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Performance Study of a Network Coded Non-orthogonal User Cooperation System over Nakagami-m Channels

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Abstract: In this study, we consider the design of a network coded non-orthogonal interleave-division multiple-access (IDMA) user cooperation system. Based on eXclusive OR (XOR) operation at relays, the source messages are re-transmitted forward to the destination simultaneously. At destination, a network coding aided iterative Multi-User Detection (MUD) scheme is proposed. And, a multi-user soft network decoding algorithm is developed. Over Nakagami-m fading channels, we examine the BER performance of the proposed network coded cooperative (NetCC) IDMA scheme in various scenarios. Simulation results confirm that NetCC IDMA scheme can provide significant BER improvement compared to the existing IDMA scheme. In addition, based on the EXtrinsic Information Transfer (EXIT) chart technique, the convergence behavior of NetCC IDMA scheme is studied. Simulations also reveal that the proposed scheme can support more users than existing IDMA scheme.

Key words: Network coding, IDMA, user cooperation, iterative MUD, EXIT charts, Nakagami-m channels

INTRODUCTION

User cooperation is recently introduced as an efficient technique to exploit the spatial diversity inherent in multi-user wireless networks. The basic idea is that single-antenna users cooperate with each other and form a virtual multiple-antenna system (Sendonaris *et al.*, 2003). Each cooperating user transmits both its own information and the partner's information. This new method can increase system throughput, improve transmission quality and enhance network coverage (Pabst *et al.*, 2004).

Many valuable user cooperation schemes have been investigated over the past few years (Sadek *et al.*, 2010; Laneman *et al.*, 2004; Weng and Murch, 2009). The system level description of the user cooperation concept is presented by Sendonaris *et al.* (2003). They show user cooperation has substantial gains over a noncooperative strategy on a higher data rate and a decreased sensitivity to channel variations. In particular, an adaptive network coding (ANCC) based user cooperation is designed by Bao and Li (2008). The central idea is to couple the instantaneous network topologies with the channel code graph. Simulations reveal that ANCC can offer the large network coding gain. However, these user cooperation strategies are based on the orthogonal channel assumption, such as time-division multiple-access (TDMA) and frequency-division multiple-access (FDMA). Several limits are needed to overcome. First, the orthogonal channel assumption (e.g., time slots) may results in the low spectral efficiency. Second, the requirement for orthogonality is difficult to satisfy, especially in large networks with many cooperating users (Huang *et al.*, 2008).

Motivated by the potential to achieve the high spectral efficiency, there has been increasing interest in non-orthogonal user cooperation systems (Zhang and Hanzo, 2009; Han *et al.*, 2009; Huang *et al.*, 2008). As an efficient non-orthogonal multiple-access scheme, interleave-division multiple-access (IDMA) provides a good multiple-user communication capability with low complexity (Ping *et al.*, 2006). To our best knowledge, there has been relatively little published on network coded non-orthogonal IDMA multi-user cooperative systems.

In this study, we propose a network coded cooperative (NetCC) IDMA transmission scheme. One advantage is that two time slots are enough in a round of multi-source multi-relay cooperation for the capacity improvement. And, at destination, a network coding assisted iterative Multi-User Detection (MUD) scheme is developed. A chip-level soft multi-user network decoding algorithm is also studied. Moreover, the Bit Error Rate

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(BER) performance and EXtrinsic Information Transfer (EXIT) charts are evaluated over Nakagami-m fading channels. And, this study can be applied to sensor networks, 3rd Generation Partnership Project Long Term Evolution (3GPP-LTE) wireless communication networks.

Notation: Boldface upper-case letters refer to matrices and boldface lower-case letters denote column vectors. Var (x) and E (x) stand for the variance and mean of random variable x, respectively. $\otimes$ denotes the element-wise eXclusive OR (XOR) operation. The superscripts $(\bullet)^{(1)}$ and $(\bullet)^{(2)}$ denote the first and second cooperation phase, respectively.

SYSTEM DESCRIPTION

Consider the user cooperation system in Fig. 1 that comprises N cooperating users, K source users (e.g., mobile stations) and (N-K) relay users. Here, source users are denoted as $\{S_i\}$, $i\epsilon[1, K]$. And, relay users are denoted as $\{R_j\}$, $j\epsilon[1, \{N\text{-}K\}]$. All cooperating users and destination (e.g., base station) are equipped with a single antenna.

As illustrated in Fig. 1a and b, an uplink cooperation round takes place in two phases, which are the broadcast phase and the relay phase. In the first broadcast phase, the source users transmit the data message to relay users and destination. And, in the second relay phase, the relay users decode and re-transmit forward the source message to the destination.

