Cooperative network coding with soft information relaying in two-way relay channels

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Abstract—**Network coding in wireless network can improve network throughput by exploiting the broadcast nature of the wireless network. Taking into consideration the error prone nature of wireless networks, we investigate the design of network coding implemented in physical layer, and propose a cooperative network coding scheme with soft information forwarding (SIR), which combines soft network coding and distributed turbo coding scheme in two-way relay channels (TWRC) in this paper. In order to mitigate the error propagation effect due to the imperfect decoding at the relay, soft network coding is deployed in the proposed scheme, where soft-input soft-output (SISO) encoder and decoder for recursive systematic convolutional (RSC) codes are implemented. Moreover, the soft information of both systematic bits and redundancy parity bits are forwarded at the relay by using higher-order constellations to achieve diversity gain. Aided by distance spectrum of turbo codes, concept of uniform interleaver, and Gaussian approximation of soft decoding information, union bound on the error performance of our scheme is analyzed. Both the analysis and simulation confirm that the proposed scheme achieves significant gain over conventional network coding in quasi-static fading channels.**

***Index Terms*— network coding; relay; soft information forwarding; decode and forward; soft-input soft-output; distributed turbo codes; Gaussian approximation**

I. INTRODUCTION

Since the introduction in [1], network coding (NC) has been investigated as a potential tool for communication network to approach the capacity limit. By exploiting the broadcast nature of wireless medium, NC firstly has been regarded as an upper layer technique and separated from other lower-layer processes, say, modulation and channel coding, in such wireless network as ad hoc network, wireless sensor network, and mesh network to enhance the achievable throughput [2]-[4], energy efficiency [5]-[7], robustness and security [8]-[10]. Recently, NC has been implemented in physical-layer and combined with the techniques that deal with the detrimental effects of wireless channel fading for relay-based cooperative network [11]-[21].

A. Physical-layer network coding in relay system

In the relay-enhanced cooperative systems, the relay processes the received signals and then forwards part of or all the information. Pertaining to the operation of the relay, several classic relaying strategies have been developed, such as amplify-and-forward (AF), decode-and-forward (DF), compress-and-forward (EF), and coded-cooperation (CC).

Using the physical-layer broadcast property offered by the wireless medium, NC was developed at the relay to effectively reduce the time consumption from four time slots to three for message exchange in bi-directional wireless relay systems [11]. Then NC is extended from GF(2) to GF(2^n) [12], real field [13] and complex field [14], and it has been proven that the NC on complex domain has higher spectrum efficiency [14]. According to the field that the NC is operated on, Zhang et al. [15] classify NC into two categories, PNC over finite field and PNC over infinite field.

In order to achieve coding gain and/or spatial diversity gain, joint network and channel code (JNCC) scheme has attracted great attention. Hausl et al. [16] [17] designed a rate-compatible JNCC scheme where the relay network encodes the estimates of the two users to provide additional redundancy. Inspired by distributed turbo code scheme, Hou et al. [18] proposed three possible schemes for performing JNCC for TWRC based on turbo codes, using either NC after channel encoding, NC before channel encoding or superposition after modulation. Based on the observation that repeating the systematic information bit by higher-order modulation scheme can save transmit power compared to the case that no systematic bits are repeated, Nguyen et al. [19] designed a JNCC scheme for one-way relay channel (OWRC) , where part of or all the estimated systematic bits are repeated.

The forwarded information at the relay in [16]-[19] are the 'hard' information in the form of 0-1 bits, and they can be termed hard-information-relaying(HIR)-based JNCC. HIR-based JNCC features easy implementation of NC and great error performance given error-free decoding at

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the relay, but degrades severely due to decoding error propagation at the relay in practical noisy channels. To mitigate the decoding error propagation, soft-information-relaying(SIR)-based JNCC schemes have been proposed where the forwarded information is often in the form of logarithm likeliness ratio (LLR). Yang et al. proposed a belief propagation approach for NC over AWGN channels [20]. Pu et al. developed continuous network coding in fading OWRC, where the network coding and channel coding are both based on soft-input soft-output (SISO) LDPC decoder and encoder over the soft bits, say, LLR.

