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Optimized Polar Coded Selective Relay Cooperation With Iterative Threshold Decision of Pseudo Posterior Probability

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ABSTRACT This paper proposes an optimized polar coded selective relay cooperation with an iterative threshold decision of pseudo posterior probability to solve the excessive redundancy of received signals and the high decoding complexity in a selective decode-and-forward (SDF) relay scheme. By sharing antennas of a relay node, a polar coded cooperation scheme is illustrated in a three-node relay transmission model, accompanied by an SDF protocol. Simultaneously, the SDF protocol is completed according to the channel status information at the relay node. In the logarithmic belief propagation algorithm, an expression of pseudo posterior probability-based stopping iteration threshold with independent and variable signal-to-noise ratios is derived to decide convergence condition and thus timely stop the iterations for low decoding complexity. And an extrinsic information transfer chart is also used to verify the completion of the iterative process. In addition, an information detection factor is introduced to check decoded bits correctly by the change of it, thereby reducing the average number of decoding iterations. It also accelerates the convergence speed of the BP algorithm by setting threshold and prejudgment, thereby improving the decoding efficiency. Simulation results show that the proposed polar coded relay cooperation scheme obtains over 2 dB performance gain, when the bit error rate (BER) is lower than 10^{-3}, compared with the existing low-density parity-check codes related schemes. It also reduces the complexity of the BP algorithm by stopping the iteration of high-reliability nodes at the cost of performance loss within 0.5 dB. Therefore, the proposed scheme obtains both good BER performance and low complexity, which endows its good applications in cooperative wireless communications.

INDEX TERMS Polar coded cooperation, outage probability, pseudo posterior probability, iterative threshold, information detection factor.

I. INTRODUCTION

Recently, cooperative diversity technology has emerged in modern wireless communications to meet the requirements of increasing speed and quality. It was first proposed with a specific cooperative transport protocol in [1]. It mainly employed the antennas of some neighbor nodes to form a virtual multiple-input multiple-output (MIMO) system for space diversity, and thus improving the capacity of an entire multiple-relay system. Then, many coded cooperative schemes started adopting efficient LDPC codes, Turbo codes, or some other codes to improve the effectiveness and reliability of the communications [2]. For instance, the LDPC coded cooperation of a single or double relays was proposed with an amplify-and-forward (AF) protocol in [3]. However, in these schemes, the AF protocol amplifies the power of both signals and noises. Thus, it was usually accompanied by a poor performance due to false message self-feedback by short loops in the Tanner graph of LDPC codes. Moreover, the error performance of a Turbo coded cooperative system

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was investigated in [4]. It used multiple relays to achieve good BER performance. However, the complexity of the algorithm also increased exponentially in proportion to the code length. Results show that the decode-and-forward (DF) protocol was more effective than the AF one. In a polar coded cooperation, a novel joint successive cancelation decoding scheme was also proposed [5]. This scheme was employed at the destination node and provided significant coding gains. However, no scheme was proposed in terms of the complexity of the algorithm in [5]. In addition, the outage probability and diversity order of a wireless network combining network coding and DF relay selection were studied, which provided a meaningful value to improve coded cooperation [6]. In sum, all above existing coded cooperation schemes showed that iterative decoding had good error performance, but the complexity in the above literature had not been greatly improved.

Polar codes have good characteristic of channel polarization. Channel polarization achieved the highest channel transmission rate under certain transmission reliability [7], [8]. A channel polarization for binary-input discrete memoryless channel was proposed in [9], where the complexity of $O(N \log N)$ was required for each polar encoding and decoding process. By channel polarization, the actual probabilistic channel was transformed into a parallel deterministic bit channel [10]. Given their advantages of approaching Shannon limit and less delay in an additive Gaussian white noise (AWGN) channel [11], polar codes were widely used in communications, such as channel coding and cooperative relaying [12]. By introducing polarization violation set and polarization reversal set, an improved approximate genetic algorithm for polar codes was proposed in [13] to solve the problem of sub-channel selection inaccuracy. It had great advantages in constructing high performance and long-length polar codes, but the procedures of coding and decoding became complicated simultaneously. In a previous study, an equivalent channel parameter universal to the cooperative relay system was given by rigorous mathematical derivation to find the optimal channel suitable for polar encoding and decoding [14]. With a fixed generator matrix, the BER performance was improved by reducing a search space for mapping patterns and combining low-order modulations [15]. Also, a maximum polarization matching strategy was also proposed to improve the systematic error performance in [16]. Therefore, the solution of high complexity and large delay in polar coded cooperation schemes is still a key issue in cooperative communications.

To improve BER performance and minimize complexity, we present a polar coded cooperation scheme based on a selective decode-and-forward (SDF) protocol in this paper. The proposed scheme is investigated in a three-node relay model with half duplex mode. A SDF protocol is employed as the forwarding protocol in the relay node, and the cyclic redundancy check (CRC) measure is introduced for checking reliability and discarding erroneous data as in [17] and [18]. Finally, the effectiveness of the proposed scheme is tested and verified by numerical simulations with some analyses of the performance improvement and complexity reduction. The main contributions are summarized as follows:

- *An efficient relay transmission scheme by employing the selective decision probability factor:* A SDF relay scheme is proposed by employing a relay selection decision probability factor according to the mutual information between the input and output of the relay node. Compared with a fixed DF relay scheme, it can selectively discard the false messages and do not forward them to the destination node to improve the systematic BER performance. In addition, it can directly transmit the messages from the source node to the destination node without any relay forwarding when the channel status is good, thereby considerably improving the transmission efficiency.
- *Computational complexity reduction with stable convergence rate using a variable iterative threshold:* Combined with EXIT charts of the proposed BP algorithm, the pseudo posterior probability of received codes is proposed to constitute a stopping iteration threshold. Different from traditional constant threshold, the number of active nodes is reduced by a changeable threshold taken with relation to the SNRs. Thus, the number of nodes without updating in each iteration is maintained to a stable level, preventing the convergence rate from decreasing. The complexity is reduced greatly at the cost of small BER loss due to incomplete iteration of some nodes.
- *Reduction of average number of iterations through prejudgment ability:* An iterative stopping condition is proposed as the objective function with a new information detection factor in which the parity check matrix and output sequence are used to predict the end of decoding in advance. Thus, it can avoid unnecessary iterations and reduce the average decoding iterations for lower complexity and less latency, when compared with those of the traditional polar coded cooperation schemes.

This paper is organized as follows. In Section II, a three-node selective coded cooperative communication system model is proposed and the protocol used in this model is determined. The polar coded cooperative process and key research objects are analyzed concretely. Then, the description of the SDF relay protocol is given and illustrated in Section III. A complexity optimization decoding in the logarithm BP algorithm of polar codes with iterative threshold and stopping condition is also proposed. In this section, polar coded cooperation is performed with the highest quality channels and the fastest iterative algorithm. In Section IV, the BER performance and complexity of the whole system are theoretically analyzed and mathematically deduced. Simulation results and related analyses show that the proposed cooperation scheme has both better BER performance and lower computational complexity than the current well designed schemes in Section V. Finally, Section VI concludes the whole paper.

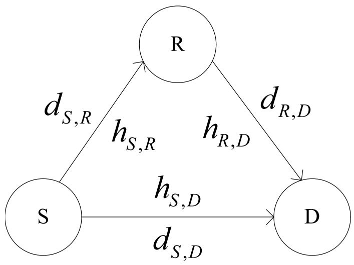


FIGURE 1. Schematic of the three-node relay channel model.

