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Description	

Wireless Mesh Networks Allowing Intra-Link Errors: CEO Problem Viewpoint

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***Abstract*—In this paper, we re-formulate an issue related to wireless mesh networks (WMNs) from a Chief Executive Officer (CEO) problem viewpoint, and provide a practical solution to a simple case of the problem. The problem is described as follows: an originator broadcasts its binary source information to several forwarding nodes over Binary Symmetric Channels (BSC); the originator's source information suffers from independent random binary errors; at the forwarding nodes, they just further interleave, encode the received bit sequence, and then forward it, without correcting errors that may be happening in the originator-forwarding node links (*intra-links*), to the final destination (FD) over Additive White Gaussian Noise (AWGN) channels. This strategy reduces the complexity of the forwarding node significantly. A joint decoding technique at the FD is proposed by using the correlation knowledge between *intra-links*. 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. Moreover, we provide BER performance comparison between joint decoding and separate decoding strategies. The optimization of coding rate at originator side is also considered in this paper. 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 convergency property of the proposed technique.**

I. 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 user, 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 Networks (WMNs) are a form of cooperative communications system, in which multiple nodes cooperate to relay messages to the destinations. High data throughput, power and spectral efficiencies, as well as better resource utilization are expected. 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.

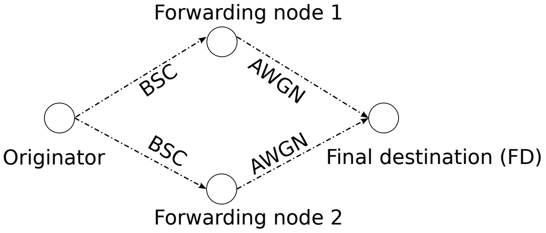

Fig. 1. The schematic diagram of WMN

A primary goal of this paper is have an insight of the WMN allowing *intra-link* errors from the viewpoint of the CEO problem. We investigate a simple system of WMN that two forwarding nodes assist to transmit the originator's message to the final destination (FD), as exemplified in Fig. 1. We model this system by a distributed remote source coding model, which is called Chief Executive Officer (CEO) problem [1] in Network Information Theory.

The terminology CEO problem originates from the situation where a CEO aims to estimate the source information which cannot be observed directly; N agents, referred to as forwarding nodes, are deployed to observe/relay 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 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. Fig. 2 shows an abstract scenario of the CEO problem. Successive coding strategy for Gaussian CEO problem is considered in [2], [3]. So far, 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 $\mathbf{W}_{1 \dots N}$, has already been solved [4]. However, CEO problems in many other cases are still left as open question.

In this work, we assume that the source information is a binary bit sequence, and suffers from random binary errors.

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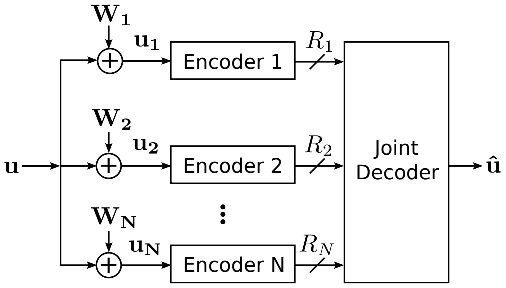

Fig. 2. An abstract model of CEO problem

Furthermore the channels from the forwarding nodes to the FD suffers from Additive White Gaussian Noise (AWGN). 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 system model used in this work is described in Section II. The proposed joint decoding strategy is detailed in Section III. In Section IV, we analyze the convergence property of 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 Section V. A short discussion on rate optimization for the originator and forwarding nodes' encoder is then provided in Section VI. Finally, the conclusions are drawn with some concluding remarks in Section VII.

II. SYSTEM MODEL

Fig. 3 shows a simple model of WMN, describing the viewpoint of the CEO problem, with only two forwarding nodes, assumed in this paper. The case of involving more forwarding nodes is further presented in [5]. 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 [6]. As noted in [6], ACC is a rate-1 systematic recursive convolutional code with which every P-th systematic bits are replaced by the accumulated coded bits.

