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GREAT-CEO: larGe scale distRibuted dEcision mAking Techniques for Wireless Chief Executive Officer Problems

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SUMMARY In this paper, we reformulate the issue related to wireless mesh networks (WMNs) from the Chief Executive Officer (CEO) problem viewpoint, and provide a practical solution to a simple case of the problem. It is well known that the CEO problem is a theoretical basis for sensor networks. The problem investigated in this paper is described as follows: an originator broadcasts its binary information sequence to several forwarding nodes (relays) over Binary Symmetric Channels (BSC); the originator's information sequence suffers from independent random binary errors; at the forwarding nodes, they just further interleave, encode the received bit sequence, and then forward it, without making heavy efforts for correcting errors that may occur in the originator-relay links, to the final destination (FD) over Additive White Gaussian Noise (AWGN) channels. Hence, this strategy reduces the complexity of the relay significantly. A joint iterative decoding technique at the FD is proposed by utilizing the knowledge of the correlation due to the errors occurring in the link between the originator and forwarding nodes (referred to as intra-link). The bit-error-rate (BER) performances show that the originator's information can be reconstructed at the FD even by using a very simple coding scheme. We provide BER performance comparison between joint decoding and separate decoding strategies. The simulation results show that excellent performance can be achieved by the proposed system. Furthermore, extrinsic information transfer (EXIT) chart analysis is performed to investigate convergence property of the proposed technique, with the aim of, in part, optimizing the code rate at the originator.
key words: *CEO problem, Slepian-Wolf theorem, wireless mesh network, wireless sensor network, extract and forward, iterative decoding, EXIT chart analysis*

1. Introduction

The research on cooperative communications using joint source, channel and network coding, has recently attracted a lot of attention with the recognition of significant importance. In cooperative communication systems, antennas of the mobile devices are shared by the multiple users, with the aim of configuring a virtual multi-terminal environment, and thereby advantageous points of network-level cooperation, rather than assembly of point-to-point (P2P), is expected to be significant.

Wireless Mesh Network (WMN) systems usually consist of a group of fixed or mobile devices and hence can be deployed smoothly and flexibly in complicated environments such as in devastated and emergency situations, tunnels, oil rigs, and/or for battlefield surveillance. WMN is a form of cooperative communications system, in which multiple forwarding nodes cooperate to relay the messages to the final destinations (FDs). Achieving high data throughput, power and spectral efficiencies, as well as efficient resource utilization are the major objectives of the WMN system design. Since the data to be delivered to FD with the help of forwarding nodes was transmitted from the same originator, the signals forwarded by multiple forwarding nodes are highly correlated, even though the signals transmitted over the links between the originator-forwarding nodes suffer from errors.

According to the Slepian-Wolf's correlated source coding theorem [1], if the source information is compressed at a coding rate less than the entropy of each source but larger than the conditional entropy, conditioned by the other source, and if the FD knows the correlation property, still the source information can be recovered without any distortion at the FD. The authors realized [2]–[5] that this theorem can well be utilized in the relaying systems, because, for example in one-way relay system, the data is originated from the one single originator, and hence the signal directly transmitted and the signal forwarded by the relay are correlated, even though the originated data is corrupted by errors in the originator-relay link (intra-link). Assuming that the error occurrence property of the intra-link can be represented by a bit-flipping model [6], which is equivalent to the binary symmetric channel (BSC) model, and if the flipping probabilities are known to the FD, iterative decoding process can well utilize the correlation property in the form of LLR updating function [3], [4].

With the Slepian-Wolf theorem based relaying system, the relay (or forwarding node) does not have to perfectly correct the intra-link errors; it can simply *extract*[*] information part from the received frame, interleave, re-encode, and then forward it to the FD. The extracted data may contain errors, but by iterative processing with the LLR updating function, the originator's data can be fully recovered. This scheme is referred to as *extract-and-forward* (ErF) technique in this paper. Reference [4] applies the ErF concept to

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[*]Full iterative decoding is not performed at the relay with the aim of reducing the computational burden on the relay. Instead, the relay performs Viterbi algorithm or only 1 iteration to get a tentative estimate of the source information sequence. This process is referred to as "extract" according to [4].

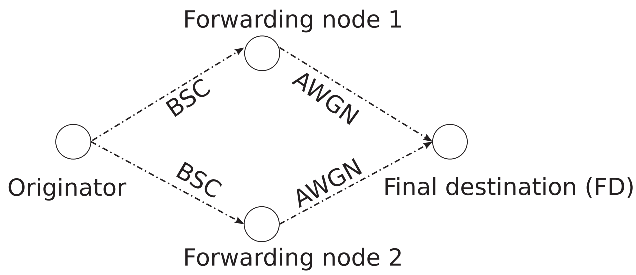

Fig. 1 The schematic diagram of a very simple WMN.

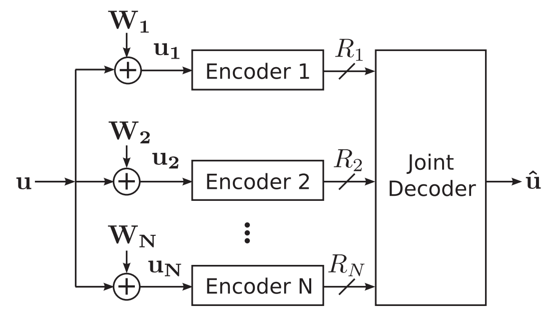

Fig. 2 A general model of CEO problems.

relay systems with the aim of exploiting source-relay correlation. A sister paper of this article in this special issue [7] combines the ErF concept with bit-interleaved coded modulation with iterative detection (BICM-ID). Reference [6] proposes a very simple serially concatenated coding scheme that can achieve near Slepian-Wolf/Shannon limit [1] performance, even though the structure is very simple. Reference [8] evaluates the outage probability of the ErF relay system in Rayleigh fading channels. The impacts of not only the source correlation but also the correlation of the link variation are theoretically analyzed in [8].