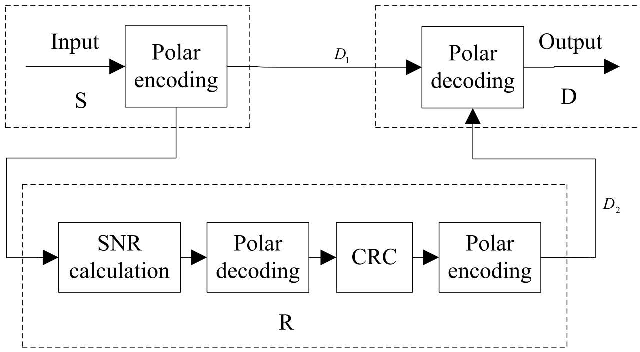


FIGURE 2. Polar coded cooperation model based on a SDF protocol.

II. THREE-NODE SELECTIVE DF RELAY COOPERATIVE MODEL OF POLAR CODES

For the ease of diversity analyses in cooperative communication systems, a three-node relay channel model is established in this paper. This model consists of a source node, a relay node, and a destination node [19]. In cooperative communications, a user node can transmit its own information, and that of other users. Meanwhile, half duplex communication is adopted. The specific processes and signal transmission modes are shown in Fig. 1.

In Fig. 1, the parameters in this model are as follows. $d_{i,j}$ ($i, j =$(S,R), (R,D), (S,D)) devotes the distance between two nodes. $h_{i,j}$ is the channel fading coefficient, and all the coefficients are independent of each other. Among them, the relay node mainly processes the received information before forwarding, and the processing method is mainly based on the formulated cooperative communication protocol. The half duplex communication mode is adopted in this paper. Also, there are three protocols to be used, including AF, DF and selective relay protocols.

The main difference between AF and DF protocols is that the relay node in a three-node relay model has different processing methods for the received signals. The relay node in the AF protocols is equivalent to a simple transponder. It only processes the received information from source nodes linearly, amplifies both the signals and noises, and finally emits the amplified noisy signals. As a result, this protocol reduces the performance of the system due to noise power amplification. To overcome this problem, we mainly use the SDF protocol for polar coded cooperative system.

In the polar coded cooperation scheme under the SDF protocol, the source node needs polar encoding. Then, it is separately modulated and sent to the relay and destination nodes. When the relay node receives the signals, the SNR at the relay node is calculated first. Then, the received signals are decoded and finally forwarded after CRC verification. To eliminate the amplified noises as much as possible, these signals are sent to the destination node for maximum ratio combining (MRC). Finally, the merge information is output at the destination node after polar decoding. The most important part of the SDF protocol is that selective relay forwarding and the CRC of the received signals are introduced into the relay node to check whether the decoding and signal transmission are accurate. The specific process is shown in Fig. 2.

The transmit power of the S and R nodes are expressed by P_1 and P_2, respectively. According to the above coded cooperation model, the received signals of the relay and destination nodes are obtained as

$$\begin{aligned} y_R &= \sqrt{P_1} h_{SR} x + n_{SR}, \\ y_{D1} &= \sqrt{P_1} h_{SD} x + n_{SD}, \\ y_{D2} &= \sqrt{P_2} h_{RD} y_R + n_{RD}, \end{aligned} \tag{1}$$

where x represents the information from the S node. n_{ij} represents additive complex Gaussian noise with zero mean and variance σ_n^2. y_R represents the information received by the relay nodes after the link S-R fading. y_{D1} represents the information received by the destination nodes during the broadcast phase via the link S-D fading. y_{D2} represents the transmitted fading information received by the link R-D in the multiple access phase.

Finally, the received information in the destination node by the MRC of y_{D1} and y_{D2} is obtained. The received information is first adjusted in phase. Then, it is added in accordance with the appropriate gain coefficients. The gain weighting factor corresponding to each branch is the ratio of the signal amplitude of the branch to the noise power [20]. In addition, power normalization is required for the noise of these two signals as shown in (2).

$$\begin{aligned} \frac{y_{D1}}{\sqrt{\delta_{SD}}} &= \frac{h_{SD} x}{\sqrt{\delta_{SD}}} + \frac{n_{SD}}{\sqrt{\delta_{SD}}}, \\ \frac{y_{D2}}{\sqrt{|h_{RD}|^2 \delta_{SR} + \delta_{RD}}} &= \frac{h_{SR} h_{RD} x}{\sqrt{|h_{RD}|^2 \delta_{SR} + \delta_{RD}}} \\ &\quad + \frac{h_{RD} n_{SR} + n_{RD}}{\sqrt{|h_{RD}|^2 \delta_{SR} + \delta_{RD}}}. \end{aligned} \tag{2}$$

As a result, the merged signals after the MRC are

$$\begin{aligned} Y = \frac{(h_{SR} h_{RD})^*}{\sqrt{|h_{RD}|^2 \delta_{SR} + \delta_{RD}}} \cdot \frac{y_{D2}}{\sqrt{|h_{RD}|^2 \delta_{SR} + \delta_{RD}}} \\ + \frac{h_{SD}^*}{\sqrt{\delta_{SD}}} \cdot \frac{y_{D1}}{\sqrt{\delta_{SD}}}. \end{aligned} \tag{3}$$

Finally, the original signals are obtained by decoding and demodulating the final signals Y.

III. JOINT CONSTRUCTION OF RELAY COOPERATION FOR PERFORMANCE IMPROVEMENT AND COMPLEXITY REDUCTION

The performance index of the system that combines cooperative communication with polar codes includes BER performance and decoding algorithm complexity. In this chapter, a SDF relay scheme in terms of BER performance is proposed, which uses relay selection decision factors to discard the error information in advance. As for algorithm complexity, a variable iterative threshold based on pseudo-posterior probability and an information detection factor for predicting iteration failure are constructed to reduce the number of unnecessary iterations in decoding. In addition, the system has high diversity gain and thus it has wide application prospects.

A. ADAPTIVE SINGLE RELAY COOPERATIVE STRATEGY ON SDF PROTOCOL

When the relay node selects the full decoding method and decodes correctly, the DF transmission protocol is equivalent to a repeated encoding scheme. At this point, the maximum mutual information I_{DF} can be obtained as

$$\begin{aligned} I_{DF} &= \min\{I_{SR}, I_{SRD}\} \\ &= \min\{1/2\log_2\left(1+SNR\left|h_{SR}\right|^2\right), \\ &\quad 1/2\log_2\left(1+SNR\left|h_{SD}\right|^2+SNR\left|h_{RD}\right|^2\right)\}. \end{aligned} \tag{4}$$

Suppose that the spectral efficiency of cooperative transmission systems is r. The transmission outage probability of the relay system in Rayleigh fading channel can be expressed as

$$\begin{aligned} P_{DF}(SNR, r) &= P(I_{DF} < r) \\ &= P[|h_{SR}|^2 < (2^{2r}-1)/SNR] + P[|h_{SR}|^2 \\ &\quad \geq (2^{2r}-1)/SNR] \cdot \\ &\quad P[|h_{SD}|^2 + |h_{RD}|^2 < (2^{2r}-1)/SNR] \\ &\quad \sim (2^{2r}-1)/(\sigma_{SR}^2 \cdot SNR). \end{aligned} \tag{5}$$

The result of (5) shows that the outage probability of the system is inversely proportional to the first order of SNR. In addition, only one-order gain diversity can be obtained. This fixed DF relay protocol can not obtain full gain diversity due to the influence of error propagation [21]. Relay nodes must forward the information selectively to improve the efficiency of relay forwarding. Thus, a SDF relay forwarding threshold is defined as

$$\theta = \left(2^{2r}-1\right)/SNR. \tag{6}$$

The channel parameters and the forwarding threshold were compared to determine whether the information is forwarded or not. The maximum average mutual information in the relay transport can be represented as

$$I' = \begin{cases} 1/2\log(1+2SNR\left|h_{SD}\right|^2), & |h_{SR}|^2 < \theta \\ \frac{1}{2}\log(1+2SNR\left|h_{SD}\right|^2+SNR\left|h_{RD}\right|^2), & |h_{SR}|^2 \geq \theta. \end{cases} \tag{7}$$