At the originator node, the original information bit sequence $\mathbf{x}$ to be transmitted 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_{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 [7].

Aiming at perfect decoding at the forwarding nodes is out of the scope of this paper, 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 channel between the transmitted information sequence $\mathbf{u}$ and the one $\mathbf{u}_i$ obtained as the result of the tentative decoding can be seen as also BSCs with the crossover probabilities p_1 and p_2, which can be modeled by the bit-flipping model, where $i = 1, 2$ is the node index.

Since perfect recovery of information sequence transmitted from the originator node is not aimed at in the forwarding nodes, the complexity of forwarding nodes is very light. Then, the encoded sequences are again interleaved by Π_3 and Π_4, and doped-accumulated by ACC with doping ratio P_{for}. The doped-accumulated bit sequences 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 between forwarding nodes and the FD. The received signal sequences can be expressed as:

$$\mathbf{y}_{i,j} = \mathbf{s}_{i,j} + \mathbf{n}_j, \tag{1}$$

where $i = \{1, 2\}$ denotes the index of the forwarding nodes and j is the symbol timing index. The modulated signal sequence is denoted by $\mathbf{s}_{i,j}$. $\mathbf{n}_j$ represents noise that are zero mean i.i.d complex value with variance σ^2 per dimension.

After receiving the signal $\mathbf{y}_{i,j}$, the channel log-likelihood ratios (LLRs) are first calculated by:

$$\mathbf{L}^{ch}_{i,j} = \log \frac{\Pr(\mathbf{y}_{i,j}|\mathbf{s}_{i,j} = +1)}{\Pr(\mathbf{y}_{i,j}|\mathbf{s}_{i,j} = -1)} = \frac{2}{\sigma^2}\mathbf{y}_{i,j}. \tag{2}$$

At the FD, joint decoding is performed by exchanging the extrinsic LLRs which is detailed in section III.

III. JOINT DECODING STRATEGY

Joint decoding process is divided into two iteration processes as depicted in Fig. 3. 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 BCJR algorithm proposed by Bahl, Cocke, Jelinek and Raviv [8].

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 C_1^{-1} or C_2^{-1} used by the forwarding node 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 times on the two *HI* loops are 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 C_1^{-1} and C_2^{-1} by exchanging the output extrinsic LLRs of uncoded (systematic) bits output from the two decoders C_1^{-1} and C_2^{-1} via an LLR updating function f_c. The purpose of *VI* is to help two decoders C_1^{-1} and C_2^{-1} cooperate each other to reconstruct information. This is because since the uncoded bit sequences, are originated from the common originator node and forwarded by the two forwarding nodes, they are correlated. Hence, the aim is to fully exploit the knowledge about the correlation at the FD node.

After performing LLR exchange several times via the *HI-VI* loops, the *a posteriori* LLRs output from C_1^{-1} and C_2^{-1}

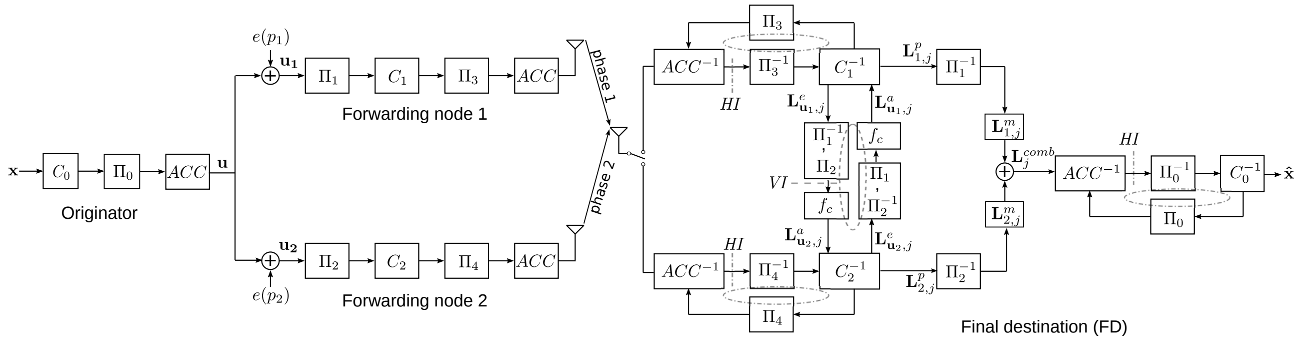

Fig. 3. Structure of the proposed system for a simplified WMN. Only two forwarding nodes are included.