In this study, we assume that source-destination channels, relay-destination channels and source-relay channels experience independent channel fading. And, the envelope α of channel coefficient follows Nakagami-m distribution, i.e.,

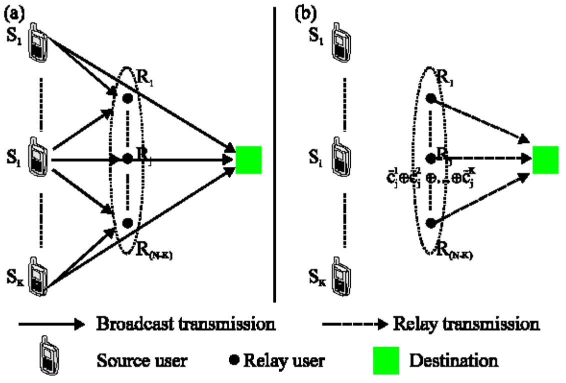

Fig. 1: Network coded user cooperation system under consideration. (a) The first cooperation phase and (b) the second cooperation phase

$$P_r(\alpha)=\frac{2m^m}{\Omega^m\Gamma(m)}\alpha^{2m-1}\exp\left(-\frac{m}{\Omega}\alpha^2\right) \tag{1}$$

where, Γ(m) is the gamma function, m is the fading parameter with $m \geq \frac{1}{2}$ and $\Omega = E(\alpha^2)$ is the mean power.

In addition, we also suppose that the entire power of proposed NetCC IDMA system is P_T, which is equally allocated to N cooperating users. That is:

$$P_i^{(1)} = P_j^{(2)} = P_T/N$$

with $1 \leq i \leq K$, $1 \leq j \leq (N\text{-}K)$, where $P_i^{(1)}$ and $P_j^{(2)}$ are transmit power of ith source user and jth relay user, respectively.

COOPERATION PROTOCOL

In this section, the network coded non-orthogonal cooperative protocol is designed.

Broadcast phase strategy: As shown in Fig. 2a-c, the broadcast phase occupies one time slot. First, the information bits $\{b_i^{(1)}[l], i, \ldots, K\}$ are encoded at time index l, $l\epsilon[1, L]$ and interleaved with user-specific interleaver $\{\Pi_i^S\}$. L is the information bits frame length. After that, the yielding sequence is modulated and broadcasted from K source users simultaneously, illustrated in Fig. 2b.

Besides, due to the broadcast character of wireless channels, the received symbol stream at destination is given by:

$$r_1^{SD}[l_s]=\sum_{i=1}^{K}h_i^{SD} * x_i^{(1)}[l_s]+n_D^{(1)}[l_s]$$

with $1 \leq l_S \leq L_S$, where $x_i^{(x)}[l_s]$ is the modulated symbol of ith source user. H_i^{SD} represents the flat fading channel from ith source user to destination. $\{N_D^{(i)}[l_S]\}$ are the additive white Gaussian noise (AWGN) samples with zero mean and a variance of σ^2_D. l_S is the time index. l_S is the length of the symbol frame. Hereafter, we omit the time index for notational simplicity.

Relay phase strategy: With help of a low-cost iteration MUD detection method (Ping *et al*., 2006), (N-K) relay users can recover the source users information as $\{\tilde{b}_j^i\}, j\in[1,(N-K)], i\in[1,K]$ After channel re-encoding, the recovered information data sequence is encoded. And, the yielding sequence is $\{\tilde{c}_j^i\}$. Here, we let the subset of candidate source users that the jth relay user serves is $\mathbb{F}_j \subseteq \{1,2,\cdots,K\}$. Then, using a linear network

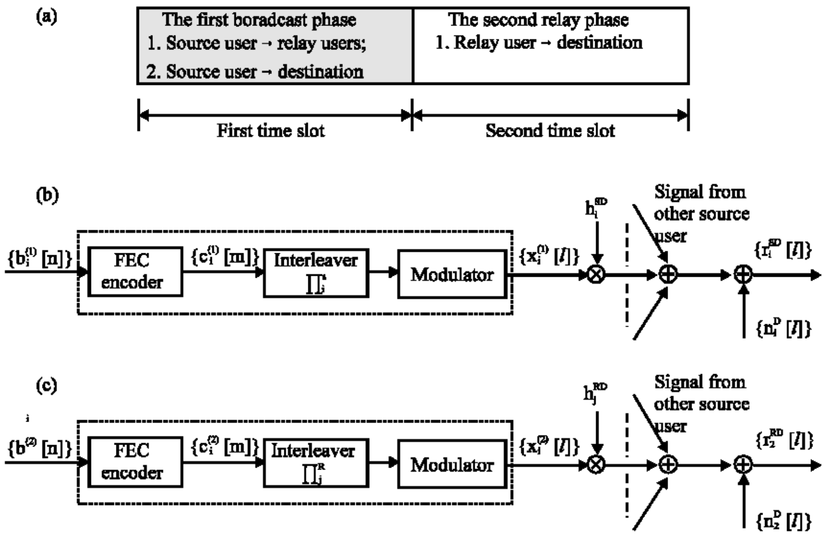

Fig. 2: Two phase cooperation protocol and transmitter structure. (a) Time slots allocation for the two phase cooperation protocol, (b) Transmitter of the ith source user in broadcast phase and (c) Transmitter of the jth relay user in relay phase

coding, each relay user XOR the encoded data and obtains the relayed forward data. Thus, the combined chip stream $c_j^R = \{c_j^R\{m\}, m = 1, ..., L_c\}$ is produced, where:

$$\left\{c_j^R[m] = \tilde{c}_j^1[m] \oplus \cdots \oplus \tilde{c}_j^i[m] \oplus \cdots \oplus \tilde{c}_j^K[m]\right\}$$

And, $i \notin \mathbb{F}_j, \tilde{c}_j^i[m] = 0_j$,. After that, with user-specific interleaving and modulation, all (N-K) relay users re-transmit forward the symbol packets to destination simultaneously.