B. Summery of our work and paper organization

Rooted in the recent development of NC in relay-enhanced cooperation systems, we propose a SIR-based JNCC scheme for three-node network in TWRC in this paper. The three-node relay system model is depicted in Figure 1. For the proposed scheme, the relay interleaves the soft decoding information from SISO decoder, and then generates soft network coded messages. In order to gain spatial diversity, the soft information of systematic bits is repeated via higher-order soft modulation, and corresponding soft modulation is designed. After theoretical analysis on the error performance and the numerical simulation, the proposed scheme is verified to outperform the reference schemes.

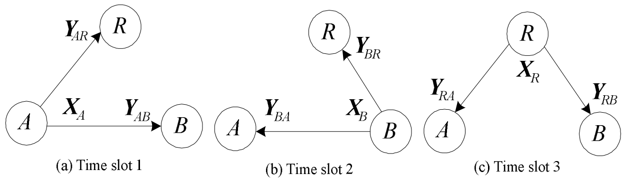


Figure 1. TWRC model

II. SYSTEM MODEL

A. Network Topology

As illustrated in Figure 1, the general two-hop relay system consists of two users (*A, B* in Figure 1) and a relay (*R*). User *A* wants to send message X_A to user *B* while user *B* wants to send message X_B to user *A*. With the help of relay *R*, the NC scheme will finish the two-way communication in three time slots when time-division half-duplex transmit mode is deployed. In time slot 1, user *A* transmits the RSC coded signal X_A to the relay *R* and user *B*. In time slot 2, user *B* transmits the RSC coded signal X_B to the relay *R* and user *A*. In time slot 3, the relay *R* broadcasts the network coded signal X_R.

Throughout this paper, subscripts *A, B, R* and *AB, AR, BA, BR, RA, RB* denotes the quantities pertaining to user *A*, user *B* and relay *R*, and those pertaining to the channels link the three nodes, respectively.

B. Channel Model

All the channels in Figure 1 are assumed to quasi-static Rayleigh fading channels with additive Gaussian noise. Since block fading channel is concerned, we only consider the signal in one frame and consequently discard the time index of the signals. The channel can be modeled as

$$Y_{ij} = \alpha_{ij} X_i + n_{ij} \tag{1}$$

where X_i is the transmitted signal after modulation from node i , Y_{ij} is the received signal after matched filter at node j , n_{ij} is the independent and identical distributed zero-mean Gaussian random noise with covariance of N_0, α_{ij} is the fading coefficient in channel *ij* which follows Rayleigh distribution and remain constant within one frame but changes independently from one frame to another. When AWGN channel is concerned, α_{ij} is constant of 1.

We assume that the average transmit power per channel bit is normalized to unit before transmission for all nodes, where the average is taken over the entire packet. As a result, the instantaneous signal-to-noise ratio (SNR) is defined as $\gamma_{ij} = |\alpha_{ij}|^2 E_s / N_0$, where E_s is the normalized signal power and is assumed to be 1 without loss of generalization.

III. NETWORK CODING SCHEME

The channel code employed in the JNCC scheme is distributed turbo code. To mitigate the decoding error propagation and achieve both coding gain and diversity gain, SISO RSC encoder and decoder, soft modulator and demodulator, and soft network coder and decoder are designed.

In this section, we firstly describe the proposed SIR-based JNCC scheme, and then present the iterative detection algorithm. Finally, the upper bound on bit error probability (BEP) performance of the proposed scheme is analyzed.

For brevity, subscripts S, P_1, P_2 denote the quantities pertaining to the systematic bit, parity bit from the first RSC encoder and parity bit from the second RSC encoder, respectively.