Using the formula of total probability theorem, we can deduce the outage probability under this transmission protocol from (7) as

$$\begin{aligned} P_{SDF}(SNR, r) &= P(I' < r) \\ &= P\{|h_{SR}|^2 < \theta\}P\{2\left|h_{SD}\right|^2 < \theta] \\ &\quad + P\{|h_{SR}|^2 \geq \theta\}P[|h_{SD}|^2 + |h_{RD}|^2 < \theta]. \end{aligned} \tag{8}$$

Different from the fixed DF relay protocol, the SDF relay protocol has an outage probability that is inversely proportional to the square of the SNR and obtains a two-order diversity gain. As a result, the forwarding information is more reliable. When random variables are all exponential variables, the outage probability that the relay is forwarded under the condition of high SNR is obtained as

$$P_{SDF}\left(I' < r\right) = \left(\frac{\sigma_{SR}^2+\sigma_{RD}^2}{2\sigma_{RD}^2\left(\sigma_{SR}^2\sigma_{RD}^2\right)}\right)\theta^2. \tag{9}$$

Thus, the inherent problems in fixed DF relay collaboration are improved. That is, when part of the signals are decoded wrongly, they are not still sent to the destination node. In this way, the BER performance of the system is promoted. In addition, according to the expression of interrupt probability, SDF relay also has the full diversity gain that does not exist in conventional DF relay cooperation.

B. IMPROVED RELAY OVERALL ARCHITECTURE FOR COOPERATIVE SYSTEMS

The relay selection system needs not only the relay nodes' participation, but also needs the destination nodes' participation and joint control to improve the utilization of spectrum resources and the capacity of the system. In the current coded cooperation, the relay node determines whether to forward or not, mainly relying on the CRC check [22]. However, this method reduces the speed of the system. To improve this existing problem, we propose a relay selection scheme suitable for coded cooperation from the threshold selection aspect.

The analyses of selective relay cooperation systems are as follows. The ratio of the instantaneous power of the received signals y_R and the power of the noise n_{SR} is calculated according to the channel state h_{SR} of the relay node, and the SNR of the received signals at the relay node is obtained as

$$S_R = (P_1\left|h_{SR}\right|^2 + \sigma_n^2)/\sigma_n^2. \tag{10}$$

Thus, the following categories and probabilities exist in the proposed relay cooperation.

1) The received SNR of the cooperative user is lower than θ and it is expressed as

$$\begin{aligned} P_{r1} &= p\left\{\left(P_1\left|h_{SR}\right|^2+\sigma_n^2\right)/\sigma_n^2 \leq \theta\right\} \\ &= 1 - e^{-(\theta-1)\sigma_n^2/2P_1\sigma_{SR}^2}. \end{aligned} \tag{11}$$

2) The received SNR of the cooperative user is higher than θ, and the correct decoding is performed.

$$P_{r2} = p\left\{\left(P_1 |h_{SR}|^2 + \sigma_n^2\right)/\sigma_n^2 > \theta\right\} p(decodecorrectly) \geq \int_{\frac{(\theta-1)^{-1/2}}{(P_1/\sigma_n^2)^{-1/2}}}^{+\infty} \left(1-\sum_d^{\infty} k(d)\, P(d|h_{SR})\right) \frac{h_{SR}}{\sigma_{SR}^2} e^{-(\frac{h_{SR}^2}{\sigma_{SR}^2})} dh_{SR}. \quad (12)$$

3) The received SNR of the cooperative user is higher than θ, but the wrong decoding is performed.

$$P_{r3} = p\left\{\left(P_1 |h_{SR}|^2 + \sigma_n^2\right)/\sigma_n^2 > \theta\right\} p(decodewrongly) \leq \int_{\frac{\sqrt{(\theta-1)}}{\sqrt{P_1/\sigma_n^2}}}^{+\infty} \{1-[(1-\sum_d^{\infty} k(d)P(d|h_{SR}))]\} \frac{h_{SR}}{\sigma_{SR}^2} e^{-(\frac{h_{SR}^2}{\sigma_{SR}^2})} dh_{SR}. \quad (13)$$

In (13), $k(d)$ indicates the number of errors at the distance of d. $P(d|h_{SR})$ stands for the conditional error probability. When S_R is large enough and the outage probability is less than the finite value, the probability that the relay node successfully decodes the source signals is high due to low noise interference. Then, the destination node performs MRC with the signals received by the relay and source nodes.

C. JOINT DECODING CONSTRUCTION BY DECODING DECISION THRESHOLD AND INFORMATION DETECTION FACTOR

The BP algorithm based on factor graph is commonly used to decode polar codes. It also has good decoding effect in LDPC codes. Before decoding, the coding aspect of the polar codes needs to be concerned. The polarization channel information of a Gaussian channel is obtained by using the Gaussian approximation method, where each sub-channel $W_N^{(i)}$ obtained after polarization of the polar code is processed separately. To construct better polar codes, the information is transmitted using the channels with smaller error probability of $Pe\left(W_N^{(i)}\right)$. According to the Gaussian approximation, the logarithmic likelihood ratio of each sub-channel has the Gaussian distribution with a variance and a half-value mean. Then, $Pe\left(W_N^{(i)}\right)$ of each polarization channel is represented as

$$Pe(W_N^{(i)}) = Q(\frac{m_N^{(i)}}{\sqrt{2m_N^{(i)}}}) = Q(\sqrt{\frac{m_N^{(i)}}{2}}), \quad (14)$$

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{+\infty} e^{-t^2/2} dt, \quad (15)$$

where $m_N^{(i)}$ denotes the mean of the likelihood density function of the i-th bit. The mean of residual sub-channels is obtained by iterative computation of Gaussian approximation as

$$m_N^{(2i)} = 2m_{N/2}^{i}$$
$$m_N^{(2i-1)} = f^{-1}(1-(1-f(m_{N/2}^{(i)}))^2). \quad (16)$$

To solve (16), we employ the following approximation of $f(x)$ in [10] as

$$f(x) = \begin{cases} e^{-0.4527x^{0.86}+0.0218}, 0 < x \leq 10 \\ \sqrt{\frac{\pi}{x}} e^{-\frac{x}{4}} (1 - \frac{10}{7x}), x > 10. \end{cases} \quad (17)$$

The choice of the efficient channels corresponds to the selection of the rows of the generator matrix G_N [23].

$$G_N = B_N F^{\otimes n}, \quad (18)$$
$$F = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}. \quad (19)$$

In (18), B_N represents bits flipping. "$\otimes$" represents tensor product. Source sequence of polar codes is mapped to coded sequence by coset code. The encoded polar codes can be expressed as (N, K, A, u_A^c) [24]. Among them, N is the length of polar codes, and K is the bit length of useful information. Then, the code rate can be described as $R = K/N$. u_A^c are the frozen bits, corresponding to the bit channels with poor performance, for transmitting fixed information.

The decoding of polar codes is completed using the logarithmic BP algorithm to make the decoding more efficient and easier to calculate after polar coding. This algorithm mainly involves message initialization, iterative operation, decoding decision, and decoding termination. The following factor diagram of the logarithmic BP algorithm is expressed in Fig. 3.

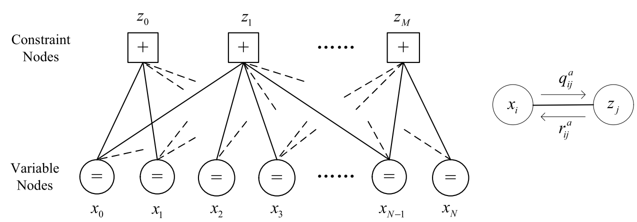


FIGURE 3. Factor graph of iterative decoding in the logarithmic BP algorithm.

Suppose that the message sequence is c, and the encoded transmission sequence is x. After the channel transmission, the received codes are y. Compared with the probabilistic BP algorithm, the logarithmic BP algorithm can reduce some multiplications in the decoding process effectively. However, the performance of decoding complexity in coded cooperation still needs to be improved. We mainly use the improved logarithmic BP algorithm by decoding decision threshold and information detection factor to reduce the complexity of decoding operations. The key steps required in the proposed algorithm are as follows.

