Bi-Directional Relay for Coded Cooperation

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***Abstract* - Coded cooperation (CC) allowing a pair of users to help each other with relaying part of partner's data is investigated to extend wireless channel reach by cooperative diversity. Taking advantage of a bidirectional property of data flows, instead of transmitting the each packet from each user in the second phase of CC, we propose to broadcast a joint packet with XOR-gated information of the two second packets from both users. The throughput is increased and the quality is also improved based on mathematical analysis and simulation.**

Keywords - coded cooperation, network coding, cooperative networking, diversity, bidirectional relay

I. INTRODUCTION

Cooperative networking diversity [1] has been proposed as an effective method to combat fading which is a challenge in wireless communications. Openness of wireless channel, which provides channel diversity, is exploited and possibly considered as an advantage rather than a disadvantage as before. In spatial diversity, replicas of original data are transmitted in different paths so that the destination can combine them to retrieve original data. Cooperative networking in which the users help each other by relaying their partner's data is based on that principle. Some typical cooperative networking algorithms are store-and-forward (S&F), amplify-and-forward (A&F), decode-and-forward (D&F) [2], compress-and-forward (C&F) [3], coded cooperation (CC) [4], and space time coded-cooperation [5]. In multi-hop scenario, an intelligent coding scheme has been proposed to generate codewords delivered over multiple paths as a diversity method [6].

Diversity makes transmission more reliable when network coding [7] is carried out at a higher layer and thus helps increase throughput by reducing bandwidth usage. Bi-directional relaying [8] is itself a special case of this method. In the coded bi-directional relay (CBR), the relay node combines the two packets from two users into a single 'joint-packet' by XOR-gating the information and multicasts it to both users. Amplify-and-forward CBR [9] utilizing the inherent packet combining that emerges from simultaneous utilization of a multiple access channel can provide a higher throughput in a errorless channel but severely degrade the performance in noisy channels compared with the former. Investigating in multiple-node cooperation, Ref. [10] assumed that every node can receive all other packets except the packet destined to it, the relay broadcasts a packet achieved from XOR-gating all transmitted packets together. However, the assumed situation is not always the case, therefore more general situation should be investigated. Adaptive network coded cooperation [11] proposed a coding method that can adapt to the current network graph.

Coded cooperation and network coding combination method was also proposed. A network coding approach to cooperative diversity [12] can be considered as a typical algorithm of this type. An encoding was proposed in which each partner transmits the algebraic superposition of its local and relayed information. Packet decoding is done by iterating between the codewords from the two partners.

Considering both upward and downward stream, we propose a method based on a combination of coded cooperation and bi-directional relaying to increase throughput of the network. System model and algorithm will be described in part II. We discuss about throughput enhancement in III by a mathematical analysis. Computer simulation is presented in IV.

II. SYSTEM MODEL AND PROPOSED METHOD

We consider a wireless network including many stations communicating with an AP. A situation where nodes X, Y exchanges packets with the AP as showed in Fig 1. We first discuss how regular CC applies to this scenario, followed by the proposed method.

A. Regular coded cooperation

We first investigate sending X_U from X and sending Y_U from Y to AP (upward transmission). In regular coded cooperation, packet X_U' after being coded by convolutional coding to X_U is punctured into two packets X_{U1} and X_{U2} (ie. $X_U' = X_{U1} + X_{U2}$) with punctuation ratio R_p i.e.

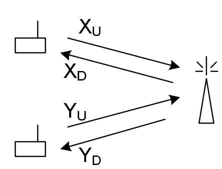

Figure 1. Network model

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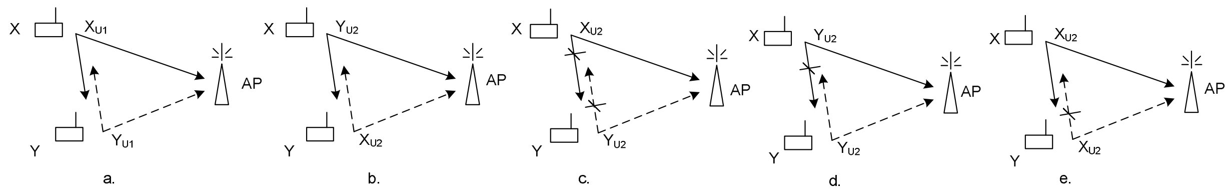

Figure 2. Fig 2 Two-phase transmissions in regular coded cooperation: a. for the first phase for transmitting the first parts of coded packets, and b. - e. for the second phases for transmitting the second parts of coded packets, case 1: All channels with retrievable errors, case 2: Cooperating channels with bidirectional irretrievable errors, and cases 3 and 4: Cooperating channels with unidirectional irretrievable errors, respectively.

$$Lx_{U1} = R_p Lx_{U2}, \quad (1)$$

where Lx_{U1} and Lx_{U2} are respectively packet sizes of X_{U1} and X_{U2}.