A. JNCC Encoder

The JNCC structure is depicted in Figure 2. In time slot 1, user A encodes the source bit sequence $\mathbf{u}_A = (u_A(1), ..., u_A(N))$ by RSC encoder with rate 1/2 to obtain the code word $\mathbf{C}_A = (\mathbf{c}_A(1), ..., \mathbf{c}_A(N))$, where $\mathbf{c}_A(i) = (u_A(i), p_{1,A}(i)), i = 1, ..., N$, $\mathbf{c}_A(i)$ is the *i*-th element of codeword $\mathbf{C}_A$, $s_A(i)$ is the *i*-th systematic bit which is $u_A(i)$, $p_{1,A}(i)$ is the *i*-th parity bit. After modulation, signal X_A is transmitted to both user B and relay R, and is also fed to JNCC decoder to subtract itself from the relay signal before decoding. The process of user B in time slot 2 is similar to user A in time slot 1. At receiving the signals from user A or user B, relay R demodulates Y_{AR} or Y_{BR} to obtain L_{AR} or L_{BR}, the *LLR* of the codeword from the channels, which is

$$L_{AR} = \frac{2\alpha_{AR}}{N_0} Y_{AR}, L_{BR} = \frac{2\alpha_{BR}}{N_0} Y_{BR} \tag{2}$$

In practical noisy channels, decoding error may happen for RSC decoder at relay R. For traditional NC schemes, the hard decision in the form of 0-1 bits of codewords are

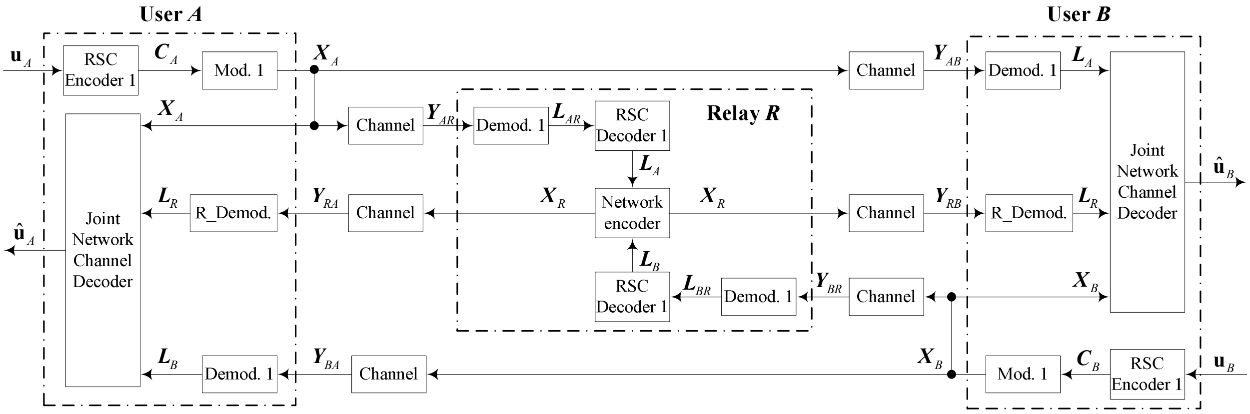


Figure 2. Block diagram for JNCC in TWRC

XORed, and error propagation is introduced which degrades severely the performance of NC scheme.

We propose a SIR-based NC scheme to mitigate the error propagation and achieve diversity gain by repeating the systematic bits via higher-order soft modulation. The structure of the proposed SIR-based network encoder is depicted in Fig. 3.

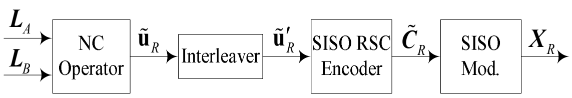


Figure 3. Block diagram of SIR-based Network encoder

The traditional NC is operated on 0-1 bits in the form of XOR, and we need to operate NC on LLR's. The RSC decoder estimates $L_i(n), i \in \{A, B\}$, the LLR of source bit $u_i(n)$, which is calculated as

$$L_i(n) = \log \frac{Pr(u_i(n)=1|\mathbf{Y}_{iR})}{Pr(u_i(n)=0|\mathbf{Y}_{iR})}, i \in \{A, B\} \qquad (3)$$

With $L_A(n)$ and $L_B(n)$, the LLR of the network coded message is calculated as [20]

$$L_R(n) = \log \frac{e^{L_A(n)} + e^{L_B(n)}}{1 + e^{L_A(n) + L_B(n)}} \qquad (4)$$

