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Description	

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Exploiting CEO Problems in Massive Multiway Multirelay Networks

Mohammad Nur Hasan and Khoirul Anwar *

Abstract— We consider multiway multirelay (MWMR) systems composed of massive number of users exchanging information among themselves via two relays. To avoid high complexity scheduling involving massive number of users, we consider a novel uncoordinated transmission schemes for MWMR systems. The relays keep forwarding (broadcasting) the received packet to all users even though it is erroneous. When both links between users and two relays are erroneous, this situation is regarded as massive and dynamic CEO problems in the uncoordinated networks. Joint decoding that exploits correlation of information received from two relays is proposed for final decoding process to reduce the power consumption of all users. The results show that the proposed techniques outperform the traditional systems in terms of bit-error-rate (BER) and throughput performances.

Keywords—Multiway multirelay, uncoordinated transmission, CEO problem, joint decoding.

I. Introduction

Multiway relay networks has been receiving a lot of attention since its potential applications such as high density area networks, wireless sensor networks, and satellite communications. It is also regarded as one of potential solutions for future networks, where massive number of devices are connected to the networks, due to its capability of serving multiple users.

In this paper, we consider systems with several multiway relays, termed as multiway multirelay (MWMR) systems, where multiple users are exchanging information among themselves with the help of the relays. To remove unnecessary transmission of noise to the destinations, we employ decode-and-forward (DF) relaying protocol. In the conventional DF relaying protocol, the relays stop transmission when error is detected. However, in this paper, we consider modern DF relaying protocol where the relays keep forwarding the information to all users even though it is possibly erroneous. Since the users may receive erroneous information from multiple relays, the situation can be viewed as Chief Executive Officer (CEO) problem [1].

Transmission process in the MWMR is divided into two phases: (i) multiple access channel (MAC) phase used by users to transmit information to the relays, and (ii) broadcast channel (BC) phase used by the relays to broadcast the information to all users. In MAC phase, we adopt uncoordinated transmission [2] scheme to avoid high complexity scheduling involving huge number of users. Each user is allowed to transmit information randomly to the relays without having coordination with the other users.

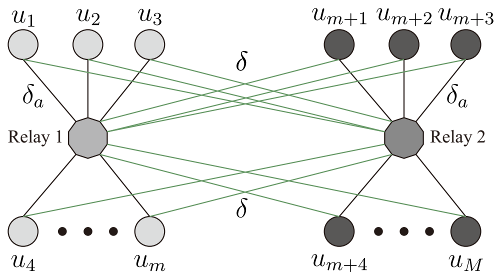

Fig. 1. MWMR systems with two groups of users and two relays.

In the BC phase, since only small number of relays are transmitting information, fixed transmission scheduling is considered.

CEO problem emerging in the systems is very challenging since it involves the uncoordinated transmission in MAC phase. As solutions, we propose: (i) graph-based successive interference cancellation (SIC) in the MAC phase and (ii) joint decoding technique in the BC phase. The uncoordinated transmission scheme can be seen as a coding structure that resembles low-density parity-check (LDPC) codes, which can be represented by a bipartite graph. Therefore, we can adopt graph-based SIC for decoding in the relays. In the final destination, we propose joint decoding technique to exploit the correlation of information received from multiple relays. The joint decoding involves two decoders that correspond to the relays. The selection of *host* decoder, of which the outputs are used for the final decision, is of importance to ensure the best decoding results. In this paper, we propose host selection based on mutual information calculated by the relays. We choose the decoder that corresponds to the relay with the highest mutual information as the host decoder.

The rest of this paper is organized as follows. Section II presents the system model assumed in this paper. Section III discusses the transmission strategies used in MAC and BC phases. Section IV focuses on the decoding strategy in the relays, while Section V describes the decoding strategy in the final destinations. Section VI provides the numerical results obtained by massive computer simulation. Finally, Section VII concludes the paper.