In the first phase, X and Y broadcast their own packets (X_{U1} and Y_{U1}) (Fig 1a). Depending on if they can correctly receive the packet from the partner or not in this phase (by checking CRC), they send their own data or partner's data in the second phase. Y achieves X_{U2} from X_{U1} by decoding X_{U1} to get X_U (convolutional coding rate is chosen high enough that decoding X_{U1} to get X_U' is possible) and puncturing X_U into X_{U1} and X_{U2} [8]. Similarly, X can get Y_{U2} from Y_{U1}. Four cases in the second phase are shown in Fig 2b (fully cooperative), c (non-cooperative), and d-e (partly cooperative).

When looking at the second phase of CC, we can see that case 1 and case 2 are symmetric (AP receive X_{U1}, Y_{U1}, X_{U2}, Y_{U2}) but case 3 and case 4 are not symmetric (AP receive X_{U1}, Y_{U1}, $2Y_{U2}$ for case 3 and X_{U1}, Y_{U1}, $2X_{U2}$ for case 4). This reduces diversity degree and therefore the performance.

B. Symmetric Coded Cooperation

Symmetric CC is similar to CC and the difference is that in symmetric CC there are not case 3 and case 4 i.e. the second phase is fully cooperative or non-cooperative. It is never partly cooperative. Because we mention symmetric CC here in order to easily make a comparison between BICC and CC only, how the users in symmetric CC know whether to choose full cooperation or non-cooperation mode is not investigated here.

On the other hand, the downward transmission is not described in CC. Based on the principle of CC, we propose a transmission scheme for the downward transmission so that BiCC performance can be compared to CC.

C. Bi-Directional Coded Cooperation (BiCC)

Instead of fully exchanging packets in the second phase, we propose a method to reduce transmission steps by broadcasting a joint packet of XOR-gated information of these packets. However, the case that the relay can decode received packets does not always occur due to transmission error. The relay checks the packet overheard from its partner by looking at CRC attached to packet. For easy understanding, we call the process of transmitting and receiving X_U and X_D is the first transmission set, the process of transmitting and receiving Y_U and Y_D is the second transmission set. For the sake of simplicity, we only investigate the first transmission set when X and AP exchange X_U and X_D packets and Y is the relay. The second transmission set is carried out in a similar way and also showed in Fig 3 as examples. The principle is as follows:

- X encodes and punctures X_U into X_{U1} and X_{U2} as in CC. X transmits X_{U1}. AP does the same processes with X_D.
- If Y can overhear and decode both X_{U1} and X_{D1}, it recovers X_{U2} and X_{D2} as in CC, and broadcasts $X_{U2} \oplus X_{D2}$; otherwise, it stays in silence.
- If X and AP do not receive $X_{U2} \oplus X_{D2}$ after waiting for a certain time period, they transmit $X_{U2} \oplus X_{D2}$, respectively.
- X and AP respectively combine the received packets to retrieve X_D and X_U.

Considering four cases for the first transmission set and four cases for the second transmission set, we have 16 cases in total. Fig. 3a shows the first case when all of the relays receive their partner's data correctly (fully cooperative in both upward and downward transmissions). In the data flow figures, small boxes are the sources of the transmissions, arrow ends are destinations, and small circles are overhearing nodes (relays). A solid line connects a source and a destination and a dashed line indicates an overheard packet. Considering both transmission sets, the total 16 cases are classified into 3 types:

1) Type 1: Full-bidirectional relaying: Type 1 is used when Y can decode X_{U1}, X_{D1} and X can decode Y_{U1}, Y_{D1} (Fig 3b). Y transmits $X_{U2} \oplus X_{D2}$ in the first transmission set. X thereafter transmits $Y_{U2} \oplus Y_{D2}$ in the second set. At X, because X_{U2} is original data, X_{D2} can be retrieved by doing $X_{U2} \oplus (X_{U2} \oplus X_{D2})$. In the same manner, X_{U2}, Y_{U2} and Y_{D2} are retrieved at correspondent destination nodes. Correspondent combining processes are achieved at the nodes to get the data. Compared to CC, the number of transmission steps is reduced by two in two transmission sets thus the throughput increases by a certain ratio α (remember that the number of steps in regular CC and symmetric CC is the same). α will be evaluated in III.

2) Type 2: Semi-bidirectional relaying: Type 2 is used when in one transmission set, the relay can decode both overheard packets (e.g. in Fig 3c, Y can decode X_{U1}, X_{D1}); whereas in the other set, the relay can not decode both overheard packets (can decode only one overheard packet or no overheard packet) (e.g. in Fig 3c, X can decode Y_{U1} but not Y_{D1}). We also show two other cases when Y can decode both overheard packets but X cannot. X can decode Y_{D1}, not Y_{U1} (Fig 3d) and X cannot decode both Y_{D1} and Y_{U1} (the first transmission sets are not showed). Compared to CC, the number of transmission steps is reduced by only one in this case thus the throughput increases by a ratio α/2.