And, the received symbol sequence at destination in the second relay phase is:

$$r_2^{RD}[l_s] = \sum_{j=1}^{N-K} h_j^{RD} * x_j^{(2)}[l_s] + n_D^{(2)}[l_s]$$

with $1 \leq l_S \leq L_S$, where $x_j^{(2)}[l_S]$ is the transmitted symbol from jth relay user. H_j^{RD} represents the fading channel from jth relay user to destination. $\{n_D^{(2)}[l_S]\}$ are AWGN samples with zero mean and a variance of σ^2_D. It is noted that, since IDMA can be regarded as a special case of CDMA, the elements of encoded bits and modulated symbols are denoted as chips (Liu *et al*., 2006; Ping *et al*., 2006).

DETECTION ALGORITHM

At the destination, the turbo-type iterative receiver architecture is shown in Fig. 3. It consists of two parts: (1) the broadcast signal processing (BSP) block; (2) the relay signal processing (RSP) block. And, each block has a soft MUD module, a network coding decoder and *a posteriori* probability (APP) soft decoder (DEC).

Network coding assisted iteration detection: Based on the chip-level Gaussian distribution approximation soft MUD method (Ping *et al*., 2006), the extrinsic Logarithm of Likelihood Ratios (LLRs) about $\{x_i^{(1)}\}$ can be obtained:

$$\mathcal{L}_{MUD}^{e}\left(x_i^{(1)}\right) = \frac{2h_i^{SD}}{\sum_{i' \neq i}\left|h_{i'}^{SD}\right|^2 \mathrm{Var}\left(x_{i'}^{(1)}\right) + \sigma_1^2}\left(r_1^{SD} - \sum_{i' \neq i} E\left(x_{i'}^{(1)}\right)\right), \quad \forall i \in [1, K] \tag{2}$$

where:

$$E\left(x_i^{(1)}\right) = \tanh\left(\tilde{\mathcal{L}}_{MUD}\left(x_i^{(1)}\right)/2\right)$$

and

$$\mathrm{Var}\left(x_i^{(1)}\right) = 1 - \left(E\left(x_i^{(1)}\right)\right)^2$$

$\tilde{\mathcal{L}}_{MUD}\left(x_i^{(1)}\right)$ is the a priori LLR about $x_i^{(1)}$, which can be approximately updated by extrinsic LLRs $\left\{\mathcal{L}_{DEC}^{e}\left(c_i^{(1)}\right)\right\}$. As shown in Fig. 3, $\left\{\mathcal{L}_{MUD}^{e}\left(x_i^{(1)}\right)\right\}$ is the extrinsic LLR output

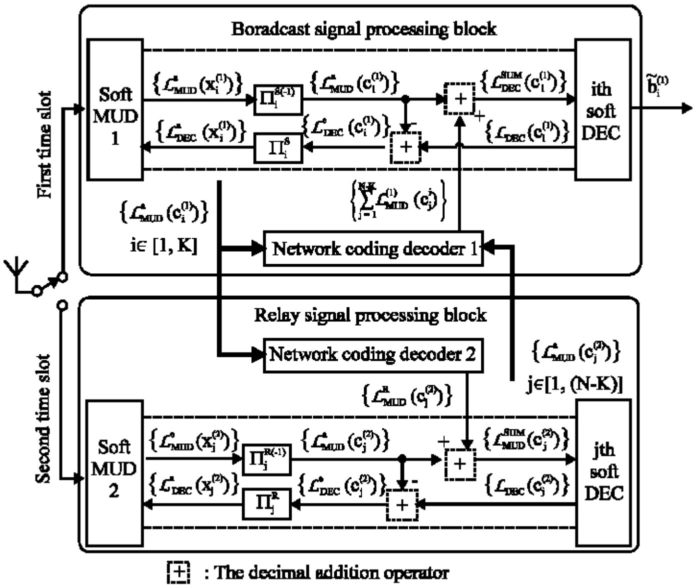

Fig. 3: Architecture of the network coding assisted IDMA receiver

from the soft MUD 1 module, which will be sent to deinterleaver. After that, the deinterleaved $\{\mathcal{L}^{a}_{MUD}(c_i^{(c)})\}$ and LLR output $\{\mathcal{L}^{(1)}_{MUD}(c_i^{j}\}$ from network coding decoder are summed together. The detailed multi-user network decoding algorithm will be studied in the next subsection. Then, $\left\{\mathcal{L}^{SUM}_{MUD}\left(c_i^{(1)}\right)\right\}$ are used as a priori information in DEC, which generates the more reliable soft information $\{\mathcal{L}_{MUD}(c_i^{(1)})\}$. After that, the subtraction is performed:

$$\left\{\mathcal{L}^{e}_{DEC}\left(c_i^{(1)}\right)=\mathcal{L}_{DEC}\left(c_i^{(1)}\right)-\mathcal{L}^{a}_{MUD}\left(c_i^{(1)}\right)\right\}$$

for the extrinsic information. And, the extrinsic LLR information $\{\mathcal{L}^{e}_{DE}(c_i^{(1)})\}$ is fed back to soft MUD module for the next iteration. After final iteration, the detected bits $\left\{\tilde{b}_i^{(1)}\right\}$ can be obtained subjected to a hard decision. And, for the RSP block, the iterative detection operates in a similar manner.

Multi-user soft network decoding algorithm: In the BSP block, the soft information contribution for ith source user from the jth relay user is calculated as (see Appendix for the proof):

For any i∈[1, K], j∈[1, (N-K)]

$$\mathcal{L}^{(1)}_{MUD}\left(c_i^{j}\right)=\log\frac{P\left(c_i^{j}=1\Big/ r_1^{SD}, r_2^{RD}\right)}{P\left(c_i^{j}=0\Big/ r_1^{SD}, r_2^{RD}\right)}=\log\frac{\alpha+\exp\left(\mathcal{L}^{a}_{MUD}\left(c_j^{(2)}\right)\right)}{1+\alpha*\exp\left(\mathcal{L}^{a}_{MUD}\left(c_j^{(2)}\right)\right)} \tag{3}$$

where:

$$\alpha=\frac{\sum\limits_{\substack{1\le l_1\le K\\ l_1\ne i}}\exp\left(\mathcal{L}^{a}_{MUD}\left(c_{l_1}^{(1)}\right)\right)+\sum\limits_{\substack{1\le l_1<l_2\le K\\ l_1\ne i, l_2\ne i}}\exp\left(\sum_{m=1}^{K-1}\mathcal{L}^{a}_{MUD}\left(c_{l_m}^{(1)}\right)\right)\cdots+\sum\limits_{\substack{1\le l_1<\cdots<l_{K-1}\le K\\ l_1\ne i, l_2\ne i,\cdots,l_{K-1}\ne i}}\exp\left(\sum_{m=1}^{K-1}\mathcal{L}^{a}_{MUD}\left(c_{l_m}^{(1)}\right)\right)}{1+\sum\limits_{\substack{1\le l_1<l_2\le K\\ l_1\ne i, l_2\ne i}}\exp\left(\sum_{m=1}^{2}\mathcal{L}^{a}_{MUD}\left(c_{l_m}^{(1)}\right)\right)+\cdots+\sum\limits_{\substack{1\le l_1<\cdots<l_{K-2}\le K\\ l_1\ne i, l_2\ne i,\cdots,l_{K-2}\ne i}}\exp\left(\sum_{m=1}^{K-2}\mathcal{L}^{a}_{MUD}\left(c_{l_m}^{(1)}\right)\right)} \tag{4}$$

Thus, the achieved LLR value of ith source user is:

$$\mathcal{L}^{SUM}_{MUD}\left(c_i^{(1)}\right)=\mathcal{L}^{a}_{MUD}\left(c_i^{(1)}\right)+\sum_{j=1}^{N-K}\mathcal{L}^{(1)}_{MUD}\left(c_i^{j}\right) \tag{5}$$

Then, $\mathcal{L}^{SUM}_{MUD}\left(c_i^{(1)}\right)$ is further forwarded to DEC as a priori information.

It is noted that, based on Eq. 5, multiple copies of soft information about $\{c_i^{(1)}\}$ is obtained from broadcast signals and relay signals. And, with more cooperating relay users, more cooperation spatial diversity gain and better system BER performance can be achieved.

Similarly, in the RSP block, $\mathcal{L}^{SUM}_{MUD}\left(c_j^{(2)}\right)$ can be calculated as:

$$\mathcal{L}^{SUM}_{MUD}\left(c_j^{(2)}\right)=\mathcal{L}^{a}_{MUD}\left(c_j^{(2)}\right)+\mathcal{L}^{R}_{MUD}\left(c_j^{(2)}\right) \tag{6}$$

where:

$$\mathcal{L}_{MUD}^{R}\left(c_j^{(2)}\right)=\log\frac{P\left(c_1^{(1)}\oplus c_2^{(1)}\oplus\cdots\oplus c_i^{(1)}\oplus\cdots\oplus c_K^{(1)}=1\Big/r_1^{SD}\right)}{P\left(c_1^{(1)}\oplus c_2^{(1)}\oplus\cdots\oplus c_i^{(1)}\oplus\cdots\oplus c_K^{(1)}=0\Big/r_1^{SD}\right)}$$
$$=\frac{\sum\limits_{1\le l_1\le K}B_{l_1}+\sum\limits_{1\le l_1<l_2<l_3\le K}B_{l_1}B_{l_2}B_{l_3}+\cdots+\sum\limits_{1\le l_1<l_2<\cdots<l_{K-1}\le K}B_{l_1}B_{l_2}\cdots B_{l_{K-1}}}{1+\sum\limits_{1\le l_1<l_2\le K}B_{l_1}B_{l_2}+\cdots+\sum\limits_{1\le l_1<l_2<\cdots<l_K\le K}B_{l_1}B_{l_2}\cdots B_{l_K}}$$
$$=\frac{\sum\limits_{1\le l_1\le K}\exp\left(\mathcal{L}_{MUD}^{a}\left(c_{l_1}^{(1)}\right)\right)+\sum\limits_{1\le l_1<l_2<l_3\le K}\exp\left(\sum\limits_{m=1}^{3}\mathcal{L}_{MUD}^{a}\left(c_{l_m}^{(1)}\right)\right)+\cdots+\sum\limits_{1\le l_1<l_2<\cdots<l_{K-1}\le K}\exp\left(\sum\limits_{m=1}^{K-1}\mathcal{L}_{MUD}^{a}\left(c_{l_m}^{(1)}\right)\right)}{1+\sum\limits_{1\le l_1<l_2\le K}\exp\left(\sum\limits_{m=1}^{2}\mathcal{L}_{MUD}^{a}\left(c_{l_m}^{(1)}\right)\right)+\cdots+\sum\limits_{1\le l_1<l_2<\cdots<l_K\le K}\exp\left(\sum\limits_{m=1}^{K}\mathcal{L}_{MUD}^{a}\left(c_{l_m}^{(1)}\right)\right)} \qquad (7)$$

And, $B_l = \exp\{\mathcal{L}^{a}_{MUD}(c_i^{(1)})\}$ with $1\le l\le K$. If $c_l^{(1)} = 0$, then $\{\mathcal{L}^{R}_{MUD}(c_j^{(2)})\}$. The $\{\mathcal{L}^{R}_{MUD}(c_j^{(2)})\}$ can be obtained from soft MUD 2 module. Then, $\mathcal{L}_{MUD}^{SUM}\left(c_j^{(2)}\right)$ will be delivered to DEC for more accurate value.

PERFORMANCE EVALUATION

The performance of NetCC IDMA scheme is evaluated in terms of BER performance and EXIT charts. And, the comparisons with existing non-cooperative IDMA scheme are also carried out. For a fair comparison, the non-cooperative IDMA and NetCC IDMA scheme has the same transmit power P_T. Thus, the power of kth user kth with $P_k^{NonC} = P^T/N$. Besides, the source-relay channels are assumed almost perfect with error-free broadcast phase cooperation (Zhang and Hanzo, 2009). And, in the following simulations, the information bits frame length L = 5114, which is a practical length in the 3rd Generation Partnership Project (3GPP) wireless communication systems. Moreover, BPSK modulation is also used.

Simulation 1: This simulation examines the BER performance of NetCC IDMA scheme and compares it with non-cooperative IDMA scheme. There are 4 source users and 1 relay user in this simulation scenario. And, the relay data:

$$\left\{c_1^R[m]=\tilde{c}_1^1[m]\oplus\tilde{c}_1^2[m]\oplus\tilde{c}_1^3[m]\oplus\tilde{c}_1^4[m]\right\}$$

Repetition code rate R_c is 1/8. Here, Nakagami-m fading parameter is 1.

As shown in Fig. 4, in good channels with high E_b/N_0, the proposed NetCC IDMA scheme can bring obvious BER improvement compared to the non-cooperative IDMA scheme. For example, if BER is 2×10^{-3}, the E_b/N_0 gain is 5.4 dB using NetCC IDMA scheme. The reason is that, in good channels, the LLR information is reliable. And, the network coding decoder can effectively provide the relayed soft information for specific source user. Thus, the cooperative diversity gain and the improved BER performance can be achieved.

On the contrary, in poor channels with low E_b/N_0, the performance of NetCC IDMA scheme becomes worse compared to non-cooperative IDMA scheme. It is because that, with bad channel quality, each user has the low reliable LLR information. After network decoding, the cooperation scheme cannot provide sufficient spatial diversity for performance enhancement. Moreover, the relay user also occupies some part of the transmit power.