The LLR of the network coded messages are interleaved and re-encoded by SISO RSC encoder, and $\mathbf{L}_{R,coded}(n)$, the LLR of soft NC codeword, is obtained. To achieve diversity gain, systematic bits are repeated via higher-order modulation. For example, if BPSK is used in *AR* link, QPSK modulation scheme should be deployed in *RB* link to transfer both the systematic bits and parity bits via which the same symbol rate is maintained as the conventional scheme where systematic bits are not forwarded. Now we design the soft modulation scheme which operates on the soft bits instead of 0-1 bits. Soft modulation includes two steps:

Step 1: calculate the soft bits $\{\widetilde{\mathbf{C}}_R(n)\}$ from $\{L_{R,coded}(n)\}$ by

$$\widetilde{C}_R(n) = \frac{e^{L_{R,coded}(n)}}{1 + e^{L_{R,coded}(n)}} \qquad (5)$$

Step 2: calculate the soft modulated signals $\mathbf{X}_R = \{X_R(n)\}$ pertaining to the modulation order.

Throughout this paper, we employ M-QAM modulation scheme, and the soft modulated signals are calculated as below.

1) BPSK: $X_R(n)$ is calculated as

$$X_R(n) = \frac{e^{L_{R,coded}(n)} - 1}{e^{L_{R,coded}(n)} + 1} = \tanh(\frac{L_{R,coded}(n)}{2}) \qquad (6)$$

2) M-QAM: Since one modulation symbol will carry $m = \log_2(M)$ soft bits, $\{X_R(n)\}, n = 0, ..., N-1$ is calculated as

$$X_R(n) = \frac{1}{\sqrt{D}} \{\sum_{i=0}^{m-2} 2^i \widetilde{C}_R(nm + 2i) + j \sum_{i=0}^{m-2} 2^i \widetilde{C}_R(nm + 2i + 1)\} \qquad (7)$$

where $D = 2, 10, 42$ for QPSK, 16QAM, and 64QAM, respectively.

B. JNCC Decoder

We take user *A* as example to introduce the joint network-channel decoder, and the decoder at user *B* is similar to that at user *A*. The structure of the decoder is depicted in Figure 4.

Before decoding, the received signals are firstly demodulated to form soft information L_R and L_B, which are the LLR extracted from *RA* link and *BA* link. Based

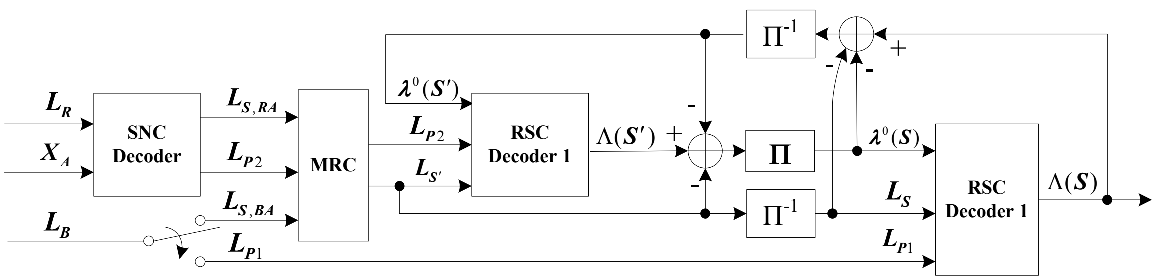


Figure 4. Block diagram of SIR-based JNCC decoder

on L_R and the modulated signal $\boldsymbol{X}_A$, Soft NC decoder calculates $\boldsymbol{L}_{B,RA} = (L_{S,RA}, L_{P_2})$, the LLR of user *B*'s codeword, as

$$\boldsymbol{L}_{B,RA} = \boldsymbol{L}_R \boldsymbol{X}_A \tag{8}$$

Since the systematic bits are transmitted twice via *RA* link and *BA* link, maximum ratio combining (MRC) is used to extract and combine the LLR from the two channels:

$$L_{S'} = L_{S',BA} + L_{S',RA} \tag{9}$$

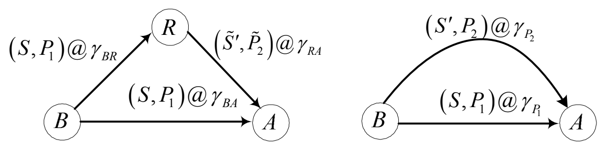
where *S*' denotes the interleaved version of *S*.