are combined. Before combing, however, the LLRs are further modified by (3) [9] [10]. We assume that the error probabilities values p_1 and p_2 are estimated at the forwarding nodes, and the estimates are forwarded to the FD with the help of higher layer protocols, however, they may be estimated at the FD only similarly to [6].[1]

$$\mathbf{L}_j^{comb} = \sum_{i=1}^{2} \mathbf{L}_{i,j}^{m} = \sum_{i=1}^{2} \log \frac{1-p_i}{p_i} \mathrm{sign}(\mathbf{L}_{i,j}^{p}). \tag{3}$$

p_i represents the error probabilities of the originator-forwarding node *link* referred to as *intra-link*. $\mathbf{L}_{i,j}^{p}$ are the *a posteriori* LLRs from C_1^{-1} and C_2^{-1}. The function sign$(\cdot)$ takes the sign (positive or negative) of its argument.

The modified LLRs $\mathbf{L}_j^{comb}$ are forwarded to another horizontal iteration loop to finally obtain the originator's source information bit sequence $\hat{\mathbf{x}}$. This process is the same as the *HI* described above. Finally, hard decisions are made on the *a posteriori* LLRs obtained by the decoder C_0^{-1}.

A. LLR updating function

As described above, the received bits sequences at two forwarding nodes are transmitted from the same originator, but corrupted by errors happening at different positions. The technique described above aims to utilize the correlation knowledge between them to achieve better performance. Although, p_i may be estimated from the *a posteriori* LLRs of the uncoded bits, we assume p_i are known at the FD that in this work.

It is very straightforward according to [7] that we can obtain the following equation:

$$\left.\begin{array}{l} \Pr(\mathbf{u}_1=0) = (1-p_1)\Pr(\mathbf{u}=0) + p_1\Pr(\mathbf{u}=1) \\ \Pr(\mathbf{u}_1=1) = (1-p_1)\Pr(\mathbf{u}=1) + p_1\Pr(\mathbf{u}=0) \end{array}\right\} \tag{4}$$

$$\left.\begin{array}{l} \Pr(\mathbf{u}=0) = (1-p_2)\Pr(\mathbf{u}_2=0) + p_2\Pr(\mathbf{u}_2=1) \\ \Pr(\mathbf{u}=1) = (1-p_2)\Pr(\mathbf{u}_2=1) + p_2\Pr(\mathbf{u}_2=0) \end{array}\right\} \tag{5}$$

Substituting (5) into (4), we can derive the probability updating equation between the two forwarding nodes, as:

$$\left.\begin{array}{l} \Pr(\mathbf{u}_1=0) = (1-\hat{p})\Pr(\mathbf{u}_2=0) + \hat{p}\Pr(\mathbf{u}_2=1) \\ \Pr(\mathbf{u}_1=1) = (1-\hat{p})\Pr(\mathbf{u}_2=1) + \hat{p}\Pr(\mathbf{u}_2=0) \end{array}\right\}, \tag{6}$$

where $\hat{p} = p_1 + p_2 - 2p_1p_2$. Eq. (6) is equivalent to the LLR updating function f_c shown in (7), based on the value $\hat{p}$ and the extrinsic LLRs of the uncoded bits obtained as the results of C_1^{-1} and C_2^{-1}.