After BPSK modulation, the initial message passes from the variable bits i to the check bits j can be computed as

$$L^{(0)}\left(q_{ij}\right) = L\left(p_i\right) = \ln \frac{p_i(0)}{p_i(1)}. \quad (20)$$

Step 1: Update of check bit information.

The bit information for checking that the check bits j pass to variable bits i can be computed as

$$L^{(l)}\left(r_{ji}\right)=\ln\frac{r_{ji}^{(l)}(0)}{r_{ji}^{(l)}(1)}. \tag{21}$$

Combining the identity $tanx=(e^x-e^{(-x)})/(e^x+e^{(-x)})$, it generates

$$L^{(l)}(r_{ji})=2\tan^{-1}\Big(\prod_{i\in N(j)|i}\tan\Big(\frac{1}{2}L^{(l-1)}(q_{ij})\Big)\Big). \tag{22}$$

Step 2: Update of variable bit information.

The information that the variable bits i pass to the check bits j can be computed as

$$L^{(l)}\left(q_{ij}\right)=\ln\frac{q_{ij}^{(l)}(0)}{q_{ij}^{(l)}(1)}=L\left(p_i\right)+\prod_{j\in M(i)|j}L^{(l)}\left(r_{ji}\right). \tag{23}$$

Step 3: Calculation of the decision information of the variable bits as

$$L^{(l)}\left(q_i\right)=L\left(p_i\right)_i+\prod_{j\in M(i)}L^{(l)}\left(r_{ji}\right). \tag{24}$$

If the calculated result is greater than zero, then $c_i=0$, otherwise $c_i=1$.

Step 4: Exclusion of nodes that do not require iterative update.

In the logarithmic BP decoding algorithm, the reliability information needs to be calculated in each iteration, generating a large amount of calculation. To accurately analyze the convergence characteristics of the BP decoding process, EXIT charts are used to track the external information exchange between variable node decoders (VNDs) and check node decoders (CNDs).

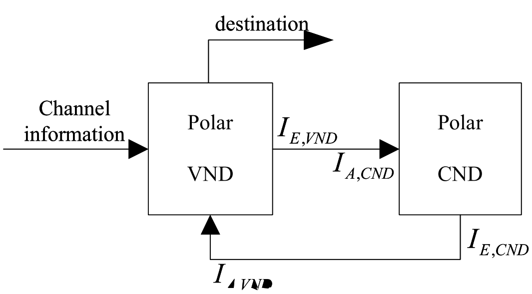


FIGURE 4. **Diagram of the external information transfer process between the VNDs and CNDs in Polar decoding.**

According to the transmission characteristics of mutual information between input and output of BP decoding algorithm shown in Fig. 4, the EXIT curves of the k-th VNDs and CNDs are expressed respectively as

$$I_{E,VND}=J\left(\sqrt{(k-1)\left[J^{-1}(I_{A,VND})\right]^2+8R\cdot SNR}\right), \tag{25}$$

$$I_{E,CND}=1-J\left(\sqrt{k-1}\cdot J^{-1}\left(1-I_{A,CND}\right)\right), \tag{26}$$

where k denotes iteration number of the EXIT chart function of the variable and check node decoders [32]. The formulation "$J(.)$" is shown in the appendix of [25]. The decoding is successful if there exists an open decoding tunnel between two node decoder EXIT curves. Otherwise, when the two EXIT curves intersect before the normalized terminal of iteration, *i.e.*, "1" in the EXIT chart, the decoding tunnel closes and the decoding fails.

To accelerate the convergence speed of iteration and thus reduce the decoding complexity, the pseudo posterior probability of received code words is used as a stopping iteration threshold to stop the subsequent iteration, in which the reliability of nodes is higher than the threshold E. And it is set as the reliability of the update information. $S(l)$ represents the bit reliability information provided by pseudo posterior probability of the received signals, defined as eqnarray (27).

$$S\left(l\right)=\left|F\left(\lambda_n\right)\right|;\quad 0\leq S\left(l\right)\leq 1, \tag{27}$$

where

$$F\left(x\right)=\left(e^x-1\right)/\left(e^x+1\right). \tag{28}$$

In addition, given the reliability of nodes in the iterative process, a great deal of instability can be observed in the first few times.Transmitting the information from an unstable node to the adjacent nodes affects the information calculation of the adjacent nodes. The convergence speed and decoding performance of the algorithm are greatly affected. Thus, the decoding scheme in this paper starts with tenth iterations to conduct threshold comparison according to the reliability of each node. When the number of iterations is greater than 10, and the decision result of received bits obtained from key Step 3) satisfies the following inequality.

$$\left|L^{(l)}\left(q_i\right)\right|\geq E. \tag{29}$$

The value of E is expressed similar to [27] as

$$E=e+\sum_{i=0}^{q}0.1/2^i,\ q=\lfloor 5\times SNR\rfloor, \tag{30}$$

where e is a constant. Then, these nodes are no longer updated during the next iterative update process. The average iteration number of the system is abated, and the computational complexity is reduced by using this stopping iteration threshold.

Step 5: Reduction of the number of the iterations.

The amount of effective information exchanged between nodes decreases as the number of iterations increases. Increasing the number of iterations indefinitely cannot continue to reduce the BER. That is, the number of iterations does not need to reach maximum, and the BER of the decoded output can be stabilized. Moreover, many additions and multiplications are involved in the iterative process of information. To reduce the complexity of the algorithm and improve the efficiency of the system, an information detection factor z is introduced to measure the error status of the output codes in this step.

$$z^{(l)}=H(\hat{c}^{(l)})^T \bmod 2. \tag{31}$$

Specify that the detection factor z remains constant in the course of 3 consecutive iterations and the number of nonzero elements remains the same. Then, the iteration is stopped, and the decoding fails. Otherwise, continue iterating until the maximum number of iterations.

IV. PRACTICAL ANALYSES OF THE PROPOSED RELAY CODED COOPERATION

A. ERROR PERFORMANCE ANALYSES OF A RELAY COOPERATIVE TRANSMISSION SYSTEM

A working cycle consists of two stages, considering that half duplex communication is adopted. The working process is as follows. K bits information is encoded to generate two parts of information x_1 and x_2. Then, these two parts of information are sent to the relay node and the destination node. Assuming that the power to transmit signals is P, and $P = P_1 + P_2$. The conditional error probability of the relay system can be expressed similarly in [26] and [27] as

$$P(d|h) = Q\left(\sqrt{2\left(P/\sigma_n^2\right)\sum_{l=1}^{M} d_l h_l^2}\right), \tag{32}$$

where d represents the Hamming distance of the codes. M represents the distance from the source node to the relay node. When the signals are transmitted from the source node to the relay node and successfully decoded, the unconditional error probability can be obtained by averaging h in eqnarray (32). The moment generating function and Gaussian Q function in Gaussian distribution are also applied and expressed in [28].

$$Q(x) = 1/\pi \int_0^{\pi/2} e^{-\left(x^2/2\sin^2\alpha\right)} d\alpha. \tag{33}$$

At this point, the error probability of the relay system can be represented as

$$\begin{aligned} P(d) &= \int_0^{\infty}\int_0^{\infty} Q\left(4\sqrt{\left(\frac{P_1}{\sigma_n^2}\right) d_1 |h_{SD}|^2 + \left(\frac{P_2}{\sigma_n^2}\right) d_2 |h_{RD}|^2}\right) p\left(h_{SD}\right) p\left(h_{RD}\right) dh_{SD} dh_{RD} \\ &= 1/\pi \int_0^{\pi/2}\left(1+\frac{\left(2P_1 d_1 \sigma_{SD}^2\right)}{\left(\sigma_n^2 \sin^2\alpha\right)}\right)^{-1}\left(1+\frac{\left(2P_2 d_2 \sigma_{RD}^2\right)}{\left(\sigma_n^2 \sin^2\alpha\right)}\right)^{-1} d\alpha \\ &\leq 1/2\left(\frac{1}{1+\left(2P_1 d_1 \sigma_{SD}^2\right)/\sigma_n^2}\right)\left(\frac{1}{1+\left(2P_2 d_2 \sigma_{RD}^2\right)/\sigma_n^2}\right). \end{aligned} \tag{34}$$

In (34), d_1 and d_2 denote the Hamming distance of x_1 and x_2, respectively, and $d = d_1 + d_2$. Transmit power of source node and relay node and Hamming distance of code words jointly determine the bit error performance at the relay node.