After obtaining the LLR of systematic bits and two versions of parity bits, classic turbo decoder is deployed to estimate the source bits $\mathbf{u}_A$.

C. Error Performance Analysis

In this section, we analyze the error performance of the proposed JNCC scheme. Due to the symmetry of the proposed JNCC in TWRC, we only take user *A* as example without loss of generality. For brevity, we omit the subscript *A* in this section when no confusion is introduced.

User *B*'s systematic bits and parity bits reach user *A* via different channels and naturally form a distributed turbo code (DTC) scheme. As a result, the PNCC scheme can be viewed as an equivalent DTC scheme which is shown in Figure 5 (a) where γ_{BR}, γ_{BA} and γ_{RA} denote the instant SNR per bit of the *BR* link, *BA* link, and *RA* link, respectively, and S, S', P_1, P_2 denotes the systematic bits, interleaved systematic bits, parity bits from RSC encoder at user *B*, parity bits from RSC encoder at relay *R*, respectively.



(a) DTC scheme (b) Equivalent scheme

Figure 5. Equivalent DTC

To facilitate the theoretical analysis, we resort to the equivalent error probability performance aspect of $(\boldsymbol{S}', \boldsymbol{P}_2)$ seeing from the destination. If we assume that $(\boldsymbol{S}', \boldsymbol{P}_2)$ are produced at user *B* and reach user *A* via a virtual *BA* channel which links user *A* and user *B* directly, and $(\boldsymbol{S}', \boldsymbol{P}_2)$ hold the same error probability as they reach user *B* via the practical *B-R-A* relay link, then we say that the virtual channel is equivalent to the practical *B-R-A* channel from the error probability aspect seeing from user *A*, and the SNR of the virtual *BA* channel is γ_{P_2} which is to be determined.

With the concept of virtual channel, the concerned DTC scheme is equivalent to the virtual scheme which is depicted in Figure 5 (b). For the virtual scheme, the relay system degrades to one-hop system with a source *B* and a destination *A* but no relay *R*, and two links connect *B* and *A* with different SNR. The coding and transmission scheme becomes that the turbo encoder with rate 1/3 is deployed at *B*, and one RSC codeword of $(\boldsymbol{S},\boldsymbol{P}_1)$ are transmitted via the link with SNR of γ_{P_1} in the first time slot, while the other RSC codeword of $(\boldsymbol{S}',\boldsymbol{P}_2)$ are transmitted via the link with SNR of γ_{P_2} in the second time slot. After receiving two RSC codewords, user *A* implements demodulation and combination, and feeds to turbo decoder the LLRs of $(\boldsymbol{L}_S, \boldsymbol{L}_{P_1}, \boldsymbol{L}_{P_2})$ with SNR of $\gamma_S = \gamma_{P_1} + \gamma_{P_2}$, γ_{P_1}, and γ_{P_2}, respectively.

To facilitate the theoretical analysis, the concept of uniform interleaver [22] is employed at relay *R*. Given the input-redundancy weight enumerating function (IRWEF) of turbo codes, the union bound on the conditional BEP of turbo code with known channel state information (CSI) at the destination is computed as

$$P_b(e|CSI) \leqslant \sum_{d=d_f}^{\infty} \sum_{w+z_1+z_2=d} \frac{w}{N} a(w,z_1,z_2) P_e(w,z_1,z_2|CSI) \tag{10}$$

where $a(w,z_1,z_2)$ is the average number of codewords with information weight w, parity weight z_1 and z_2 pertaining to the parity bits transmitted via the two channels with different SNR. d_f is the free distance of the codeword. $P_e(w,z_1,z_2|CSI)$ is the pairwise error probability (PEP) given the CSI which is the instantaneous SNR or the fading coefficients.