The Slepian-Wolf theorem based relaying systems assume that the information to be transmitted to the FD does not suffer from the errors *before it is encoded*, at the originator. However, if, as shown in Fig. 1, the originator's data is relayed by multiple forwarding nodes, each using the ErF scheme, there is a possibility that none of the forwarding nodes can extract error-free information sent from the originator. This scenario may happen in WMN systems using the ErF strategy, and the FD has to estimate the information sent from the originator from the forwarded sequences, all suffering from errors *before encoding* at the relays.

In network information theory, such problem is classified into Chief Executive Officer (CEO) problem [9]. A primary goal of this paper is to have an insight of the WMN allowing *intra-link errors* from the viewpoint of the CEO problem. We investigate a very simple system of WMN that two forwarding nodes assist to transmit the originator's message to the final FD, as exemplified in Fig. 1.

The terminology CEO problem originates from the situation where a CEO aims to estimate the source information cannot be observed directly; N agents, referred to as forwarding nodes, are deployed to observe/relay the independently corrupted versions of source information sequence $\mathbf{u}$. The observations $\mathbf{u}_i,\ i = 1, 2, \cdots, N$ are separately encoded and forwarded to the FD over transmit power-limited and rate-constrained channels; the FD, which works like a chief executive officer of an organization, tries to reconstruct the source information sequence from the N noisy observations while keeping the distortion lower than an acceptable level. Figure 2 shows the abstract scenario of the CEO problem.

Successive coding strategy for Gaussian CEO problem is considered in [10], [11]. So far, for the quadratic Gaussian CEO problem, where the source $\mathbf{u}$ is represented by a memoryless Gaussian codebook and suffers from independent and identically distributed (i.i.d) Gaussian noise $\mathbf{W}_i,\ i = 1, 2, \cdots, N$, the distortion rate region has already been identified by [12]. However, CEO problems in many other cases are still left as open question. In this paper, we assume that the source information is a binary bit sequence, and suffers from random binary errors, according to the bit flipping model. Furthermore the channels from the forwarding nodes to the FD suffer from zero mean Additive White Gaussian Noise (AWGN) with variance σ^2. Joint decoding is performed at the FD by utilizing the correlation knowledge between the forwarding nodes.

The rest of this paper is organized as follows. The ErF relaying system based on the Slepian-Wolf theorem is briefly introduced in Sect. 2, and then the WMN system model used in this work is also described in Sect. 2. The proposed joint decoding strategy is detailed in Sect. 3. In Sect. 4, we analyze the convergence property of the proposed technique by using the extrinsic information transfer (EXIT) chart. Results of simulations conducted to verify the performance of the proposed technique are shown in Sect. 5. A short discussion on rate optimization for the originator node is then provided in Sect. 6. A consideration on the applicability of the proposed structure to wireless sensor networks (WSNs) is provided in Sect. 7, where the originator in the WMN is replaced by a transition-emitting Markov source. Finally, conclusions are drawn with some concluding remarks in Sect. 8.

2. System Model

2.1 ErF Relaying System Based on Slepian-Wolf Theorem

As shown in Fig. 3, according to the Slepian-Wolf theorem, the admissible rate region is constituted as an unbounded polygon. The source information can be recovered only when the compressed rate pair falls into this area. For instance, we consider the case that two binary information sequences $\mathbf{b}_1$ and $\mathbf{b}_2$ are separately encoded and jointly decoded. If $\mathbf{b}_1$ is compressed at the rate R_1 which is equal to its entropy $H(\mathbf{b}_1)$, then $\mathbf{b}_2$ can be compressed at the rate R_2 which is less than its entropy $H(\mathbf{b}_2)$, but must be greater than its conditional entropy $H(\mathbf{b}_2|\mathbf{b}_1)$, or vice versa. The admissible rate region of the Slepian-Wolf compression is given by the following three inequalities [1]:

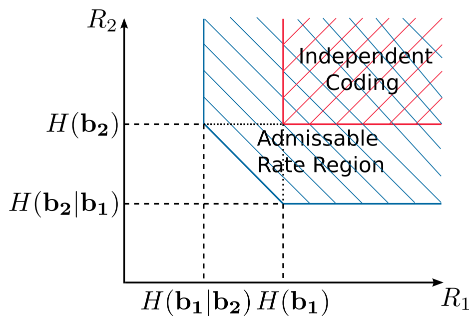

Fig. 3 The admissible rate region of Slepian-Wolf theorem. $\mathbf{b}_1$ and $\mathbf{b}_2$ represent two correlated sources.

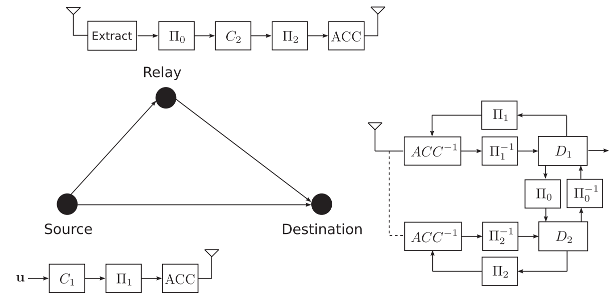

Fig. 4 Extract-and-Forward Relay System. D_1 and D_2 denote the decoders of the channel codes C_1 and C_2 used by the source and the relay, respectively. ACC and ACC^{-1} are the accumulator and de-accumulator, respectively.

$$R_1 \geq H(\mathbf{b}_1|\mathbf{b}_2), \tag{1}$$

$$R_2 \geq H(\mathbf{b}_2|\mathbf{b}_1), \tag{2}$$

$$R_1 + R_2 \geq H(\mathbf{b}_1, \mathbf{b}_2). \tag{3}$$

By exploiting the correlation knowledge of the data streams at the destination, the distributed source coding can achieve the same compression rate as the optimum single encoder which compresses the sources jointly.