Simulation 2: This simulation investigates the impact of relay user number on the BER performance. The scenario has 8 source users and relay users number is 1, 2, 4, respectively. The repetition coding rate R_c = 1/12. And, Nakagami-m fading parameter is 1. Here, the network coded relaying scheme is:

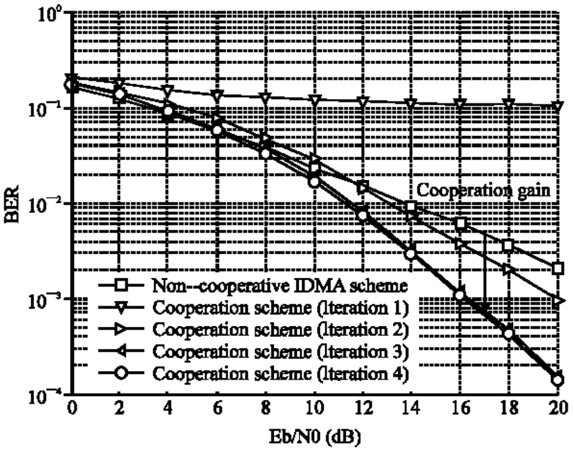

Fig. 4: Comparison between NetCC IDMA and non-cooperative IDMA scheme

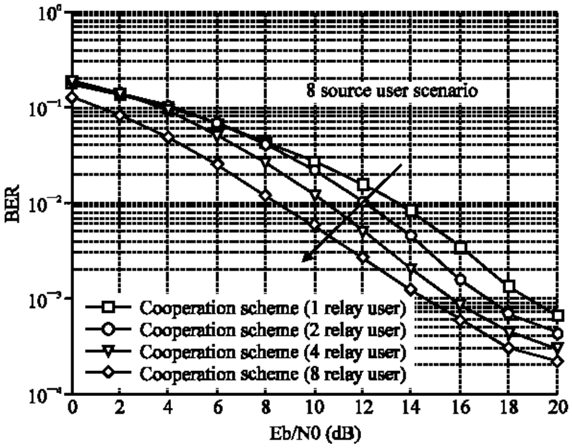

Fig. 5: Impact of relay user number on BER performance of NetCC IDMA scheme

$$\left\{c_j^{(2)} = \tilde{c}_j^{(j-1)*G+1} \oplus \tilde{c}_j^{(j-1)*G+2} \oplus \cdots \oplus \tilde{c}_j^{(j-1)*G+G}\right\}$$

for $1 \leq j \leq (N-K)$, $1 \leq i \leq K$ and $G = K/(N-K)$. For example, for 8 source users and 2 relay users scheme, the network coded chips are:

$$\left\{c_1^{(2)} = \tilde{c}_1^1 \oplus \tilde{c}_1^2 \oplus \tilde{c}_1^3 \oplus \tilde{c}_1^4\right\}$$

and

$$\left\{c_2^{(2)} = \tilde{c}_1^5 \oplus \tilde{c}_1^6 \oplus \tilde{c}_1^7 \oplus \tilde{c}_1^8\right\}$$

In Fig. 5, a significantly reduced BER performance can be obtained with increasing relay user number. For instance, if BER is 10^{-3}, 8 relay users scheme has 4.2 dB gain compared to 1 relay user scheme. The reason is that, in the NetCC IDMA system, each cooperating user experiences the independent channel fading. More relay users can bring more cooperation diversity gain and better BER performance.

Moreover, it is worth pointing out that, in order to enhance system BER performance, more powerful FEC codes (e.g., turbo codes, low-density parity-check (LDPC) codes) can be considered in further studies.

Simulation 3: This simulation examines the effect of Nakagami-m fading on the BER performance. The scenario has 8 source users with 2 relay users. Figure 6 shows that the BER degrades with decreasing fading parameter m. Moreover, such degradation becomes more significant in low parameter m region, which represents the severe fading environment.

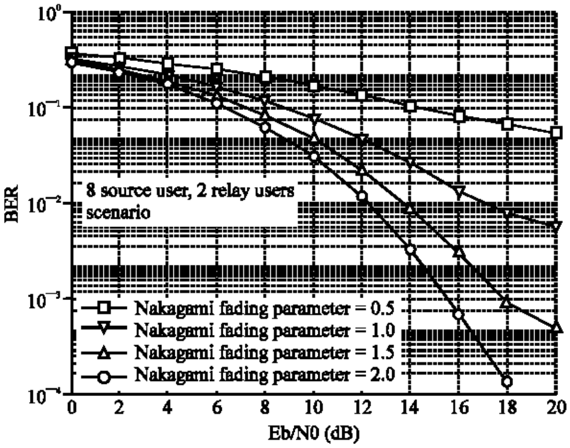

Fig. 6: Impact of Nakagami-m fading parameters on BER performance

Simulation 4: This simulation studies the mutual information gain using the proposed NetCC IDMA scheme based on EXIT charts. The EXIT chart was initially introduced by Brink (2001) as an efficient technique to investigate the convergence property of iterative detector.

In this simulation, 4 source users with 4 relay users cooperation scheme are considered. And, Nakagami-m fading parameter is 1. The results are portrayed in Fig. 7a, where RDEC consists of network coding decoder and FEC decoder.

First, in high mutual information region, the noticeable mutual information gain can be obtained based on NetCC IDMA scheme. Since, in this region, the multi-user interference is greatly mitigated with the reliable chips estimation. Using network decoding, the larger mutual information is achieved due to cooperation diversity gain. It results in the better BER performance and more supportable user number.