$$\mathbf{L}^a_{\mathbf{u}_1,j} = f_c(\mathbf{L}^e_{\mathbf{u}_2,j}, \hat{p}) = \log \frac{(1-\hat{p}) \cdot \exp(\mathbf{L}^e_{\mathbf{u}_2,j}) + \hat{p}}{(1-\hat{p}) + \hat{p} \cdot \exp(\mathbf{L}^e_{\mathbf{u}_2,j})}, \tag{7}$$

where, $\mathbf{L}^e_{\mathbf{u}_2,j}$ denotes the extrinsic LLRs of the uncoded bit sequence from C_2^{-1}. By performing the operation f_c, the extrinsic LLRs are updated, which takes into account the *intra-link* errors. The LLR updating function for $\mathbf{u}_2$ can be easily obtained in the similar way.

IV. EXIT CHART ANALYSIS

Result of EXIT chart analysis [11] that indicate the convergency properties of the proposed system is provided in this section. The EXIT chart analysis covers the iterations $ACC^{-1} \rightleftharpoons C_i^{-1}$ and $ACC^{-1} \rightleftharpoons C_0^{-1}$, where notation "$\rightleftharpoons$" denotes LLR exchange. We use three-dimensional (3D) EXIT chart to visualize the extrinsic information exchange between ACC^{-1} and C_1^{-1} as well as C_1^{-1} and C_2^{-1}. As shown in the Fig. 3, two *a priori* LLR sequences are fed to C_1^{-1}. Therefore, we evaluate the transfer function for C_1^{-1} in the form of:

$$I^e_{c_1} = T_1(\mathbf{L}^a_{\mathbf{c}_1,j}, f_c(\mathbf{L}^e_{\mathbf{u}_2,j}, \hat{p})), \tag{8}$$

where $I^e_{c_1}$ represents the mutual information between the LLRs of the coded bits obtained by C_1^{-1}, and their corresponding transmitted bits . $\mathbf{L}^a_{\mathbf{c}_1,j}$ denotes the *a priori* LLRs provided into C_1^{-1}, which is equivalent to the extrinsic LLRs of coded bits output from ACC^{-1}. The extrinsic LLRs of the uncoded bits output from C_2^{-1}, $\mathbf{L}^e_{\mathbf{u}_2,j}$, is updated by the f_c function and then fed to C_1^{-1}. The transfer function for C_2^{-1} can be obtained in the same way as (8) was derived.

The 3D EXIT chart illustrated in Fig. 4 is with parameters BSC crossover probabilities $p_1 = 0.05$, $p_2 = 0.06$ and doping ratio $P_{for} = 2$ at SNR $= -3.6$ dB for both the channels between the forwarding nodes and the FD. Since the C_1^{-1} and C_2^{-1} are symmetric, we only show the 3D EXIT chart of the *HI* loop for the transmission chain of the forwarding node 1 and trajectory which is obtained by evaluating the mutual information between extrinsic LLRs and the corresponding information bit sequence, by independent (non

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[1] Techniques to estimate p_1 and p_2 will be presented in another paper.

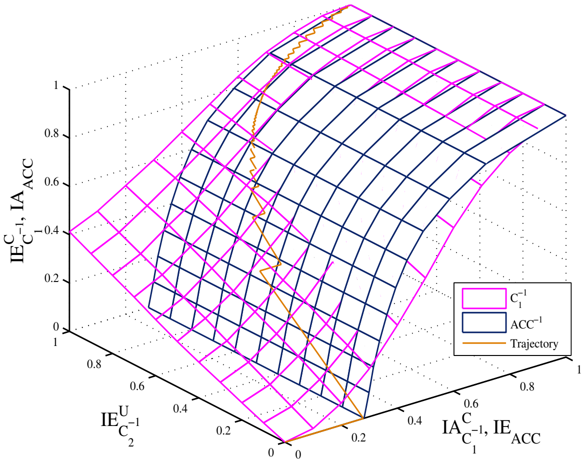

Fig. 4. The 3D EXIT chart of the HI loop for the transmission chain of the forwarding node 1. The doping ratio for ACC is P_{for} = 2 and the crossover probabilities for the BSC channels are $p_1 = 0.05$ and $p_2 = 0.06$. For the both links between the forwarding nodes and FD, SNR $= -3.6$ dB.