If the correlation model of the sources can be expressed as the bit-flipping model [13], i.e., $\mathbf{b}_2 = \mathbf{b}_1 \oplus \mathbf{e}$ and $\Pr(\mathbf{e} = 1) = p_e$, where p_e is the bit-flipping probability and $\oplus$ denotes modulo-2 addition, the Slepian-Wolf theorem can be utilized in relaying systems. Assume that the appearance probabilities of the source information is equiprobable. Then, $H(\mathbf{b}_1) = H(\mathbf{b}_2) = 1$, $H(\mathbf{b}_1|\mathbf{b}_2) = H(\mathbf{b}_2|\mathbf{b}_1) = H(p_e)$, $H(\mathbf{b}_1; \mathbf{b}_2) = 1 + H(p_e)$ with $H(p_e) = -p_e \log_2(p_e) - (1 - p_e)\log_2(1 - p_e)$. Now, let us consider a one-way relaying system, where the relay does not aim to perfectly recover the original information transmitted by the source, but it only "extracts" the source information, even though the relay knows that extracted sequence may contain some errors. As shown in Fig. 4, the extracted sequence representing an estimate of the original information sequence, which is then interleaved and transmitted to the common destination. Obviously, the original and extracted sequences are correlated. If we assume block fading and no heavy decoding of the channel code is performed at the relay, it is reasonable that the source-relay (SR) link can be expressed by the bit-flipping model within the block.

As noted in Introduction, excellent performance can be achieved [2]–[5] through the LLR exchange in the vertical iterations between the two decoders, where to take into account the correlation, represented by the error probability of the intra-link, the LLR is updated by (10) shown in Sect. 3.1. The major aim of this paper is to extend the ErF idea to more generic WMN systems.

2.2 A Very Simple WMN Model

If the ErF strategy is used in more complicated networks having many forwarding nodes, it is quite likely that none of the forwarding nodes at the final stage has error-free information part, nevertheless, performs re-encoding of the error-corrupted versions of the information part, and forward it to the FD. Figures 1 and 4 show the simplest examples of ErF based WMN and ErF relay systems, respectively. It is found that in the case of WMN, none of the signals received by the FD have the originated information part suffering from no errors, because with the ErF scheme, the forwarding nodes do not necessary to completely eliminate the errors in the intra-link. Hence, the issues related to WMN utilizing the ErF scheme belong to the CEO problem.

Figure 5 shows a simple model of WMN, describing from the viewpoint of the CEO problem, with only two forwarding nodes, assumed in this paper. For the encoders C_0, C_1 and C_2 in this model, we use only memory-1 $(2,3)_8$ half rate ($R = 1/2$) convolutional codes. The structure of doped-accumulator (ACC) can be found in references [4]. As noted in [4], ACC is a rate-1 systematic recursive convolutional code, where every P-th systematic bit is replaced by the accumulated coded bits.

At the originator node, the original binary information sequence to be transmitted, $\mathbf{x}$, is first encoded by C_0. The encoded bit sequence is then interleaved by random interleaver Π_0 and doped-accumulated by ACC with doping ratio $P = P_{ori}$. The output of ACC, $\mathbf{u}$, is broadcasted to the two forwarding nodes over independent Binary Symmetric Channels (BSC) with crossover probabilities p_1 and p_2, respectively, which can be modeled by the bit-flipping model. Note that in this paper, p_1 and p_2 are assumed to be known at the FD with the help of higher layer protocol.

As in the ErF relay system, aiming at perfect decoding at the forwarding nodes is out of the scope, because it needs very strong *link-level* codes. Instead, each forwarding node makes only tentative decision on the received bit sequences, of which results $\mathbf{u}_1$ and $\mathbf{u}_2$ are first permutated by Π_1 and Π_2 and further encoded by C_1 and C_2, respectively. The encoded sequences are again doped-accumulated by ACC with doping ratio $P = P_{for}$. The doped-accumulated bits are modulated by BPSK, i.e., $0 \to -1$ and $1 \to +1$, and then forwarded to the FD at different time slots over AWGN channels. We assume the signal-to-noise ratios (SNRs) are the same in the two channels. The received signal sequence can be expressed as:

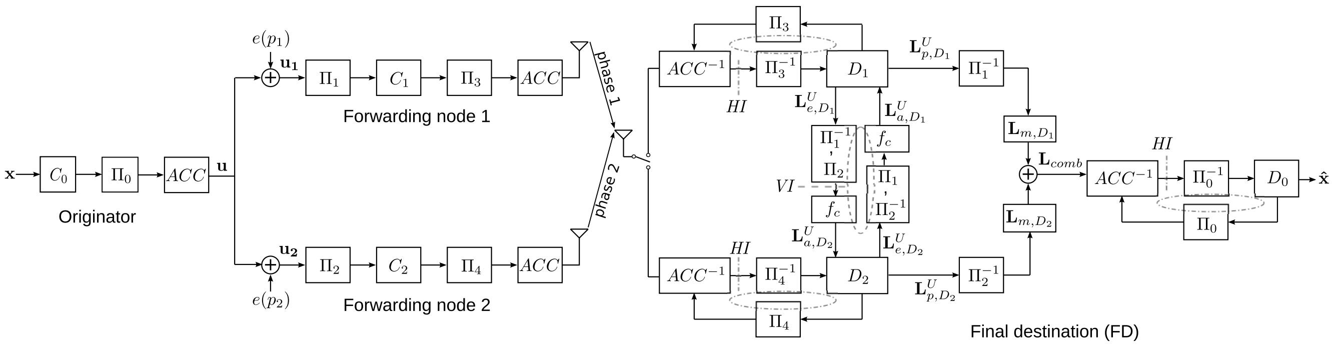

Fig. 5 Structure of the proposed system for a very simple WMN. Only two forwarding nodes are considered.