II. System Model

Fig. 1 illustrates the MWMR systems considered in this paper. There are M users, $\mathcal{U} = \{u_1, u_2, ..., u_M\}$, and two relays, relay 1 and relay 2, in the systems. Each user wants to know the information from the other $(M-1)$ users. The users are divided into two groups. The users in group 1 have distance δ_a from relay 1, and δ from relay 2, where $\delta_a < \delta$. On the other hand, the users in group 2 have

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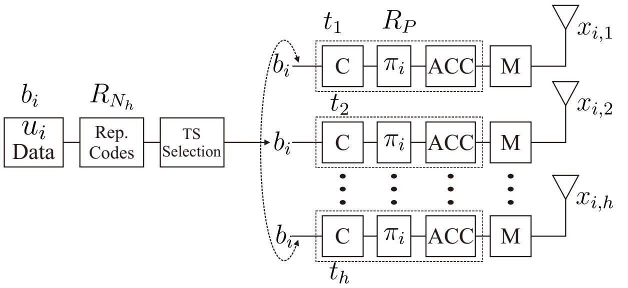

Fig. 2. Transmitter structure of user in u_i with two encoders: network encoder R_{N_h} and physical encoder R_P.

distance δ from relay 1, and δ_a from relay 2. We assume that there is no direct link between any user in the systems.

Using δ with signal-to-noise power ratio (SNR) γ_δ as the reference, the SNR δ_a is defined as

$$\delta_a = \left(\frac{\delta}{\delta_a}\right)^n \gamma_\delta, \tag{1}$$

where n is path-loss exponent with $2 \leqslant n \leqslant 6$. In this paper, we use $n = 3.52$ [3].

We assume half-duplex mode in the transmission scheme with perfect frame and slot synchronizations. All users are exchanging information within one *contention period* composed of $L = (N + 2M)$ time slots (TS). Each TS has equal time duration T_s. The first N of L TSs are utilized in MAC phase, while the remaining $2M$ TSs are used in BC phase.

We define logical offered traffic, G, as number of messages to be sent divided by number of TSs used to deliver the messages. Assuming that each user has one message, the offered traffic for *one user* is defined as

$$G_{\text{U}} = \frac{M-1}{L} = \frac{M-1}{N+2M}. \tag{2}$$

For the BC phase, since the relays requires $2M$ TSs in total to transmit all the messages of M users, the offered traffic addressed to *only one user* is fixed to

$$G_{\text{B}} = \frac{M-1}{2M}. \tag{3}$$

Unlike BC phase, MAC phase is more dynamic with the uncoordinated transmission schemes. Number of TSs N can be optimized to maximize the throughput of the systems. The offered traffic in the MAC phase is given by

$$G_{\text{M}} = \frac{M}{N}. \tag{4}$$

III. Transmission Strategy in MAC and BC Phase

A. Uncoordinated Transmission in MAC Phase

The transmitter structure of user u_i is illustrated in Fig. 2. We utilize two encoders: *network encoder* that is used to combat the error or interference caused by *uncoordinated* networks, and *physical encoder* that acts as channel encoder.

Set of *packet-oriented* repetition code types, $\mathcal{C} = \{c_h\}_{h=2}^{n_c}$, are available in the systems to be picked by each user as the the network encoder. For $h \in \{2, 3, ..., n_c\}$, the code $c_h \sim (h, 1)$ has length h, dimension 1, and rate $R_{N_h} = 1/h$.[1] User u_i encodes its information data, b_i, using $c_h \sim (h, 1)$ that is drawn randomly without coordination with other users from set $\mathcal{C}$ according to probability mass function (*pmf*) $\Lambda = \{\Lambda_h\}_{h=2}^{n_c}$, where $\sum_{h=2}^{n_c} \Lambda_h = 1$. We then define the *average network rate* as

$$R_N = \frac{1}{\overline{h}}, \tag{5}$$

where $\overline{h} = \sum_{h=2}^{n_c} \Lambda_h h$ is the expected length of the codes.