Besides, the block error rate (BLER) of polar codes should satisfy the following relationship [29] as

$$P_e(N, K, A) \leq \sum_{i \in A} Z\left(W_N^{(i)}\right). \tag{35}$$

B. ANALYSES OF SYSTEMATIC COMPLEXITY IN THE RELAY COOPERATIVE TRANSMISSION SYSTEM BY USING DECODING THRESHOLD AND ITERATIVE PREDICTION

According to [29], the time complexity of the traditional BP decoding algorithm is $O(N\log N)$. With the increase in the code length, the computational complexity of the algorithm increases. To solve this problem, we determine the reliability of the bits by using the pseudo posterior probability of the received codes in the iterative process. A pseudo posterior probability threshold E is proposed to filter out the nodes with high reliability so that they are not be updated in subsequent iterations to reduce the complexity of the scheme.

When $S(l) = 1$, the received bit is "0" or "1". However, in the actual iterative process, the reliability of information can not reach 1. With the increase in SNR, the reliability of each node increases meanwhile. When the SNR is high enough, the convergence speed of the algorithm slows down. Therefore, such as the decoding process in key step 4), the received information pseudo posteriori probability is set as the threshold E to balance the iterative convergence rate of the algorithm. When the reliability information is greater than the threshold, the next iteration does not need to update this bits information. Thus, it can reduce the number of active nodes in each iteration, and then the decoding complexity can be reduced.

Apart from reducing the number of active nodes in each iteration outside, the algorithm can also reduce complexity by reducing the average number of iterations. To avoid unnecessary iterations, the algorithm introduces an iterative detection factor to predict whether a codeword can be decoded successfully. Specific settings of iterative detection factor are shown in Step 5) of Subsection III(B). If decoding fails, then the iteration is terminated. Therefore, it can reduce the average iteration times of the entire iterative process.

The complexity of the improved logarithmic BP algorithm proposed in this paper is analyzed as follows. When using the logarithmic BP decoding algorithm based on factor graph, the factor graph of the polar code with a code length of N consists of n stages and $N(n+1)$ nodes ($N = 2n$). The proposed algorithm changes the decision rule for exchanging information between nodes and the average iteration times in the traditional BP decoding algorithm, thereby reducing the time and computational complexity of polar decoding. According to node update expression, the calculation of (22) and (23) requires one tangent function, one inverse tangent function, four multiplications, and two additions. When the maximum iteration number is set to t ($t \geq 40$), the number of iterations of each node in the improved algorithm is greatly reduced due to the existence of the iterative threshold and the information detection factor. When $e = 0.90$, the number of iterations is basically maintained from 15 to 30. Then, the average number of iterations is assumed to be 25. Therefore, the computational complexity of the BP algorithm before and after the improvement is summarized as TABLE 1.

TABLE 1. Comparisons of decoding complexities between two different BP algorithms.

Computational complexity	Traditional BP algorithm	Improved logarithmic BP algorithm
Threshold computation	No calculation required	Each SNR needs an addition
Average decision computation	$N(n+1)t$ comparison operations	$25N(n+1)$ comparison operations
Average decoding computation	$N(n+1)t$ tangent $+N(n+1)t$ inverse tangent $+\,4N(n+1)t$ multiplications $+2N(n+1)t$ additions	$25N(n+1)$ tangent $+25N(n+1)$ inverse tangent $+100N(n+1)$ multiplications $+\,50N(n+1)$ additions

In Tab. 1, tangent function consists of two exponential functions, one multiplication, and two additions. In addition, the inverse tangent function consists of one logarithm function, two multiplications, and two additions.

V. SIMULATION RESULTS AND ANALYSES

A. PERFORMANCE SIMULATION AND ANALYSES OF THE PROPOSED POLAR CODED COOPERATION SCHEME

In this section, the BER performance of the proposed scheme is simulated under different coding and decoding conditions. The experimental results are compared with the counterparts of the existing LDPC coded cooperation scheme. In simulations, irregular systematic bilayer LDPC codes are used in cooperative relay schemes, and the specific construction scheme is consulted in [30]. The simulation parameters are configured as follows.

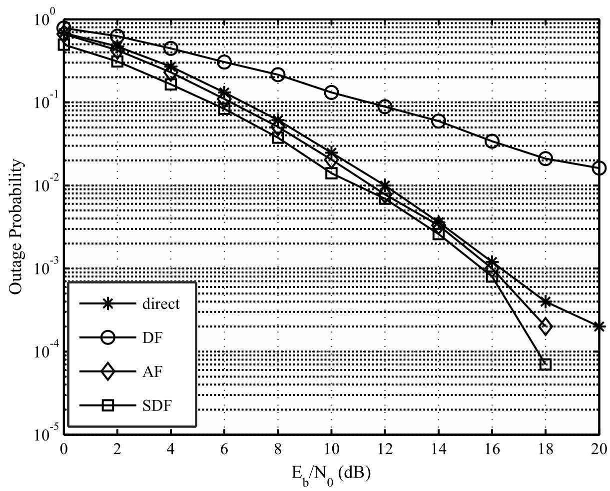


FIGURE 5. The outage probability of the AF, the DF, and the SDF cooperative protocols.

After the channel polarization of polar codes, the cooperative communication system can transmit the signals through the polarization channel. To simplify the simulation, we consider the distance between the nodes in the relay channel mode as the unit distance. The outage performances of the AF, the DF, and the SDF transport protocols are compared in Fig. 5. Assume that the wireless channel is a Rayleigh fading channel and the parameters σ_{SR}^2, σ_{SD}^2, and σ_{RD}^2 are all 1. The spectral efficiency of the system, *i.e.*, r, is set to 1 bit/s/Hz.

In Fig. 5, the performance of the fixed relay DF protocol is worse than that of direct transmission, which indicates that directly decoding and forwarding could lead to error propagation and even influence direct communication. The slope of the outage rate curve for AF and SDF is approximately the same, and full diversity gain can be obtained. However, the SDF protocol also adopts the relay selection method, which eliminates the noise interference and avoids the error propagation. Thus, its performance is better than that of the AF protocol. It also shows that the reliability of the coded cooperative system can be effectively improved by ensuring the correctness of the information transmission in relay nodes.

Then, to verify the effectiveness of the proposed decoding algorithm, when code length and rate are 2048 and 0.25, respectively, polar codes are then decoded by SC, SCL, pruned SCL and improved BP algorithm in cooperative communication individually. Subsequently, the diagram of the systematic error rate simulation can be obtained and shown in Fig. 6.

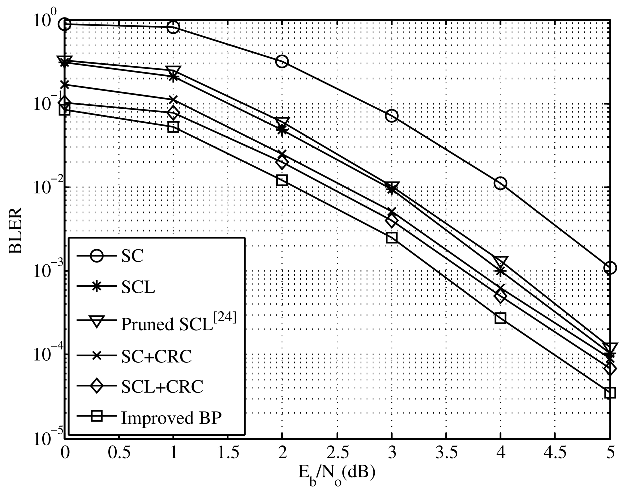


FIGURE 6. Comparison of BLER performance of polar coded cooperation using different decoding algorithms.