$$\mathbf{y}_i = \mathbf{s}_i + \mathbf{n}_i, \tag{4}$$

where $i = 1, 2$ and $\mathbf{s}_i$ denotes the modulated signal sequence. $\mathbf{n}_i$ are zero mean i.i.d complex Gaussian noise with variance σ^2 per dimension. After receiving $\mathbf{y}_i$, the channel LLRs are first calculated by

$$L_{ch}(y_i^k) = \log \frac{\Pr(y_i^k|s_i^k = +1)}{\Pr(y_i^k|s_i^k = -1)} = \frac{2}{\sigma^2} y_i^k, \tag{5}$$

where y_i^k and s_i^k are the k-th symbol of $\mathbf{y}_i$ and $\mathbf{s}_i$, respectively. At the FD, joint decoding is performed by exchanging the extrinsic LLRs which is detailed in next section.

3. Proposed Joint Decoding Strategy

Joint decoding process is divided into two iteration processes as depicted in Fig. 5. We refer these two processes to Horizontal Iteration (*HI*) and Vertical Iteration (*VI*). To perform the channel decoding for convolutional codes C_0, C_1 and C_2 as well as for ACC, we perform Maximum A Posteriori (MAP) decoding using the Bahl-Cocke-Jelinek-Raviv (BCJR) algorithm [14].

In the *HI*, the extrinsic LLRs are exchanged through the corresponding interleaver/de-interleaver between the soft-in-soft-out (SISO) decoder ACC^{-1} and SISO decoder D_1 or D_2 used by the forwarding nodes 1 and 2, respectively. The extrinsic information exchange is performed via *HI* until no more significant mutual information (MI) improvement can be achieved. However, activation order on the two *HI* loops are the design parameters and hence optimization of the activation ordering is out of the scope of this paper. After each *HI* step, we activate *VI* loop between D_1 and D_2 by exchanging, via an LLR updating function f_c, the output extrinsic LLRs of uncoded (systematic) bits output from the two decoders D_1 and D_2. The purpose of *VI* is to help the two decoders D_1 and D_2 cooperate each other to reconstruct originator's information. This is because since the uncoded bit sequences are originated from the common originator and forwarded by the two forwarding nodes, they are correlated. Hence, the aim is to fully exploit the knowledge about the correlation, available at the FD node.

After performing LLR exchange several times via the *HI*-*VI* loops, the *a posteriori* LLRs output from D_1 and D_2 are combined. Before combining, however, the LLRs are further modified by [15], [16]

$$\mathbf{L}_{m,D_i} = \log\left(\frac{1-p_i}{p_i}\right) \cdot \mathrm{sign}(\mathbf{L}^U_{p,D_i}), \tag{6}$$

where $i = 1, 2$ and p_i represents the error probabilities of the intra-links. $\mathbf{L}^U_{p,D_i}$ are the *a posteriori* LLRs of the uncoded bits output from D_i.

The combined modified LLRs, $\mathbf{L}_{comb}$, is forwarded to another horizontal iteration loop at the FD to finally obtain the originator's information bit sequence. This process is the same as the *HI* described above. Finally, hard decisions are made on the *a posteriori* LLRs obtained by the decoder D_0.

3.1 LLR Updating Function

As described above, the received bit sequences at the two forwarding nodes are transmitted from the same originator, but corrupted by errors quite likely occurring at different positions. The technique described above aims to utilize the correlation knowledge between them to achieve better performance.

It is quite straightforward according to [4], [6] that we can obtain the following equations:

$$\begin{cases} \Pr(u_1^k = 0) = (1-p_1)\Pr(u^k = 0) + p_1 \Pr(u^k = 1), \\ \Pr(u_1^k = 1) = (1-p_1)\Pr(u^k = 1) + p_1 \Pr(u^k = 0), \end{cases} \tag{7}$$

$$\begin{cases} \Pr(u^k = 0) = (1-p_2)\Pr(u_2^k = 0) + p_2 \Pr(u_2^k = 1), \\ \Pr(u^k = 1) = (1-p_2)\Pr(u_2^k = 1) + p_2 \Pr(u_2^k = 0), \end{cases} \tag{8}$$

where u^k, u_1^k and u_2^k denotes the k-th symbol of $\mathbf{u}$, $\mathbf{u}_1$ and $\mathbf{u}_2$, respectively. Substituting (8) into (7), and after several mathematical manipulations, we can derive the probability updating equation between the two forwarding nodes, as:

$$\begin{cases} \Pr(u_1^k = 0) = (1-\hat{p})\Pr(u_2^k = 0) + \hat{p}\Pr(u_2^k = 1), \\ \Pr(u_1^k = 1) = (1-\hat{p})\Pr(u_2^k = 1) + \hat{p}\Pr(u_2^k = 0), \end{cases} \tag{9}$$

where $\hat{p} = p_1 + p_2 - 2p_1 p_2$. Equation (9) is equivalent to the LLR updating function f_c for u_1^k as

$$L(u_1^k) = f_c[L(u_2^k), \hat{p}] = \log \frac{(1-\hat{p}) \cdot \exp[L(u_2^k)] + \hat{p}}{(1-\hat{p}) + \hat{p} \cdot \exp[L(u_2^k)]}, \quad (10)$$

based on the value $\hat{p}$ and the LLRs of u_2^k. The LLR updating function for u_2^k can be obtained in the similar way.