Network encoder produces h packets of b_i, and therefore the user requires h TSs to transmit them. The h TSs are chosen uniformly random from set of TSs $\mathcal{S} = \{s_1, s_2, ..., s_N\}$, which are the first N TSs of the contention period. As an example, in Fig. 2, we show $\text{TS} = \{t_1, t_2, ..., t_h\}$ as the selected TSs by user u_i. User u_i then encodes b_i using physical encoder of serially concatenated convolutional codes (SCC). The SCC is composed of convolutional codes C, random interleaver π_i, and doped-accumulator ACC [4]. The total rate of physical encoder is R_P. The outputs of ACC are modulated by M, producing x_i. In this paper, we assume x_i is a binary phase shift keying (BPSK) symbol having $E[|x_i|^2] = 1$. Prior to transmission via the selected TSs, the packets are equipped with a pointer that contains information about location of packets. The pointer is exploited for the successive interference cancellation (SIC) in the decoding process.

For all the TS s_j, $j \in \{1, 2, ..., N\}$, the received signal at relay r is

$$Y_r = AX_r + Z_r, \tag{6}$$

with

$$Y_r = [y_{r,1}, y_{r,2}, ..., y_{r,N}]^T, \tag{7}$$

$$X_r = [\sqrt{\gamma_{r,1}}x_1, \sqrt{\gamma_{r,2}}x_2, ..., \sqrt{\gamma_{r,M}}x_M]^T, \tag{8}$$

$$Z_r = [z_r, z_r, ..., z_r]^T, \tag{9}$$

$$A = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,M} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,M} \\ \cdots & \cdots\cdot & a_{j,i} & \cdots \\ a_{N,1} & a_{N,2} & \cdots & a_{N,M} \end{bmatrix}, \tag{10}$$

where $y_{r,j}$ is the received signal at relay r at TS s_j , $\gamma_{r,i}$ is SNR between relay r and user u_i, x_i is the signal from user u_i, z_r is zero-mean white Gaussian noise at relay r with variance $\sigma_r^2 = 1$, and $a_{j,i}$ takes value 1 if TS s_j is selected by user u_i, or 0 otherwise.

After N TSs, the relays decode all information sent by all users. The details of decoding algorithm in the relays is discussed in the Section IV.

B. Transmission in BC Phase

Since modern DF relaying protocol is assumed in this paper, the relays keep forwarding the decoded packet to all users even though error detected. This strategy is more advantageous when source correlation is exploited.

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[1] Please note that we do not use repetition code with degree 1, $c_1 \sim (1, 1)$, since it causes instability of the systems.

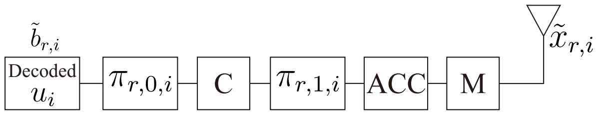

Fig. 3. Transmitter structure of relay r.

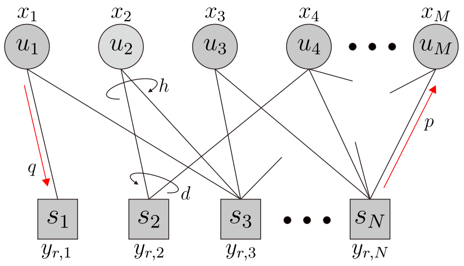

Fig. 4. Bipartite graph representing the uncoordinated transmission schemes from all users to relay r.

The transmitter structure of BC phase is shown in Fig 3. The decoded packet $\tilde{b}_{r,i}$ is first interleaved using random interleaver $\pi_{r,0,i}$, encoded using encoder C, and again interleaved using random interleaver $\pi_{r,1,i}$, and then doped-accumulated using ACC. The outputs of ACC are modulated by M to produce $\tilde{x}_{r,i}$.

The encoded packets of all users, are transmitted via the last $2M$ TSs of the contention period. At TS s_j, $j = N + (2i-1)$, the relay 1 broadcasts the encoded packet of user u_i, $\tilde{x}_{r,i}$. While the relay 2 broadcasts $\tilde{x}_{r,i}$ at TS s_{j+1}. The signals received by user u_k, $k \in \{1, 2, ..., M\}$, in BC phase is expressed as

$$\tilde{y}_{k,j} = \sqrt{\gamma_{1,k}}\tilde{x}_{1,i} + z_k \tag{11}$$

$$\tilde{y}_{k,j+1} = \sqrt{\gamma_{2,k}}\tilde{x}_{2,i} + z_k, \tag{12}$$

where z_k is the zero-mean Gaussian noise at user u_k with variance $\sigma_k^2 = 1$. Joint decoding exploiting the source correlation via vertical iteration (*VI*) [3], is adopted in the final decoding process.