From the comparison of the above four decoding algorithms, the proposed BP algorithm can effectively improve the BLER performance of the system. According to Fig. 6, when the BLER is 10^{-3}, the SNR performance of the proposed algorithm can be improved by about 1.4 dB, 0.5 dB and

0.6 dB, respectively, compared with those of the SC, the SCL and the pruned SCL algorithms. In addition, adding CRC check to the polar decoding algorithm can further effectively improve the BLER performance of the system. Furthermore, the improved BP algorithm can also effectively reduce the computational complexity of the original algorithm, just as that of the pruned SCL algorithm in [24]. However, the former outperforms the latter in the BLER performance. Therefore, the proposed BP algorithm has advantages in terms of both the BLER performance and the computational complexity among these decoding algorithms. Therefrom, the BER performance of polar codes with different code lengths, bit rates, and node distances are also studied under improved BP decoding algorithm. And they are simulated and analyzed subsequently as follows.

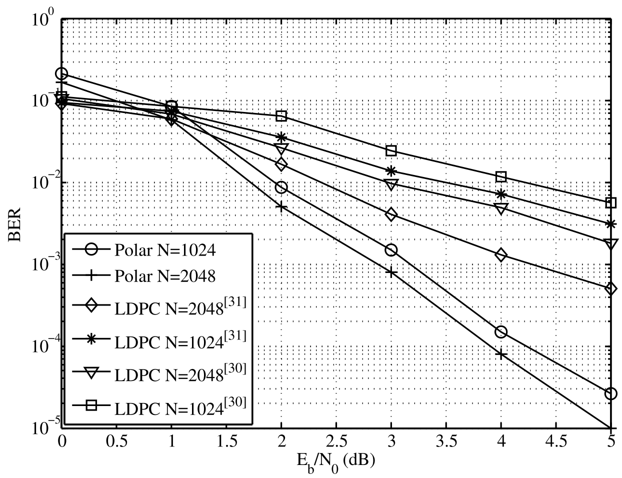


FIGURE 7. Influence of code lengths on performance of the polar coded cooperative schemes.

Fig. 7 shows the BER performance simulation of the polar coded cooperation scheme under the SDF protocol with same code rate and different code length. The simulation curves of the corresponding LDPC coded cooperative system under the same conditions are also given. The simulation parameters are set in Tab. 2.

TABLE 2. Simulation parameters of code lengths in the polar coded cooperative schemes.

Code length	1024, 2048
Code rate	0.25
Modulation mode	BPSK
Maximum iteration	40

The polarization effect becomes more obvious with the increase in code length. Under the same bit rate, with the increase of code length, the bit channel quality used to transmit the user information and the BER performance of polar codes improve. Fig.7 and Fig.8 compare the BER performance of the proposed polar coded cooperative scheme and other existing LDPC schemes. In Fig. 7, the BER curve of the polar coded cooperative system is gradually improved with the increase of code length. This phenomenon coincides with the theory of channel polarization. The curves of polar and LDPC codes show that, when the SNR is larger than 1 dB, the BER of the polar code is obviously better than those of LDPC codes in [30] and [31], and it tends to approach zero as the SNR increases. Under the same BER, *e.g.*, BER $= 5\times10^{-3}$, compared with the LDPC coded cooperative systems in [30] and [31], the channel gains by employing proposed polar coded scheme can be obtained about 0.8 dB and 2.4 dB, respectively.

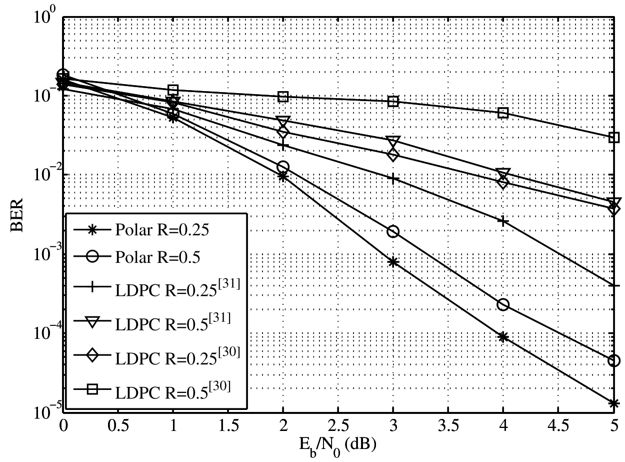


FIGURE 8. Impact of code rates on the performance of the polar coded cooperative schemes.

Similarly, with same code length, the BER of polar codes with different code rates in the cooperative scheme under the SDF protocol is described in Fig. 8. The simulation curves of the corresponding LDPC coded cooperative system under the same conditions are also given. The simulation parameters are configured in Tab. 3.

TABLE 3. Simulation parameters of code rates in the polar coded cooperative schemes.

Code length	1024
Code rate	0.25, 0.5
Modulation mode	BPSK
Maximum iteration	40

When the code rate R changes, the number of channels K used to transmit useful information is mutative. When N is fixed, the number of K increases with the increase in code rate. In the encoding and decoding of polar codes, the key step is how to select the high-quality channels to transmit the useful information, and the parameters used to measure channel quality are $Z\left(W_N^{(i)}\right)$. Then, the K channels with small parameters are chosen to transmit the information. The remaining $N-K$ channels are used to transmit frozen bits of information. When the number of K increases, the quality of the bit channel selected for transmitting information becomes poor. In Fig. 8, when the code length remains the same, the BER performance of the cooperative communication system becomes significantly worse with the increase in code rate. When the SNR is greater than 0.8 dB, the BER performance of the polar coded cooperative system is better than those of the LDPC coded systems. Under the same BER, *e.g.*, BER= 5×10^{-3}, compared with LDPC coded cooperative systems in [30] and [31], the channel gain between polar codes and LDPC codes are 1 dB and 2.8 dB, respectively.

In Fig. 7 and Fig. 8, the code length and the code rate of polar codes are closely related to the BER performance of the coded cooperative communication system. The effect of code rate on BER performance is faster and more efficient than that of code length. When code length is sufficient and the code rate is low, the polar coded cooperative communication system based on the SDF cooperative protocol can reach the Shannon channel limit approximately.

The above simulation results are all obtained in the relay model of unit distance. However, the actual cooperative communication systems are generally the asymmetric network, and the location of mobile terminals changes at any time. Therefore, the relationship between the distance and the coded cooperative performance should be studied. Polar codes with code length of 1024 and code rate of 0.25 are used under the SDF cooperative protocol. By transforming the distance between the source and relay nodes, the corresponding BER performance is simulated and shown in Fig. 9.

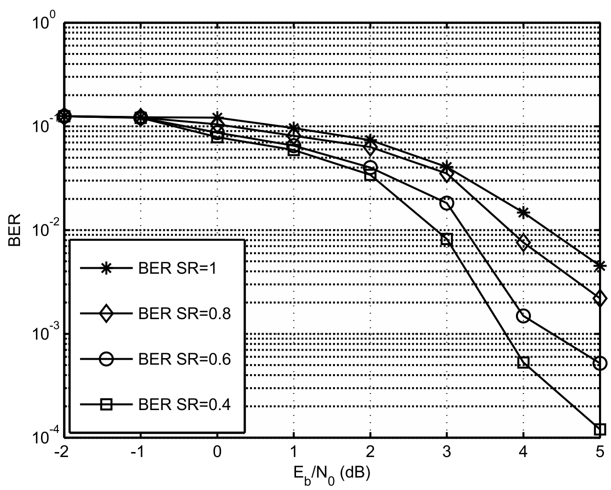


FIGURE 9. Influence of distance among relay nodes on the performance of the polar coded cooperative schemes.