In summary, the *VI* operation of the proposed decoder, as shown in Fig. 5, can be expressed as

$$\mathbf{L}^U_{a,D_1} = f_c\{\Pi_1[\Pi_2^{-1}(\mathbf{L}^U_{e,D_2})], \hat{p}\}, \quad (11)$$

$$\mathbf{L}^U_{a,D_2} = f_c\{\Pi_2[\Pi_1^{-1}(\mathbf{L}^U_{e,D_1})], \hat{p}\}, \quad (12)$$

where $\Pi_i(\cdot)$ and $\Pi_i^{-1}(\cdot)$ denote interleaving and de-interleaving functions corresponding to Π_i, respectively, $i = 1, 2$. $\mathbf{L}^U_{a,D_1}$ and $\mathbf{L}^U_{e,D_1}$ denote the *a priori* LLRs fed into, and extrinsic LLRs generated from D_1, both for the uncoded bits, respectively. Similar definitions can apply to $\mathbf{L}^U_{a,D_2}$ and $\mathbf{L}^U_{e,D_2}$. By performing the *VI* operation with f_c function, the extrinsic LLRs are updated, which takes into account the impact of intra-link error probabilities.

4. EXIT Chart Analysis

Result of EXIT chart analysis [17], [18] that indicate the convergence properties of the proposed system is provided in this section. The EXIT chart analysis for the iterations $ACC^{-1} \rightleftharpoons D_i$, $i = 0, 1, 2$ are presented, where notation "$\rightleftharpoons$" denotes LLR exchange between the two components on both ends. In the simulations for EXIT chart analysis, 12000 information bits were used.

First of all, the *HI* between *ACC* decoder and D_1 is considered. As shown in the Fig. 5, two *a priori* LLR sequences, $\mathbf{L}^C_{a,D_1}$ and $\mathbf{L}^U_{e,D_2}$, are fed into D_1, while only one LLR sequence, $\mathbf{L}^U_{a,ACC}$, is fed into *ACC*. Therefore, we evaluate the transfer function for D_1 and *ACC* as

$$I^C_{e,D_1} = T^C_{D_1}(I^C_{a,D_1}, I^U_{e,D_2}, \hat{p}), \quad (13)$$

$$I^U_{e,ACC} = T^U_{ACC}(I^U_{a,ACC}, SNR), \quad (14)$$

where I^C_{e,D_1} represents the MI between the extrinsic LLRs of the coded bits generated from D_1, $\mathbf{L}^C_{e,D_1}$, and the transmitted coded bits. Similar definitions should apply to I^C_{a,D_1}, I^U_{e,D_2}, $I^U_{a,ACC}$ and $I^U_{e,ACC}$. From (13) and (14), it is quite straightforward that we use three-dimensional (3D) EXIT chart [13], [19] to visualize the extrinsic MI exchange between *ACC* decoder and D_1 as well as D_1 and D_2, as shown in Fig. 6. Note that since interleaving/de-interleaving does not change mutual information, $I^U_{a,ACC}$ and $I^U_{e,ACC}$ are equal to I^C_{e,D_1} and I^C_{a,D_1}. The doping ratio for *ACC* is set as $P_{for} = 2$ and the crossover probabilities of the BSC channels are set as $p_1 = 0.05$, $p_2 = 0.06$. For both the channels between the forwarding nodes and the FD, SNR = −3.6 dB. The trajectory was obtained by evaluating the MI between extrinsic LLRs and the corresponding information bits, by partially independent simulations using the EXIT chart projection technique [19]. It can be observed that with SNR = −3.6 dB,

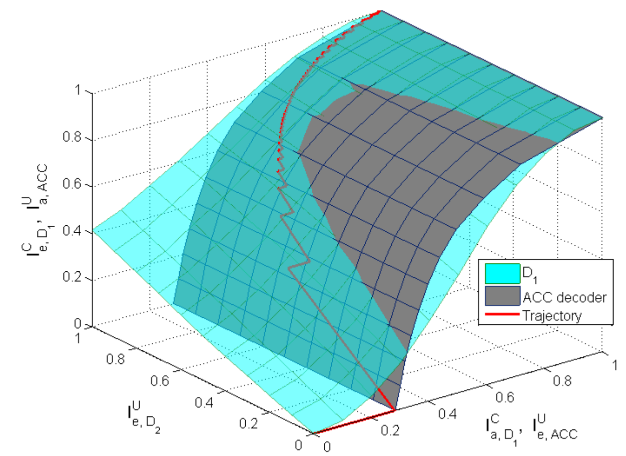

Fig. 6 The 3D EXIT chart of the *HI* loop for the transmission chain of the forwarding node 1. The doping ratio for *ACC* is $P_{for} = 2$ and the crossover probabilities for the BSC channels are $p_1 = 0.05$ and $p_2 = 0.06$. For the both links between the forwarding nodes and the FD, SNR = −3.6 dB.