IV. Decoding Strategy in Relays

In the MAC phase, the uncoordinated transmission scheme that is expressed by matrix A in (10), can also be represented by a bipartite graph $\mathcal{G} = (\mathcal{U}, \mathcal{S}, \mathcal{E})$ as shown in Fig. 4. The graph is comprised of set of *user nodes* $\mathcal{U} = \{u_1, u_2, ..., u_M\}$ representing the users, set of *slot nodes* $\mathcal{S} = \{s_1, s_2, ..., s_N\}$ representing the TSs, and set of edges $\mathcal{E}$ connecting the user nodes and slot nodes.[2] An edge $e_{j,i}$ connects user node u_i to slot node s_j if and only if $a_{j,i} = 1$.

As shown in Fig. 4, user nodes have degree h and slot nodes have degree d. Degree h of user node u_i has meaning that user u_i picks the code c_h, and thus transmits its information h times. On the other hand, degree d of slot node s_j has meaning that there are d users that select the TS s_j to transmit their information simultaneously to the relays.

A. Decoding Strategy

Decoding is performed iteratively between network decoding in user nodes and physical decoding in slot nodes.[3] The user nodes network corresponds to decoding of repetition code. Whereas physical decoding of slot nodes corresponds to decoding of SCC.

Decoding in the relays is started by finding degree $d = 1$ slot node and performing network decoding in the slot node. The results are passed to the connected user node to be used in user node physical decoding. The user node passes his results to the connected slot nodes. Subsequently, successive interference cancellation (SIC) is performed by subtracting the decoded information from the composite signals in the corresponding slot nodes. The aforementioned processes are repeated until there is no more degree $d = 1$ slot node found or until maximum iteration is reached.

B. Asymptotic Analysis

We conduct asymptotic analysis, i.e. density evolution, to investigate the behavior of uncoordinated MAC phase [2][5][6][7]. We assume that SNR is high and $\{M,\ N\} \rightarrow \infty$, while $G_M = M/N$ is constant.[4] We first define degree distributions of both nodes. Degree distribution of user nodes from nodes perspective follows the *pmf* of network encoder selection, Λ. It is expressed as

$$\Lambda(x) = \sum_{h=2}^{n_c} \Lambda_h x^h. \tag{13}$$

From edges perspective, the degree distribution of user nodes is defined as

$$\lambda(x) = \frac{\Lambda'(x)}{\Lambda'(1)} = \sum_{h=2}^{n_c} \lambda_h x^{h-1}, \tag{14}$$

where $\lambda_h = \Lambda_h h/\overline{h}$.

Being different from the degree distribution of user nodes, the degree distribution of slot nodes follows Poisson distribution since the selection of TS is uniformly random. The degree distribution of slot nodes from nodes perspective and from edges perspective are the same, which are given by

$$\Psi(x) = \rho(x) = e^{-\frac{G_M}{R_N}(1-x)}. \tag{15}$$

User nodes and slot nodes are exchanging variables q and p, the probabilities of an edges carrying erasure packet from user nodes to slot nodes and from slot nodes to user nodes , respectively, as shown in Fig. 4. They are defined as

$$q = p^{h-1}, \tag{16}$$

$$p = 1 - (1-q)^{d-1}. \tag{17}$$

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[2] We use the same notation for user nodes (slot nodes) and user (TS) since they are corresponding each other.

[3] The decoding is performed iteratively inside the relays.

[4] High SNR is assumed only for asymptotic analysis. In the computer simulation we evaluate systems having various SNR values.