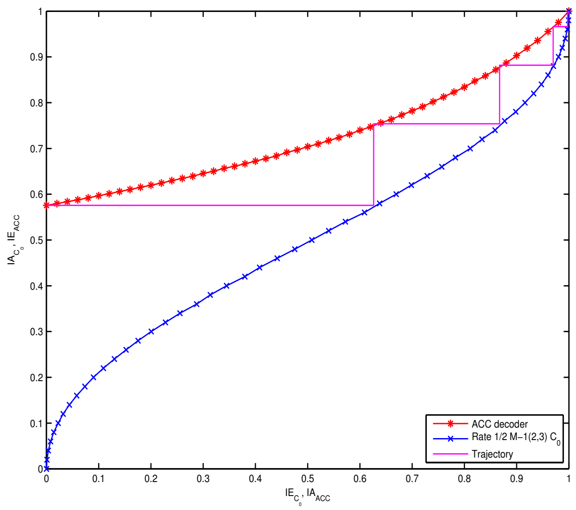

Fig. 5. EXIT curves of ACC^{-1} with doping ratio $P_{ori} = 2$ and C_0^{-1} with rate $1/2$. BSC crossover probabilities $p_1 = 0.05$ and $p_2 = 0.06$.

chained) simulation. Under large enough SNR and sufficient times of iterations, the trajectory can finally reach a point very close to the (1.0,1.0,1.0) MI point, which indicates that the original message, relayed by the forwarding nodes, can be reconstructed perfectly.

Fig. 5 shows the EXIT curves and trajectory of the decoders ACC^{-1} and C_0^{-1} where $p_1 = 0.05$, $p_2 = 0.06$ and $P_{ori} = 2$. After several iterations, the trajectory achieve (1.0,1.0) point and the originator's information be recovered completely. It should be emphasized here that Fig. 5 indicates the case where two *HI's* perform as many iterations as no more gain in mutual information can be achieved. However, even without full iterations of two *HI* loops, which results in even smaller value of mutual information after the *a posteriori* LLRs combining, the EXIT curves of ACC^{-1} and C_0^{-1} do not intersect until a point very close to the (1.0, 1.0) MI point. According to our

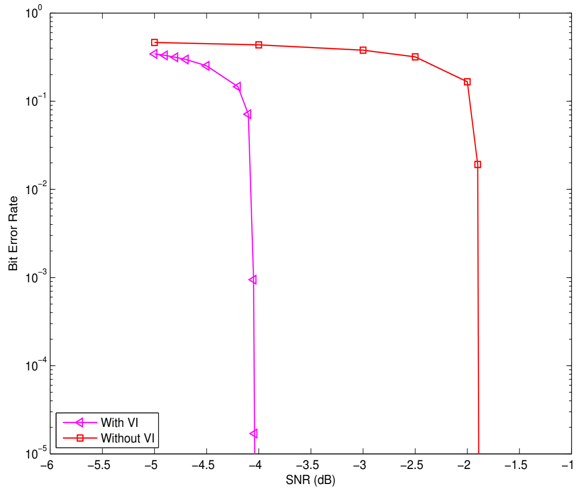

Fig. 6. BER performances of proposed system on $p_1 = 0.05$ and $p_2 = 0.06$

simulations, mutual information of 0.73 after the *a posteriori* LLRs combining which is the case of non-full iterations over two *HI's*, can still keep the tunnel open.

V. SIMULATION RESULTS

BER performances of the proposed system with a two representative value pairs of p_1 and p_2 are shown in Fig. 6 and Fig. 7. In our simulations, we set the frame length at 100000 bits. 30 *HI's* and 5 *VI's* are performed in the joint decoding part at the FD. After LLRs combing, we performed 6 and 3 *HI's* for the p_1 and p_2 value sets, shown in Fig. 6 and Fig. 7, respectively.