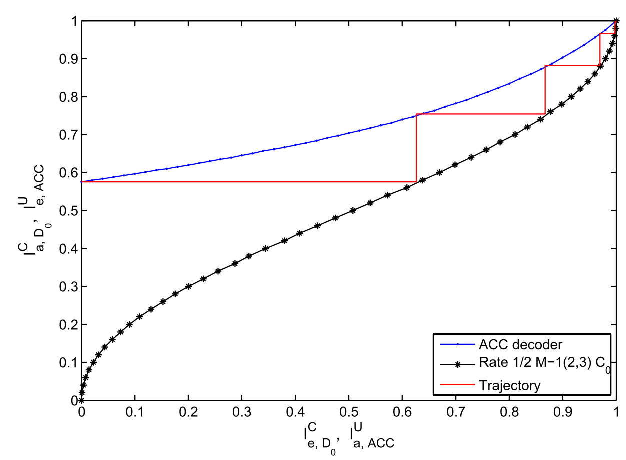

Fig. 7 The EXIT chart of the *HI* loop for the transmission chain of the originator. The doping ratio for *ACC* is $P_{ori} = 2$ and the crossover probabilities for the BSC channels are $p_1 = 0.05$ and $p_2 = 0.06$.

after sufficient times of iterations, the trajectory can finally reach a point very close to the (1.0,1.0,1.0) MI point. Since D_1 and D_2 are identical, the 3D EXIT chart of the *HI* loop for the transmission chain of the forwarding node 2 can be obtained in the same way.

Figure 7 shows the EXIT curves and trajectory of the *ACC* decoder and D_0 where $p_1 = 0.05$, $p_2 = 0.06$ and $P_{ori} = 2$. After several iterations, the trajectory achieves (1.0,1.0) point and the originator's information be recovered completely. It should be emphasized here that Fig. 7 indicates the case where the two *HI*s were performed as many times as no more gain in MI can be obtained. However, even without full iterations of the two *HI* loops, which results in even smaller value of MI after the *a posteriori* LLRs combining, the EXIT curves of *ACC* decoder and D_0 do not intersect until a point very close to the (1.0, 1.0) MI point. According to our simulations, MI = 0.73 after the *a posteri-*

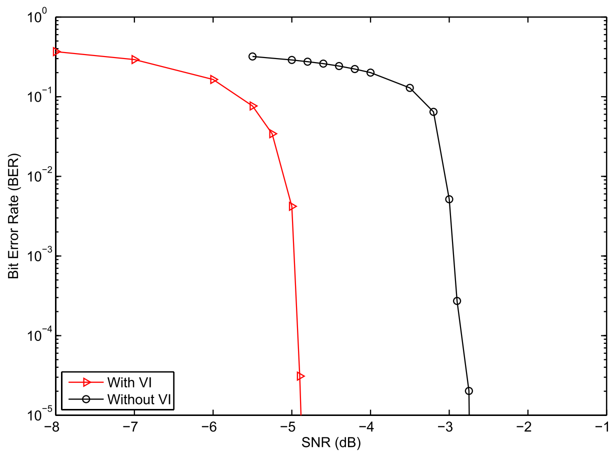

Fig. 8 BER performance for the proposed system. The crossover probabilities for the BSC channels are $p_1 = 0.01$ and $p_2 = 0.02$.

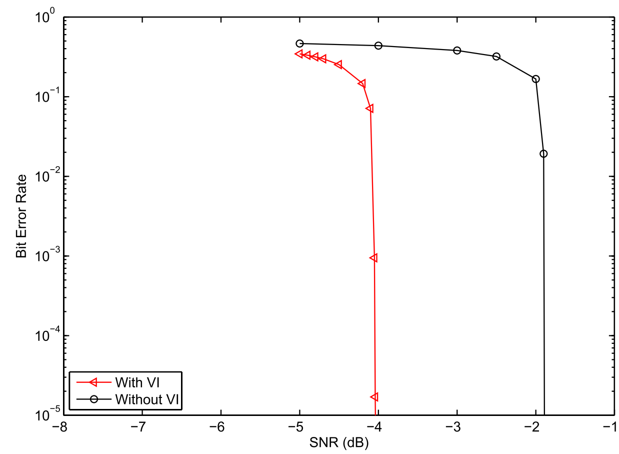

Fig. 9 BER performance for the proposed system. The crossover probabilities for the BSC channels are $p_1 = 0.05$ and $p_2 = 0.06$.

ori LLR combining, which is the case of non-full iterations of the two *HI*s, can still keep the tunnel open.

5. Simulation Results

BER performances of the proposed system with three representative value pairs of p_1 and p_2 are shown in Fig. 8, Fig. 9 and Fig. 10, respectively. In our simulations, we set the frame length at 100000 information bits. 30 *HI*s and 5 *VI*s are performed in the joint decoding part at the FD. After LLR combing according to (6), 10 *HIs* are performed to get the estimate of the original information.

The BER performance of the proposed system for two relatively small p_1 and p_2 value pairs, which are described in the figure captions, are illustrated in Figs. 8 and 9, respectively. It is found that, clear turbo cliff can be achieved over the AWGN channel. Also, we can see that, a performance gain of about $2-3$ dB can be achieved with *VI* over without *VI*. The larger the gain, the smaller the $\hat{p}$ value, in which case the two forwarding nodes are highly correlated.

Figure 10 shows the BER performance for a relatively large p_1 and p_2 value pair ($p_1 = 0.1, p_2 = 0.2$). Since with such high intra-link error probabilities, the area of the admissible rate region supported by the Slepian-Wolf theorem is relatively small, compared with the independent coding case. Hence, the benefit of the proposed structure decreases. As shown in Fig. 10, turbo cliff can be achieved even without *VI* and performance gain of about 0.7 dB can be achieved with *VI* over without *VI*. Figure 10 also shows the BER curve without the LLR modification before combining them, performed to take into account the intra-link error probabilities by (6). It can be seen that without the LLR modification, the error floor appears at very high BER range ($\approx 10^{-1}$), compared with that with modification.