The method to compute IRWEF or distance spectrum of DTC is similar to that of typical turbo codes except that the parity weight are separated into two parts, z_1 and z_2, according to the parity bits which are transmitted via different channels.

Using the method developed in [23], the PEP with known CSI and BPSK is

$$P_e(w,z_1,z_2|CSI) \leqslant Q(\sqrt{2(w\gamma_S + z_1\gamma_{P_1} + z_2\gamma_{P_2})}) \tag{11}$$

It is easy to know that γ_{P_1} is $\gamma_{P_{BA}}$, but γ_{P_2} is not obvious. Now we calculate γ_{P_2} from the viewpoint of equivalent BEP performance as explained before.

Using the similar theoretical analysis method proposed in [24], the soft RSC decoder at relay *R* can be regarded as a SNR amplifier, and the combination of the *BR* link and the soft decoder at relay *R* can be modeled as a virtual block fading channel with effective SNR of

$$\gamma_l \triangleq \frac{\tilde{\mu}_l^2}{2\tilde{\sigma}_l^2} \tag{12}$$

where $\tilde{\mu}_l = \mu_l/\sqrt{P_l}$, $\tilde{\sigma}_l^2 = \sigma_l^2/P_l$, and they satisfy $\tilde{\mu}_l^2 + \tilde{\sigma}_l^2 = 1$, μ_l and σ_l^2 are the mean and variance of the output LLRs from RSC decoder.

The output LLRs from SISO RSC encoder and SISO modulator, $L_B(X_2) = (\tilde{S}', \tilde{P}_2)$, are the linearly-transformed version of $L_B(X_1) = (\tilde{S}, \tilde{P}_1)$, and reach user *A* via block fading Rayleigh channels. The relay signals arriving at user *A* are

$$y_{RA}(i) = \alpha_{RA}\tilde{\mu}_l X_2(i) + \alpha_{RA} n_l(i) + n_{RA}(i) \tag{13}$$

Then the effective SNR of the virtual *BA* channels is computed as

$$\gamma_{P_2} = \frac{2\gamma_l \alpha_{RA}^2}{\alpha_{RA}^2 + (1+2\gamma_l)N_0} \tag{14}$$

It should be noted that the effective SNR γ_{P_2} is derived under the assumption that the messages of user A are perfectly removed by network decoding and consequently the relay signals are corrupted only by the channel fading and the additional white Gaussian noise. However, decoding error may exist, and the message of user A's cannot be perfectly deleted by himself and consequently self interference is introduced. As a result, γ_{P_2} calculated by the above method is a little higher.

From (11) and (14) we can compute the unconditional BEP by averaging (10) over the fading distribution. We use the limit-before-average technique [25] to obtain the tight upper bound in the fading channels, which is computed as (15) shown in the bottom of the page.

IV. SIMULATION

In this section we evaluate the error performance of our scheme in TWRC.

The SNR setting of the concerned two-hop relay system is shown in Figure 6. We assume both relay channels have better link quality than the direct BA channel, while two relay channels have the same SNR value. All channels experience independent quasi-static Rayleigh fading. Both users employ BPSK modulation and RSC code of rate 1/2 with generator $(7,5)_{oct}$ and codeword length of 96 bits. At relay R, the soft modulation order is 4 to carry both systematic bits and parity bits.

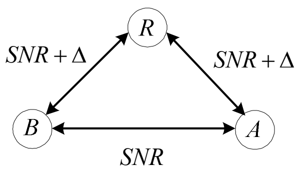


Figure 6. SNR setting for simulation

We compare our proposed scheme with two reference NC schemes. One is the traditional HIR-based JNCC scheme which employs 'hard' RSC decoder and 'hard' RSC encoder at relay R and joint DTC decoder and network decoder at destination A and B. The other one is SIR-based JNCC scheme which differs with our scheme on that only parity bits are forwarded by relay R. These two reference schemes are termed TNC-HIR and TNC-SIR, respectively.