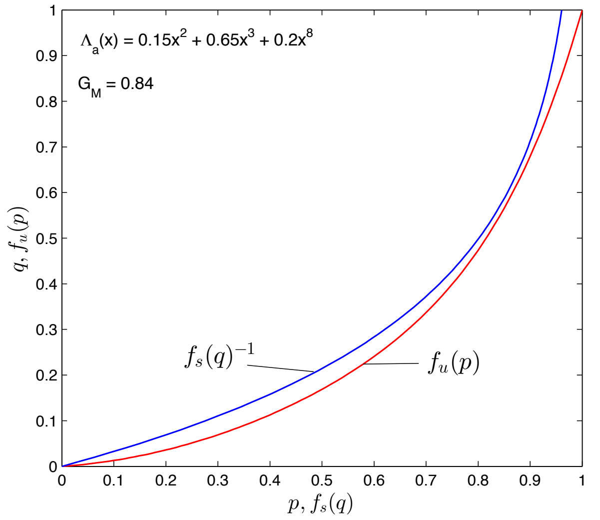

Fig. 5. EXIT chart of uncoordinated transmission scheme in MAC phase with user nodes degree distribution $\Lambda_a(x)$.

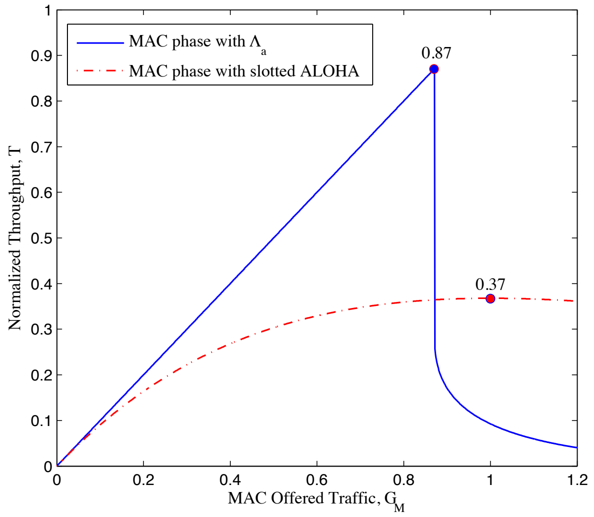

Fig. 6. Asymptotic throughput in MAC phase using $\Lambda_a(x)$.

In the density evolution, the average erasure probabilities during ℓ iteration is defined as

$$q_\ell = \sum_{h=2}^{n_c} \lambda_h p_{\ell-1}^{h-1} := f_u(p_{\ell-1}), \tag{18}$$

$$p_\ell = 1 - e^{-q_\ell \frac{G_M}{R_N}} := f_s(q_\ell). \tag{19}$$

Using (18) and (19), we plot the EXIT chart to characterize the convergence behavior of the decoding. We provide an example of EXIT chart for systems having user nodes degree distribution $\Lambda_a(x) = 0.15x^2 + 0.65x^3 + 0.2x^8$ and $G_M = 0.84$ in Fig. 5. The successful decoding is characterized by the existence of ”open tunnel” between two curves in the EXIT chart. In other words, two curves do not intersect each other, yielding $p_\ell \to 0$ when $\ell \to \infty$.

The threshold of offered traffic G_M^* is defined as the maximum value of G_M such that the successful decoding condition is satisfied. The G_M^* also corresponds to the maximum throughput in MAC phase that can be achieved asymptotically by systems with a certain user nodes degree distribution. As exemplified in Fig. 6, the systems with $\Lambda_a(x)$ has maximum asymptotic throughput around 0.87 packets/slot, which agrees with the EXIT chart presented in Fig. 5. Compared to conventional slotted ALOHA, the graph-based uncoordinated transmission asymptotically achieves almost three times higher throughput in MAC phase.