It is found from the BER simulation results that, we can achieve clear turbo cliff over the AWGN channel. Also, we can see that, a performance gain of about $2-3$ dB can be achieved by performing *VI*. The larger the gain, the smaller the $\hat{p}$ value, in which case the two forwarding nodes are highly correlated.[2]

VI. RATE OPTIMIZATION

Since the gaps between the EXIT curves of ACC^{-1} and C_0^{-1} are very large as shown in Fig. 5, we can increase the rate of C_0 by, for example using punctured convolutional codes to achieve better matching of the two EXIT curves. As shown in Fig. 8, it is found that even we can increase the coding rate of C_0 from $1/2$ to $2/3$, still it can possible to achieve arbitrarily low BER. However, since the gaps between 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 code rates and Hamming distortion [12] 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

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[2] The CEO problem belongs to distributed lossy compression problem in Network Information Theory, and the limits for this problem, are not yet known, except for some special cases.

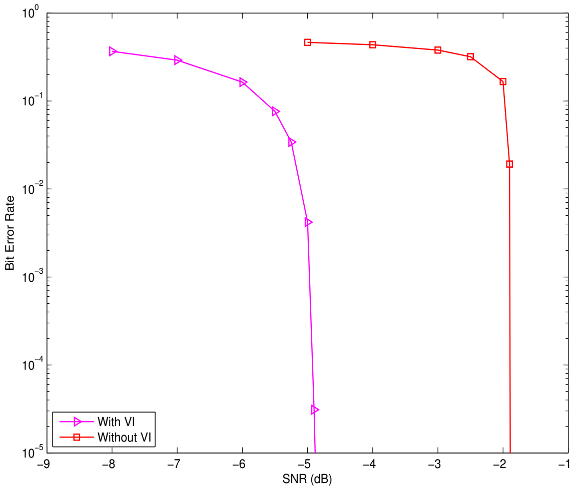

Fig. 7. BER performances of proposed system on $p_1 = 0.01$ and $p_2 = 0.02$

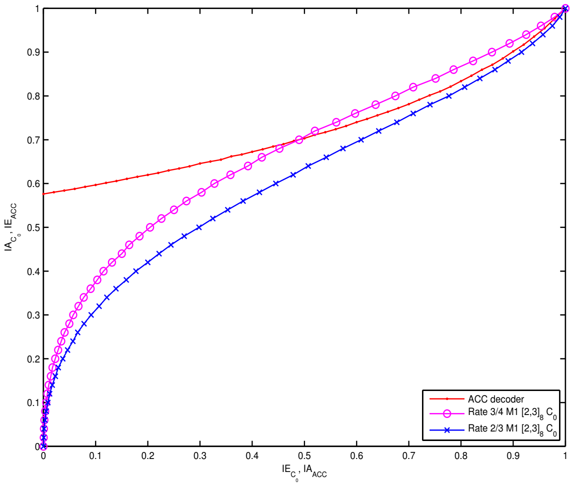

Fig. 8. EXIT curves of ACC^{-1} with doping ratio $P_{ori} = 2$ and C_0^{-1} with different coding rates. BSC crossover probabilities $p_1 = 0.05$ and $p_2 = 0.06$.

the relationship in the information theoretic framework of the CEO problem. Especially, the rate of C_0 should be determined by the rate-distortion function, which takes into account the Hamming distortion and allocated rate to the nodes in the network, in general. It is expected that the more forwarding nodes involved, still error-free communication is possible with a high rate of C_0, and ultimately, we may be able to eliminate C_0.

VII. CONCLUSION

In this paper, we 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 small transceiver with low power consumption, where energy is very scarce. 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 signals received by the forwarding nodes, they are correlated because of coming from the same originating node. Therefore, utilization of the Slepian-Wolf theorem allowing distorted source recovery should be the theoretical basis of the WMNs transmission chain design. The simulation results show that we can achieve roughly $2-3$ dB gain 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. More fundamental question is that how the relationship between the code rates and Hamming distortion can be formulated, and how it can be solved with the aim of their applications to WMNs. This is left as future study.

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