The distance between the link R-D and S-D are fixed at 1. Only the distance of the link S-R is changed. According to Fig. 9, a decrease in the distance between the source and relay nodes indicates the attenuation of signals because the link begins to decrease. Correspondingly, the BER performance of the polar coded cooperative continues to improve. Thus, in the practical application of cooperative communication, how to select the location of relay nodes is also very important.

B. COMPLEXITY ANALYSES AND SIMULATION OF THE PROPOSED CODED COOPERATION SCHEME

Through the above simulations and analyses, the polar coded cooperative communication system under the DF cooperative protocol has good BER performance. The logarithmic BP decoding algorithm needs to calculate the reliability information in each iteration and contains many exponential operations and a large number of multiplication operations. Therefore, in this paper, a strain threshold and an information detection factor are firstly set up to reduce the complexity of the algorithm. Then, the simulations and complexity analyses of the proposed scheme with different threshold values are given. The simulation parameters are configured in Tab. 4.

TABLE 4. Simulation parameters of polar coded cooperative communications with different thresholds.

Code length	1024
Code rate	0.25
Threshold values (e)	0.9, 0.88, 0.86
Maximum iteration	40

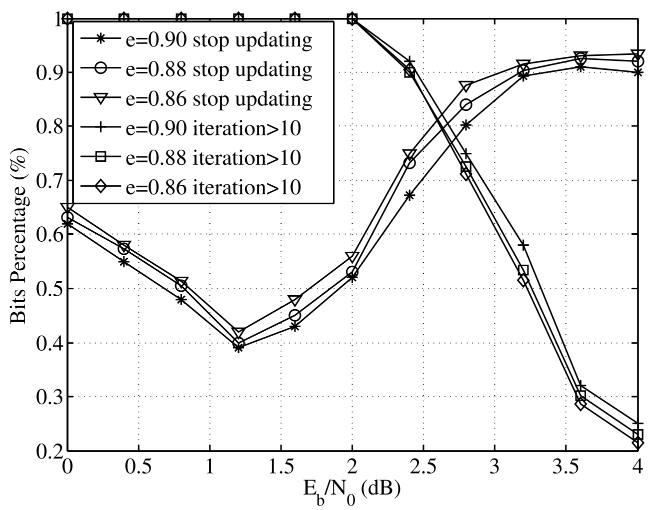


FIGURE 10. Simulation of active bit transitions under different iterative stopping thresholds.

As shown in Fig. 10, the iteration number of the algorithm exceeds 10 when the SNR is less than 2 dB by adding the threshold value and information detection factor in the traditional logarithmic BP algorithm. At least 30% of the nodes need not be updated at each iteration. A large amount of computation is reduced for each iteration. As the SNR increases, the average reliability of each node increases as well. When the SNR is less than 1.2 dB, the added value of the node reliability is lower than the enhancement of threshold. Thus, the percentage of nodes that can stop iteration is reduced. At this point, the percentage of nodes that stop iteration shows a downward trend. When the SNR is between 2 dB and 4 dB, bits that the iterations more than 10 times begins to decrease. However, the percentage of nodes that stop updating in each iteration increases. When the SNR is greater than 3.2 dB,

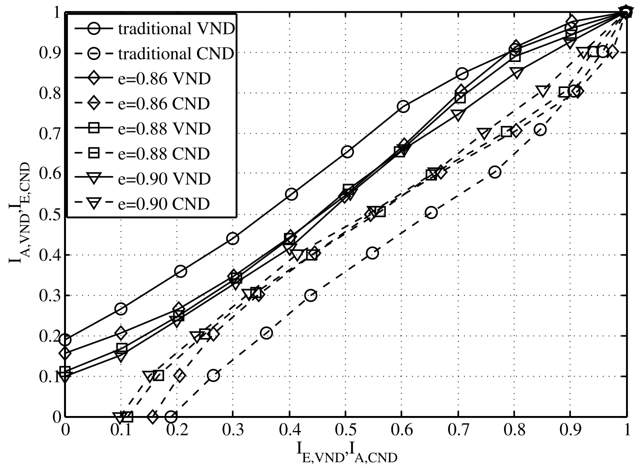


FIGURE 11. EXIT charts for polar decoding with different iterative stopping thresholds.

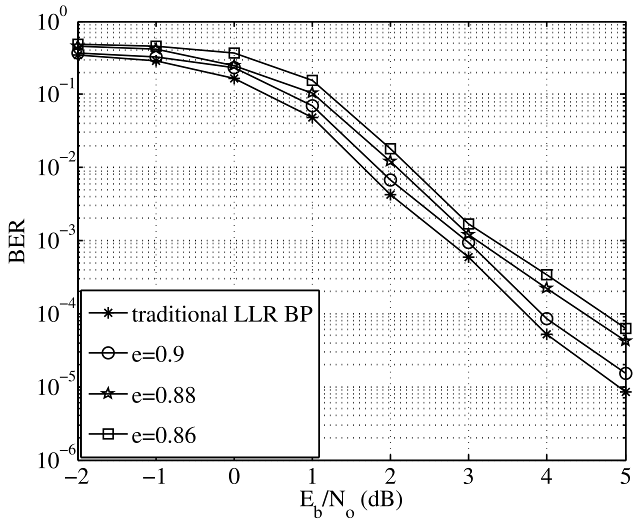


FIGURE 12. BER performance of the polar coded schemes with different iterative stopping thresholds.

the proportion of nodes to be updated in each iteration is basically maintained above 90%, thus saving a great deal of iterative computation. To reduce the complexity of the whole cooperative communication system effectively, the BER performance of the system must be considered simultaneously.

In addition, to illustrate decoding process under different thresholds more accurately, the iteration decoding trajectories corresponding to threshold values of 0.86, 0.88 and 0.90 are given by using the EXIT charts. As shown in Fig. 11, the EXIT curves of the CNDs and the VNDs intersect at the position close to "1" as the iteration proceeds. In this case, the decoding soft information has high reliability and it can be decoded successfully. However, when the iteration threshold is added, the decoding tunnel will be reduced to a certain extent, resulting in a slight reduction in the BER performance. And the BER performance under different iterative stopping thresholds is shown in Fig. 12.

As shown in Fig. 12, the BER performance of the proposed algorithm decreases compared with that of the traditional logarithmic BP algorithm, when the threshold value is reduced. As the threshold gradually decreases, the range of BER performance degradation increases. When the SNR is greater than 4 dB, the BER performance is almost zero. Thus, in the decoding process, by setting appropriate threshold value, the complexity of the logarithmic BP algorithm can be greatly reduced at the expense of slight error performance.

VI. CONCLUSION

In consideration of the existing relay channel signal transmission problem and the advantage of polar codes related channel polarization, a polar coded cooperative transmission scheme employing the SDF relay protocol is proposed in this paper. A concrete scheme model and mathematical derivation are given combining with the classical three-node relay system. The proposed BP algorithm has better BLER performance than the commonly used SC and SCL algorithms. The impacts of polar code length, rate, and other factors on the performance of the proposed coded cooperative scheme are mainly studied, and they are compared with those of current LDPC coded cooperation schemes under same conditions. The results show that the proposed scheme can achieve a large coding gain at high SNR. Compared with the LDPC coded cooperative scheme under the SDF protocol, the proposed scheme has better BER performance. Under same simulation conditions in the AWGN, the proposed scheme can increase the coding gain over 2 dB. In addition, the complexity performance of the algorithm is improved. On the basis of the traditional logarithmic BP algorithm, the appropriate decision threshold expression and the information detection factor are configured. At the expense of a certain amount of performance cost, it greatly reduces the complexity of the cooperative system.