V. Decoding Strategy in Destinations

As described previously, the relays keep forwarding the received packets in MAC phase even though they possibly contain errors. All users receive packets that are originallty sent by user u_i at TSs s_j and s_{j+1}, $j = N + (2i - 1)$, from relay 1 and relay 2, respectively. Since originally sent by the same user, the packets received from the relays are correlated. Correlation between these packets are then exploited in the final decoding to achieve better performances. Assuming the users know the error probability of user u_i packet, $\tilde{p}_{r,i}$, $r \in \{1, 2\}$, in MAC phase at relay r, authors of [8] explained that the correlation of these packets can be calculated by $\tilde{p}_i = \tilde{p}_{1,i} + \tilde{p}_{2,i} - 2\tilde{p}_{1,i}\tilde{p}_{2,i}$. However, in practice we assume that the users have no knowledge about the error probabilities $\tilde{p}_{r,i}$. Instead of estimating the error probabilities, relay r calculates the mutual information of user u_i packet, $\mathrm{I}_{r,i}$. The $\mathrm{I}_{r,i}$ is then transmitted to all users, using a specific field in a header, at every packet transmission. In the users as the final receivers, the correlation of two received packets is calculated by

$$\hat{p}_i = \frac{1}{K} \sum_{l=1}^{K} \frac{\exp\left(L_{\hat{b}_{1,i}}\right) + \exp\left(L_{\hat{b}_{2,i}}\right)}{(1 + \exp\left(L_{\hat{b}_{1,i}}\right))(1 + \exp\left(L_{\hat{b}_{2,i}}\right))}, \tag{20}$$

where $L_{\hat{b}_{r,i}}$ is *a posteriori* LLRs of $\hat{b}_i$ from relay r decoder, K is number of reliable *a posteriori* LLRs [3].

Fig. 7 describes the final decoding process, which is basically a joint decoding between two channel decoders. The joint decoding is divided into two iteration processes: horizontal iteration (*HI*) and vertical iteration (*VI*). In the *HI*, the demapper M^{-1} together with ACC^{-1} are exchanging extrinsic LLRs with decoder C^{-1} through the corresponding interleaver and de-interleaver. After some *HI* iterations, the *VI* is performed by exchanging extrinsic LLRs between two decoders C^{-1} through the corresponding interleaver, de-interleaver, and f_c function [3]. The LLRs output of f_c function are given by

$$L_{\text{out}} = f_c(L_{\text{in}}) = \log \frac{(1 - \hat{p}_i). \exp(L_{\text{in}}) + \hat{p}_i}{(1 - \hat{p}_i) + \hat{p}_i. \exp(L_{\text{in}})}, \tag{21}$$

where, L_{in} is the LLRs input of f_c function.

In the final step, the decision, from which decoder C^{-1} the $L_{\hat{b},i}$ is obtained, is very important. To select the best C^{-1}, we propose a selection method based on the highest

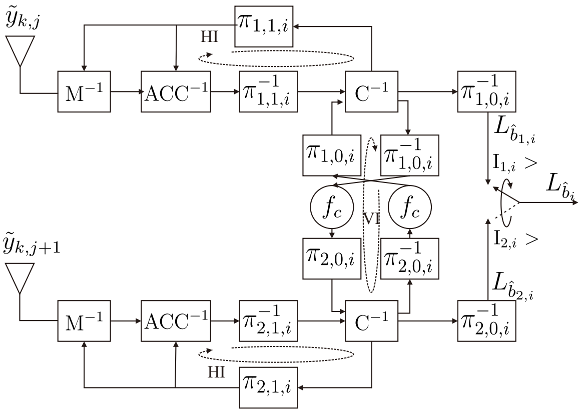

Fig. 7. Final decoding at user u_k to decode information of user u_i.

mutual information. In the relays, the mutual information can be estimated using

$$I_{r,i} \approx 1 - \frac{1}{\mathcal{L}} \sum_{l=1}^{\mathcal{L}} H_b \left(\frac{e^{\frac{+|L_{\tilde{b}_{r,i,l}}|}{2}}}{e^{\frac{+|L_{\tilde{b}_{r,i,l}}|}{2}} + e^{\frac{-|L_{\tilde{b}_{r,i,l}}|}{2}}} \right), \qquad (22)$$

where $\mathcal{L} = T_s R_p$ is length of message b_i, H_b is binary entropy function, and $L_{\tilde{b}_{r,i}}$ is LLRs value of decoded packet $\tilde{b}_i$ at relay r, as used in [9]. This equation is practical because the relays do not need to know the original message b_i to estimate the mutual information.[5]

VI. Numerical Results

We conducted computer simulations to simulate MWMR systems serving 100 users, which are divided into two groups. Each group consists of 50 users and are separated by δ and δ_a from both relays. Using δ as reference, we set the value of δ_a equal to $3/4\delta$. Therefore the SNR for δ_a is expressed by $\gamma_{\delta_a} = \gamma_\delta + 4.3978$ dB.

