_{equiv\_RS_i}x_{S_i}$, and we regard it as approximately Gaussian distributed with the mean value $m_{N_{S_i}}$ and the variance $\sigma^2{}_{N_{S_i}}$. The employment of the TCQ is a realization of the minimum mean-square error quantizer. Since the mean value of the output of a minimum mean-square error quantizer is equal to the mean value of the input; thus, the mean value of the quantization noise is 0. Besides, since $\mathrm{E}\left(e_{S_i} x_{S_i}\right) = 0$, we have $m_{N_{S_i}} = 0$ and $\sigma^2_{N_{S_i}} = \beta^2 \psi_1^2 \psi_2^2 \left(\sigma^2_{e_{S_1}} + \sigma^2_{e_{S_2}} + \sigma^2_{e_{S_1}} \sigma^2_{e_{S_2}}\right) + \sigma^2_{equiv\_RS_i}$, where $\sigma^2_{e_{S_i}}$ denotes the variance of the soft noise e_{S_i}, and $\sigma^2_{equiv\_RS_i}$ represents the variance of the quantization noise, which is a statistic in practical situations.

V. SIMULATION RESULTS

In the simulation, we consider Rayleigh fading channels. During each transmission period, each source transmits one block which contains 1000 binary symbols. Channels between the sources and the relay, namely h_{S_1R}, h_{S_2R}, h_{RS_1}, h_{RS_2}, are all with unit variance. Channels between the two sources, i.e. $h_{S_1S_2}$, $h_{S_2S_1}$, are both with the variance of 0.36. Besides, the transmission power and the receiver noise variance at both the relay and the sources are assumed to be equal. In the simulation, we set the threshold P_{th} to be $1/1000$. At the relay, if the instantaneous BER of the received signal is less than the threshold P_{th}, the EF with TCQ codewords repeat scheme is applied. Otherwise, the EF with TCQ scheme using the codebook generated by the Lloyd-Max quantizer is used. The TCQ/M system employs a rate-$1/2$ convolutional encoder shown in the left side of Fig. 3. We apply the QPSK constellation with natural mapping in the TCM and choose the codebook of [-1 1 1 -1] for the EF with TCQ codewords repeat scheme, as discussed in Section III. Finally, we take the system BER as the average value of BERs calculated at the two sources.

The AF, DF and EF protocols are taken as benchmarks in the simulation. In Fig. 5, X axis denotes the transmission SNR, i.e. E_S/σ^2. As can be seen from Fig. 5, both with transmission rate 1, the DF protocol has only one diversity gain, but the proposed protocol can achieve full diversity. Furthermore, the proposed protocol has about 1 dB coding gain compared to the AF protocol at a BER of 10^{-3}. With the increase of the SNR, the probability that the instantaneous BER of the received signals falls below the threshold increases, thus the times of operating the EF with TCQ codewords repeat scheme will grow, and the performance of this protocol approximates more towards that of the EF protocol in the high SNR region.

VI. CONCLUSION

In this paper, we propose a practical 1-bit soft forwarding protocol in the TWRC. We take advantage of the joint TCQ/M system to forward the soft information. When the source-to-relay channel SNR is low, we apply the Lloyd algorithm to generate the codebook for the TCQ. When the source-to-relay channel SNR is high enough that the soft information is equivalent to its hard decision, we propose to use the EF with TCQ codewords repeat scheme to implement the information delivery at the relay. We have found that the proposed protocol outperforms the AF protocol and the DF protocol over the slow fading TWRC. It also well approximates the EF protocol which assumes the soft information can be forwarded to the receivers without quantization.

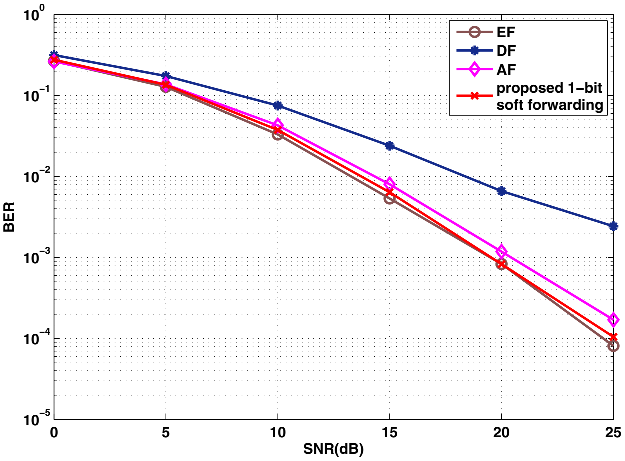

Fig. 5. BER performance for fading channels.

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