We present the BER performance in Figure 7 and Figure 8 for two scenarios where the SNR setting is $\gamma_{BR} = \gamma_{RA} = \gamma_{BA} + 2$ and $\gamma_{BR} = \gamma_{RA} = \gamma_{BA} + 5$ respectively. From the curves in both Figure 7 and Figure 8 we can observe that our scheme outperforms the other two traditional JNCC schemes. For example, when the BER is 10^{-3}, our scheme outperform TNC-HIR scheme by about 3.5 dB and outperform TNC-SIR scheme by about 2 dB in Figure 7. In the lower BER range, our scheme can outperform the other two schemes better. We also present the upper bound on BEP of our scheme, which is much loose in the low SNR region but becomes tight in the high SNR region. For example, when SNR per bit is 30 dB in Figure 7, the analytical BEP approaches the simulation. From this result we can use the theoretical analysis method to predict the error performance of our scheme in high SNR range to save the lengthy simulation.

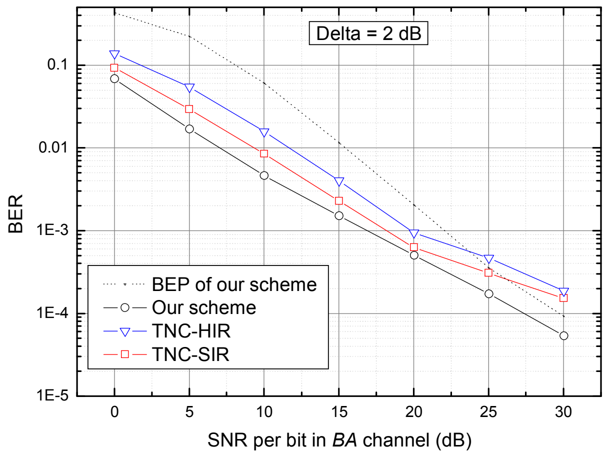


Figure 7. BER performance with Delta=2 dB

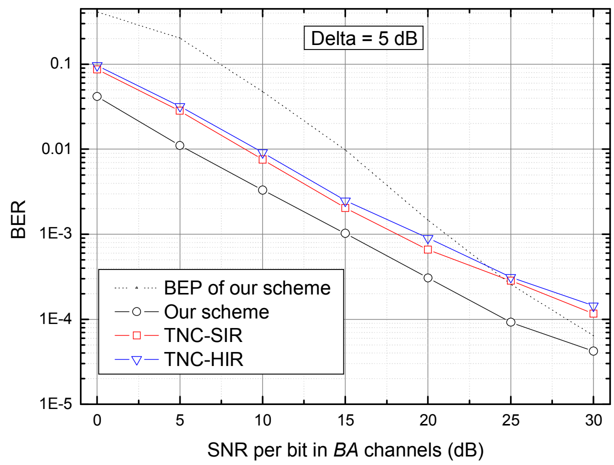


Figure 8. BER performance with Delta=5 dB

V. CONCLUSION

In this paper we propose a cooperative network coding scheme with soft information relaying in two-way relay channels. To mitigate decoding error propagation at relay, we develop the soft-input soft-output channel coding and decoding method and soft network coding method. In order to achieve diversity gain, we repeat the soft systematic bits by higher-order modulation and consequently design the soft modulation scheme. Both

$$P_b(e) \leqslant \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} min\{0.5, \sum_{d=d_f}^{\infty} \sum_{w+z_1+z_2=d} \frac{w}{N} a(w,z_1,z_2) Q(\sqrt{(w+z_1)\gamma_{P_1} + (w+z_2)\gamma_{P_2}}\} p(\gamma_{P_1}) p(\gamma_{P_2}) d\gamma_{P_1} d\gamma_{P_2} \tag{15}$$

theoretic analysis and numerical simulation verify that our scheme can enhance the error performance of relay systems and outperform traditional network coding schemes in practical fading two-way relay channels.

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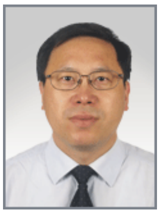

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