6. Rate Optimization

Since the gaps between the EXIT curves of *ACC* decoder and D_0 is large as shown in Fig. 7, we can increase the rate of

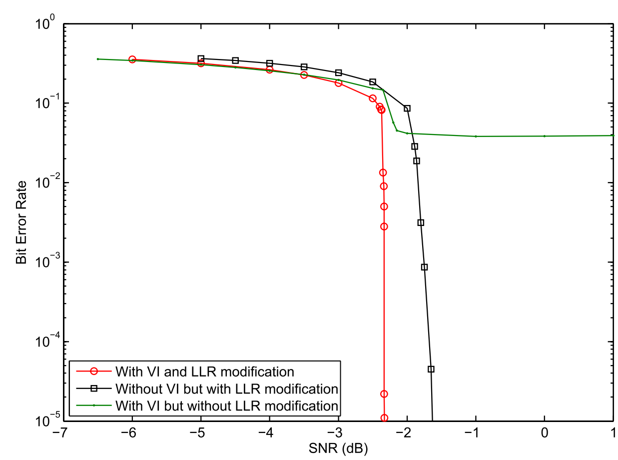

Fig. 10 BER performance for the proposed system. The crossover probabilities for the BSC channels are $p_1 = 0.1$ and $p_2 = 0.2$.

C_0, for example by using punctured convolutional codes, to achieve better matching of the two EXIT curves. As shown in Fig. 11[†], it is found that even if we increase the coding rate of C_0 from 1/2 to 2/3, still it is possible to achieve arbitrarily low BER. Because the convergence tunnel is open until a point very close to the (1.0, 1.0) MI point. However, since the gap between the two EXIT curves is still not very small, reducing the gap, which is related to the optimal code design issue, is left as future study.

In fact, we do not provide in-depth information theoretic considerations on the relationship between the distortions and rate region [20] in this paper. However, when we seek for the optimal rate allocations to the codes used by the originator and forwarding nodes, we have to first identify the relationship from the viewpoint of the CEO problem.

It is expected that the more forwarding nodes involved, still error-free communication is possible with a high rate

[†]The decoding trajectory is not shown in this figure, because the purpose of this figure is to confirm the matching issue of the EXIT curves.

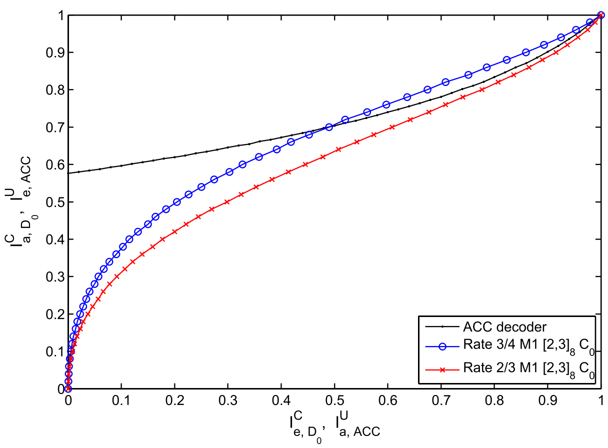

Fig. 11 EXIT curves of *ACC* decoder and D_0 with different coding rates for C_0. The doping ratio for *ACC* is $P_{ori} = 2$ and the crossover probabilities for the BSC channels are $p_1 = 0.05$ and $p_2 = 0.06$.

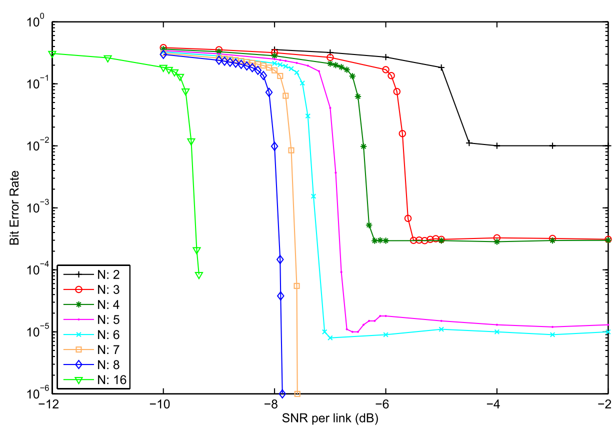

Fig. 12 BER performance of proposed coding scheme with different number of forwarding nodes, C_0 and ACC in the originator node are eliminated. The crossover probabilities of the BSC channels are $p_i = 0.01$, $i = 1, 2, \cdots, N$.

of C_0, and ultimately, we may be able to eliminate C_0 [21], [22]. Figure 12 demonstrates the BER performance of the proposed coding scheme versus SNR per link with different number of forwarding nodes as a parameter. Channel coding is not performed at the originator (i.e., C_0 and ACC are eliminated). The crossover probabilities of all the BSC channels are assumed to be the same, as $p_i = 0.01,\ i = 1, 2, \cdots, N^{\dagger}$. It is found that as the number of forwarding nodes is increased, the BER performance of the system is improved at the cost of higher receiver complexity. To achieve lower error floor, a larger number of parallel links must be employed, for example, 7 or more forwarding nodes are needed to guarantee error-free communication, as shown in Fig. 12. It should be noted here that the error floor is defined by the number of forwarding nodes and the crossover probabilities of the BSC channels, thus the error floor is independent of the SNR value [22].