REFERENCES

[1] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.
[2] M. Zhu, Q. Guo, H. Xu, B. Bai, and X. Ma, "A multiple-voting-based decoding algorithm for nonbinary LDPC-coded modulation systems," *IEEE Access*, vol. 5, pp. 9739–9747, May 2017.
[3] S. Bharadwaj and N. B. Mehta, "Accurate performance analysis of single and opportunistic AF relay cooperation with imperfect cascaded channel estimates," *IEEE Trans. Commun.*, vol. 61, no. 5, pp. 1764–1775, May 2013.
[4] H. Kaya and E. Öztürk, "Effects of opportunistic relay selection on the performance of distributed Turbo coded cooperative systems," in *Proc. IEEE Signal Process. Commun. Appl. Conf. (SIU)*, Mugla, Turkey, May 2012, pp. 1–4.
[5] S. Ejaz, Y. FengFan, and T. H. M. Soliman, "Multi-level construction of polar codes for half-duplex wireless coded-cooperative networks," *Frequenz*, vol. 69, nos. 11–12, pp. 509–517, Nov. 2015.
[6] T. X. Vu, P. Duhamel, and M. Di Renzo, "On the diversity of network-coded cooperation with decode-and-forward relay selection," *IEEE Trans. Wireless Commun.*, vol. 14, no. 8, pp. 4369–4378, Aug. 2015.
[7] H. Saber and I. Marsland, "Design of generalized concatenated codes based on polar codes with very short outer codes," *IEEE Trans. Veh. Technol.*, vol. 66, no. 4, pp. 3103–3115, Apr. 2017.

[8] H. Si *et al.*, "Polar coding for fading channels: Binary and exponential channel cases," *IEEE Trans. Commun.*, vol. 62, no. 8, pp. 2638–2650, Aug. 2014.

[9] E. Arıkan, "Channel polarization: A method for constructing capacity-achieving codes for symmetric binary-input memoryless channels," *IEEE Trans. Inf. Theory*, vol. 55, no. 7, pp. 3051–3073, Jul. 2009.

[10] D. Wu, Y. Li, and Y. Sun, "Construction and block error rate analysis of polar codes over AWGN channel based on Gaussian approximation," *IEEE Commun. Lett.*, vol. 18, no. 7, pp. 1099–1102, Jul. 2014.

[11] A. Alamdar-Yazdi and F. R. Kschischang, "A simplified successive-cancellation decoder for polar codes," *IEEE Commun. Lett.*, vol. 15, no. 12, pp. 1378–1380, Dec. 2011.

[12] L. Jin and H. Yang, "Joint source-channel polarization with side information," *IEEE Access*, vol. 6, pp. 7340–7349, Jan. 2018.

[13] J. Dai, K. Niu, Z. Si, C. Dong, and J. Lin, "Does Gaussian approximation work well for the long-length polar code construction?" *IEEE Access*, vol. 5, pp. 7950–7963, Apr. 2015.

[14] X. Ma, L. Li, M. Zhu, W. Chen, and Z. Han, "Multilevel polar-coded modulation based on cooperative relaying," in *Proc. Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Nanjing, China, Oct. 2017, pp. 1–4.

[15] K. Chen, K. Niu, and J.-R. Lin, "An efficient design of bit-interleaved polar coded modulation," in *Proc. IEEE 24th Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, Sep. 2013, pp. 693–697.

[16] D.-M. Shin, S.-C. Lim, and K. Yang, "Mapping selection and code construction for 2^m-ary polar-coded modulation," *IEEE Commun. Lett.*, vol. 16, no. 6, pp. 905–908, Jun. 2012.

[17] Q. Li, R. Q. Hu, Y. Qian, and G. Wu, "Cooperative communications for wireless networks: Techniques and applications in LTE-advanced systems," *IEEE Wireless Commun.*, vol. 19, no. 2, pp. 22–29, Apr. 2012.

[18] D. Jia, Z. Fei, J. Yuan, S. Tian, and J. Kuang, "A hybrid EF/DF protocol with rateless coded network code for two-way relay channels," *IEEE Trans. Commun.*, vol. 64, no. 8, pp. 3133–3147, Aug. 2016.

[19] F.-S. Tseng, W.-J. Huang, and W.-R. Wu, "Robust far-end channel estimation in three-node amplify-and-forward MIMO relay systems," *IEEE Trans. Veh. Technol.*, vol. 62, no. 8, pp. 3752–3766, May 2013.

[20] R. Tanbourgi, H. S. Dhillon, J. G. Andrews, and F. K. Jondral, "Effect of spatial interference correlation on the performance of maximum ratio combining," *IEEE Trans. Wireless Commun.*, vol. 13, no. 6, pp. 3307–3316, Apr. 2014.

[21] R. P. Sirigina and A. S. Madhukumar, "On the symbol error rate and diversity gain region of the relay-assisted z-channel," *IEEE Trans. Wireless Commun.*, vol. 15, no. 3, pp. 1965–1978, Mar. 2016.

[22] K. Niu and K. Chen, "CRC-aided decoding of polar codes," *IEEE Commun. Lett.*, vol. 16, no. 10, pp. 1668–1671, Oct. 2012.

[23] H. Mahdavifar, M. El-Khamy, J. Lee, and I. Kang, "Polar coding for bit-interleaved coded modulation," *IEEE Trans. Veh. Technol.*, vol. 65, no. 5, pp. 3115–3127, May 2016.

[24] K. Chen, K. Niu, and J. Lin, "A reduced-complexity successive cancellation list decoding of polar codes," in *Proc. IEEE Veh. Technol. Conf. (VTC Spring)*, Dresden, Germany, Jun. 2013, pp. 1–5.

[25] S. ten Brink, G. Kramer, and A. Ashikhmin, "Design of low-density parity-check codes for modulation and detection," *IEEE Trans. Commun.*, vol. 52, no. 4, pp. 670–678, Apr. 2004.

[26] C. Li, H. Wang, Y. Yao, Z. Chen, X. Li, and S. Zhang, "Outage performance of the full-duplex two-way DF relay system under imperfect CSI," *IEEE Access*, vol. 5, pp. 5425–5435, Apr. 2017.

[27] B. J. Choi and M. H. Sunwoo, "Efficient forced convergence algorithm for low power LDPC decoders," in *Proc. IEEE Soc Design Conf. (ISOCC)*, Busan, South Korea, Nov. 2013, pp. 372–373.

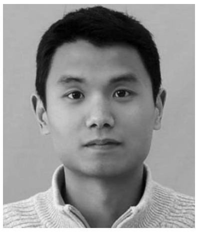
[28] A. A. Haghighi and K. Navaie, "Outage analysis and diversity-multiplexing tradeoff bounds for opportunistic relaying coded cooperation and distributed space-time coding coded cooperation," *IEEE Trans. Wireless Commun.*, vol. 9, no. 3, pp. 1198–1206, Mar. 2010.

[29] E. Arıkan, "A performance comparison of polar codes and Reed-Müller codes," *IEEE Commun. Lett.*, vol. 12, no. 6, pp. 447–449, Jun. 2008.

[30] J. Chen, F. Yang, S. Zhang, L. Tang, L. Luo, and T. Le-Ngoc, "Joint iterative decoding for irregular-LDPC-based coded cooperation over a non-ideal relay channel," in *Proc. Int. Conf. Wireless Commun. Signal Process. (ICWCSP)*, Nanjing, China, Nov. 2009, pp. 447–449.

[31] T. V. Nguyen, A. Nosratinia, and D. Divsalar, "Bilayer protograph codes for half-duplex relay channels," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1969–1977, May 2013.

[32] Q. Zhang, A. Liu, Y. Zhang, and X. Liang, "Practical design and decoding of parallel concatenated structure for systematic polar codes," *IEEE Trans. Commun.*, vol. 64, no. 2, pp. 456–466, Feb. 2016.



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