For simplicity, we conduct simulation over additive white Gaussian noise (AWGN) channel, and hence the complex channel between users and relays are equal to 1. Convolutional codes memory-1 $(2,3)_8$ with half rate is used as encoder C in all terminals. All the terminal also use the same doped accumulator ACC with unity rate. For the network encoder, we utilize repetition code that has distribution $\Lambda(x) = 0.15x^2 + 0.65x^3 + 0.2x^8$ and average network rate $R_N = 0.2597$. We set the offered traffic for MAC phase to $G_M = 0.5$.

We investigate performances of the systems in terms of bit-error-rate (BER) and throughput performances. Fig. 8 shows the average BER per user. As comparison, we also perform BER evaluation for traditional system without CEO problems consideration (relay keeps silent when error is detected). It is confirmed that the proposed technique requires lower power consumption compared to the traditional one by about 1.25 dB at BER of 10^{-2}. The proposed technique also outperforms the traditional technique in term of throughput, as shown in Fig. 9.

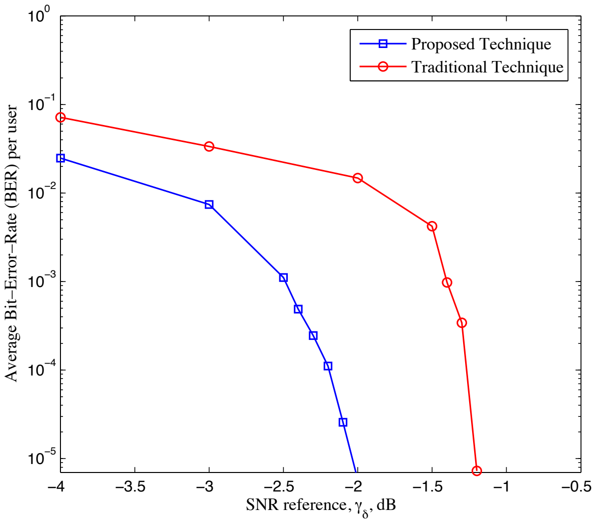

Fig. 8. Average BER performance per user.

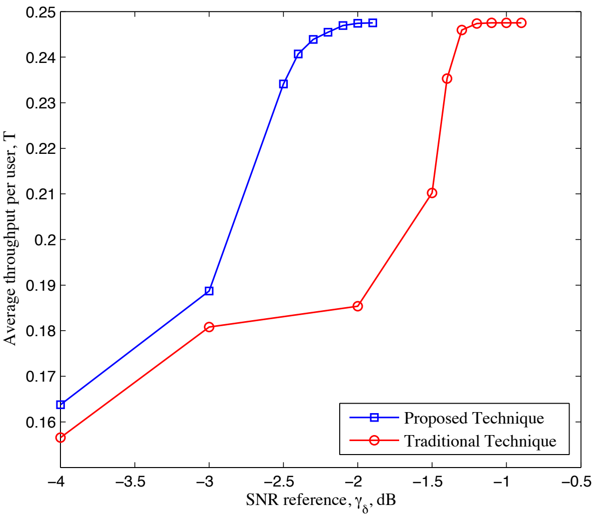

Fig. 9. Throughput performance per user.

VII. Conclusion

We considered CEO problems emerged in MWMR systems having massive number of users. To avoid high complexity scheduling, we proposed uncoordinated transmission schemes for the systems. In the relays, we adopted graph-based successive interference cancellation (SIC) to resolve the packets transmitted in uncoordinated fashion by the users. We also proposed joint decoding via vertical iteration to exploit the source correlation. We select a relay having the highest mutual information to be the host decoder of joint decoding. We showed that the proposed techniques outperform the traditional systems in terms of BER and throughput performances.

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[5] This equation may not be the real mutual information as defined in many literatures of information theory. However, it is very helpful and confirmed to be effective in practice.

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