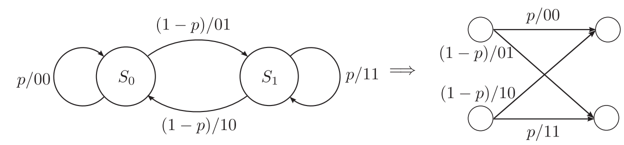

Fig. 13 State transition emitting Markov model and its trellis diagram. Transition $S_i \to S_j$ generates (i, j), $i, j \in \{0, 1\}$.

7. Application to Wireless Sensor Network

In WSN, a number of sensors are deployed to observe the sensing target. In this section, the results of the investigations we have made above are applied to a very simple WSN, where the observations at each sensor are corrupted by a bit-flipping error. Thus the source-sensor link can be modeled as a BSC channel. After obtaining the observations, the sensors will encode and transmit the encoded bits to the FD over AWGN channels. Finally, the FD performs joint decoding to retrieve the original source sequence. When comparing the WSN model to the WMN model, it is found that the source corresponds to the originator and the sensors to the forwarding nodes. Therefore, it is reasonable to apply the proposed coding/decoding scheme to WSN. It should be emphasized that the source itself does not have the capability for encoding/decoding, which means that the C_0 and ACC in the originator and its corresponding *HI* in the FD should be eliminated. However, according to the dynamics that governs the temporal behavior of the sensing object, the source information sequence are temporally correlated, which can be modeled as a Markov source. In this paper, we assume that the source is modeled as a state transition emitting Markov source, as shown in Fig. 13. The source decoding can be performed by using the BCJR algorithm based on its trellis diagram.

Figure 14 shows the BER performance for the proposed technique applied to WSN. For the sake of simplicity, only two sensors are considered. It can be observed that with the help of the Markov source decoding, the performance of the system can be improved. However, the temporal property of the Markov source can be used to correct errors if the BER before source decoding p_b and the state transition probability p satisfy the following condition [23]

$$p_b \geq \frac{(1-p)^2}{p^2 + (1-p)^2}. \tag{15}$$

As can be seen from the figure, if the SNR value is larger than −4 dB, $p_b \approx 0.01$. For Markov sources with $p = 0.9, 0.8, 0.7$, p_b and p do not satisfy this inequality. Therefore, the error floor remains the same even with different p values ($p = 0.9, 0.8, 0.7$). On the contrary, when SNR falls

† For the case $N > 2$, the *VI* is performed in a pairwise manner between all the *HI*s of the corresponding forwarding nodes, according to (11) and (12). For every single *HI*, the updated extrinsic LLRs from all the other *HI*s are then combined and fed into the *HI* of interest as *a priori* LLRs.

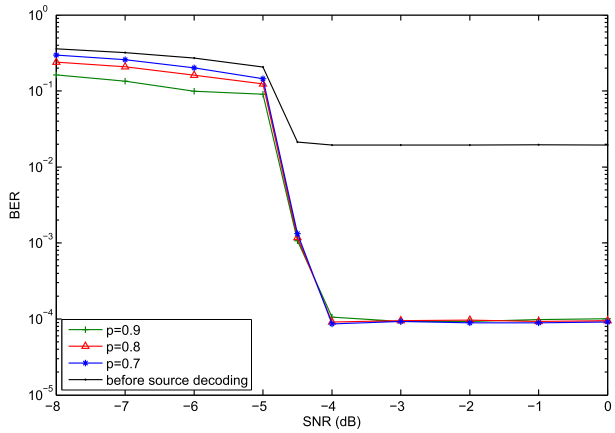

Fig. 14 BER performance for the proposed technique applied to WSN, the source is assumed to be a transition emitting Markov source. Only two sensors are considered, the crossover probabilities are $p_1 = 0.01$ and $p_2 = 0.02$.

under −5 dB, p_b and p satisfy (15) and the Markovianity of the source can be used to correct errors. It can be found that the BER becomes smaller as the state transition probability p increases. However, the BER curves still stay impractically high.

8. Conclusions

In this paper, we have examined coding and decoding strategies on the issue of WMNs from the CEO problem viewpoint. In WMNs, the energy and spectrum efficiencies should be optimized as the whole network rather than an assembly of many P2P connections. Each forwarding node is assumed to be a small transceiver, where energy consumption is a serious problem. We thereby proposed a very simple strategy at the forwarding nodes and a *joint* decoding scheme by exploiting the correlation knowledge among *intra-links* at the FD. Even though errors are detected in the sequences received by the forwarding nodes, they are correlated. Hence, the lossy distributed correlated source coding [20] should be the theoretical basis of the WMNs transmission chain design.

The simulation results show that considerable gains can be achieved, compared with separately decoding scheme. By optimizing the code parameters, close-limit BER performance can be expected, which belongs to the issue of the standard EXIT matching problem. If more forwarding nodes are involved, still error-free (or, at least, very low BER) communication can be achieved even if no channel coding is performed at the originator, which is demonstrated by the simulation results. The proposed coding/decoding strategies have been applied to WSNs where the source is modeled as a state transition emitting Markov source. The simulation results indicate that the source decoding can help improve the BER performance of the system. However, whether the Markovianity can be used to correct errors depends on the relationship between the state transition probability of the source and the BER before source decoding.

Acknowledgments

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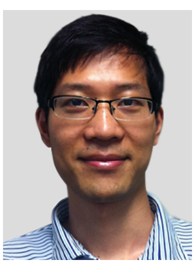

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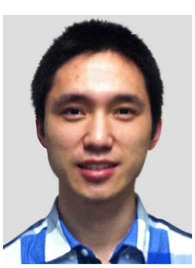

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