Second, in low mutual information region, the improvement is limited. The reason is that, in this region, multi-user interference is strong and LLR information has low reliability. The network coding decoder is hard to provide accurate LLR information estimation, yielding the low cooperation gain.

Simulation 5: This simulation analyzes the iteration convergence property based on the trajectory of EXIT chart. The scenario has 8 source users and 2 relay users. And, Nakagami-m fading parameter is 1. The results are depicted in Fig. 7b.

First, the simulated trajectory almost touches the EXIT curves of MUD and RDEC, which confirms the accuracy of EXIT charts simulation. Second, Fig. 7b

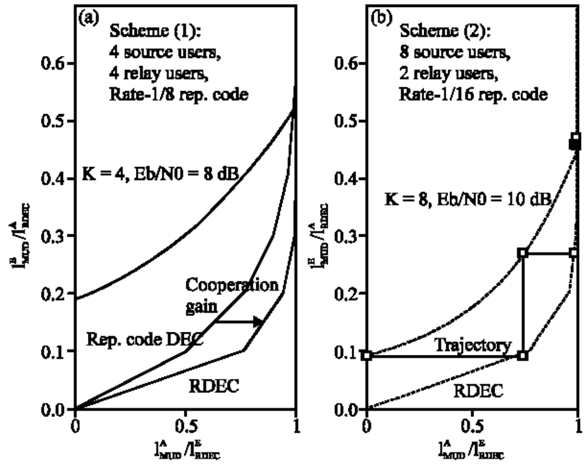

Fig. 7: EXIT charts of NetCC IDMA scheme

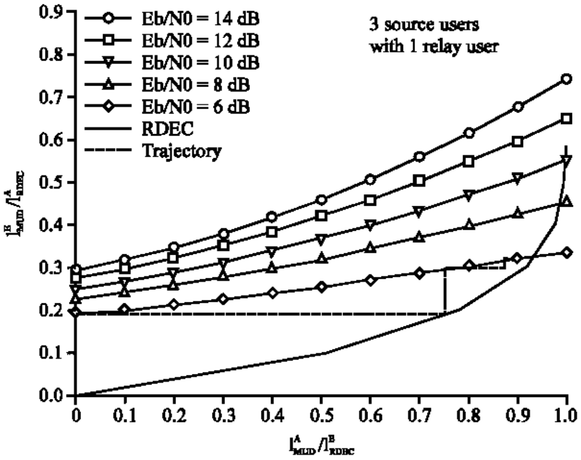

Fig. 8: EXIT charts with various E_b/N_0

also shows that 8 source users can be supported at E_b/N_0=10 dB with 2 relay users cooperation. And, the required iteration number is 3. It reveals that the proposed NetCC iteration MUD algorithm is efficient with the rapid convergence property.

Simulation 6: This simulation investigates the impact of E_b/N_0 on EXIT charts. The scenario has 3 source users and 1 relay user. The repetition coding rate is 1/8. And, Nakagami-m fading parameter is 1.

In Fig. 8, there is an intersection between the MUD and RDEC EXIT curves. It means that the system cannot support 3 source users at E_b/N_0=6 dB. But, with increasing E_b/N_0, the EXIT curve of MUD has higher extrinsic mutual information. When E_b/N_0=12 dB, there exists an open tunnel, which means that 3 source users become supportable. These results and simulation method are useful for analyzing the multi-user capacity of NetCC IDMA system.

CONCLUSIONS

This study designed a network coded non-orthogonal IDMA cooperation system. A linear network coding assisted iterative MUD method was proposed. And, a soft multi-user network decoding algorithm was also studied. Over Nakagami-m channels, the BER performance and EXIT charts were evaluated in various scenarios. Numerical results have confirmed that the proposed NetCC IDMA scheme can achieve obvious BER improvement and extrinsic mutual information enhancement compared to the existing IDMA scheme. Moreover, the proposed cooperation strategy can also bring benefits of low time cost and flexible network deployment for multi-user cooperative systems.

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APPENDIX

In this appendix, we will prove Eq. 3, which is the chip-level multiuser soft network decoding algorithm.

Without loss of generality, we assume that source user number K is even. The case that K is odd can be extended in a straightforward manner:

$$\begin{aligned}\mathcal{L}_{\text{MUD}}^{(1)}\left(c_i^j\right) &= \log\frac{P\left(c_i^j=1\big/\boldsymbol{r}\right)}{P\left(c_i^j=0\big/\boldsymbol{r}\right)}\\ &= \log\frac{P\left(c_j^{(2)}\oplus\left(c_1^{(1)}\oplus c_2^{(1)}\oplus\cdots\oplus c_{i-1}^{(1)}\oplus c_{i+1}^{(1)}\oplus\cdots\oplus c_K^{(1)}\right)=1\big/r_1^{\text{SD}},r_2^{\text{RD}}\right)}{P\left(c_j^{(2)}\oplus\left(c_1^{(1)}\oplus c_2^{(1)}\oplus\cdots\oplus c_{i-1}^{(1)}\oplus c_{i+1}^{(1)}\oplus\cdots\oplus c_K^{(1)}\right)=0\big/r_1^{\text{SD}},r_2^{\text{RD}}\right)}\\ &= \log\frac{P\left(c_j^{(2)}=0\big/r_2^{\text{RD}}\right)\zeta+P\left(c_j^{(2)}=1\big/r_2^{\text{RD}}\right)(1-\zeta)}{P\left(c_j^{(2)}=0\big/r_2^{\text{RD}}\right)(1-\zeta)+P\left(c_j^{(2)}=1\big/r_2^{\text{RD}}\right)\zeta}\\ &= \log\frac{\alpha+\exp\left(\mathcal{L}_{\text{MUD}}^{\mathbf{a}}\left(c_j^{(2)}\right)\right)}{1+\alpha*\exp\left(\mathcal{L}_{\text{MUD}}^{\mathbf{a}}\left(c_j^{(2)}\right)\right)}\end{aligned} \quad (8)$$

where, $r = \{r_1^{SD}, r_2^{RD}\}$. And:

$$\zeta = P\left(\frac{1-(-1)^{c_1^{(1)}+c_2^{(1)}+\cdots+c_{i-1}^{(1)}+c_{i+1}^{(1)}+\cdots+c_K^{(1)}}}{2} = 1 \Big/ r_1^{SD} \right) \tag{9}$$

$$\begin{aligned}
\alpha &= \frac{\zeta}{1-\zeta} \\
&= \frac{P\left(\frac{1-(-1)^{c_1^{(1)}+c_2^{(1)}+\cdots+c_{i-1}^{(1)}+c_{i+1}^{(1)}+\cdots+c_K^{(1)}}}{2} = 1 \Big/ r_1^{SD} \right)}{P\left(\frac{1-(-1)^{c_1^{(1)}+c_2^{(1)}+\cdots+c_{i-1}^{(1)}+c_{i+1}^{(1)}+\cdots+c_K^{(1)}}}{2} = 0 \Big/ r_1^{SD} \right)} \\
&= \frac{\sum\limits_{\substack{1\le l_1\le K \\ l_1\ne i}} A_{l_1} + \sum\limits_{\substack{1\le l_1<l_2<l_3\le K \\ l_1\ne i, l_2\ne i, l_3\ne i}} A_{l_1}A_{l_2}A_{l_3} + \cdots + \sum\limits_{\substack{1\le l_1<\cdots<l_{K-1}\le K \\ l_1\ne i, l_2\ne i, \cdots, l_{K-1}\ne i}} A_{l_1}A_{l_2}\cdots A_{l_{K-1}}}{1 + \sum\limits_{\substack{1\le l_1<l_2\le K \\ l_1\ne i, l_2\ne i}} A_{l_1}A_{l_2} + \cdots + \sum\limits_{\substack{1\le l_1<\cdots<l_{K-2}\le K \\ l_1\ne i, l_2\ne i, \cdots, l_{K-2}\ne i}} A_{l_1}A_{l_2}\cdots A_{l_{K-2}}} \\
&= \frac{\begin{gathered}\sum\limits_{\substack{1\le l_1\le K \\ l_1\ne i}} \exp\left(\mathcal{L}^{a}_{MUD}\left(c_{l_1}^{(1)}\right)\right) + \sum\limits_{\substack{1\le l_1<l_2\le K \\ l_1\ne i, l_2\ne i}} \exp\left(\sum_{m=1}^{K-1} \mathcal{L}^{a}_{MUD}\left(c_{l_m}^{(1)}\right)\right)\cdots \\ + \sum\limits_{\substack{1\le l_1<\cdots<l_{K-1}\le K \\ l_1\ne i, l_2\ne i, \cdots, l_{K-1}\ne i}} \exp\left(\sum_{m=1}^{K-1} \mathcal{L}^{a}_{MUD}\left(c_{l_m}^{(1)}\right)\right)\end{gathered}}{\begin{gathered}1 + \sum\limits_{\substack{1\le l_1<l_2\le K \\ l_1\ne i, l_2\ne i}} \exp\left(\sum_{m=1}^{2} \mathcal{L}^{a}_{MUD}\left(c_{l_m}^{(1)}\right)\right) + \cdots \\ + \sum\limits_{\substack{1\le l_1<\cdots<l_{K-2}\le K \\ l_1\ne i, l_2\ne i, \cdots, l_{K-2}\ne i}} \exp\left(\sum_{m=1}^{K-2} \mathcal{L}^{a}_{MUD}\left(c_{l_m}^{(1)}\right)\right)\end{gathered}}
\end{aligned} \tag{10}$$

where, $A_l = \exp\{\mathcal{L}^{R}_{MUD}(c_l^{(1)})\}$, $1 \le l \le K$, $1 \ne i$. If $c_l^{(1)}$, then $\{\mathcal{L}^{a}_{MUD}(c_l^{(1)})\}$.

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