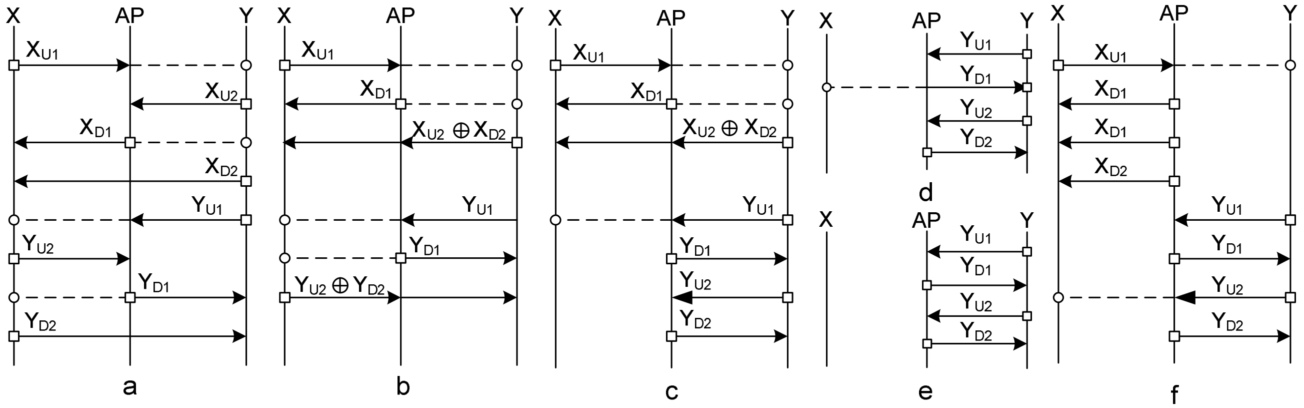

Figure 3. a. Regular coded cooperation, b. Full-bidirectional relaying, c, Semi-bidirectional relaying, d and e. Semi-bidirectional relaying (second transmission set) f. Non-bidirectional relaying. Dashed lines indicate overheard packets.

3) Type 3: Non-bidirectional relaying: Type 3 is used when no relay can decodes both overheard packets in both transmission sets (an example is showed in Fig 3f). Both relays react similarly as Y in the example we considered in type 2. We cannot reduce any transmission step here and throughput remains the same as CC.

For easy understanding, the improvement from CC to BiCC can be separated into two steps. Firstly, due to symmetry, BER of symmetric CC is lower than that of CC. Secondly, due to broadcasting a joint packet, BiCC has a higher throughput although BER is maintained as in symmetric CC case.

In BiCC, the transmission may follow one of the three types discussed above. The full-bidirectional relaying gives us the highest throughput increase, the semi-bidirectional relaying can give half of the first case's increase whereas the last one give no increase because the number of steps it used is same as CC. The probability of each type will be estimated in the next section. Accordingly, the general throughput of the system can be defined.

III. THROUGHPUT ANALYSIS

Compared with symetric CC, type 1 can save one transmission step in one CC procedure (four steps) by broadcasting $X_{U2} \oplus X_{D2}$ instead of transmitting X_{U2} and X_{D2} individually. Therefore, we can say that, from (1), the transmission time duration of symmetric CC is

$$X_U = X_{U1} + X_{U2} = (R_p + 1)X_{U2}$$

Here we simply use X_U instead of Lx_U for packet size of X_U. The same rule is applied in the following inductions. The transmission time duration in type-1 case is

$$X_{U1} + \frac{X_{U2}}{2} = \left(R_p + \frac{1}{2}\right)X_{U2}$$

Factor 1/2 comes from the effective bandwidth occupation by broadcasting one packet ($X_{U2} \oplus X_{D2}$). With the same bandwidth used, throughput is inversely proportional to transmission time. Thus when type 1 is used instead of symmetric CC, the throughput increase is

$$\frac{(R_p + 1)}{\left(R_p + \frac{1}{2}\right)} = \left(1 + \frac{1}{2R_p + 1}\right). \qquad (2)$$

Throughput of type 3 can be evaluated as symmetric CC throughput (since the transmission step number is the same) as

$$T_3 = T_B(1 - P_e)$$

where P_e is the packet error rate and T_B is the throughput when the channels are ideally error-free. If type 1 is used, throughput is increased by a ratio as (2) thus can be written as follows:

$$T_1 = T_B(1 - P_e)\left(1 + \frac{1}{2R_p + 1}\right).$$

With a similar way, we can get throughput for type 2 as

$$T_2 = T_B(1 - P_e)\left(1 + \frac{1}{2(2R_p + 1)}\right).$$

Let P_i the probability that type i is used and will be evaluated later. The system throughput can be easily obtained as

$$\begin{aligned} T &= \sum_{i=1}^{3} T_i P_i \\ &= P_1 T_1 + P_2 T_2 + (1 - P_1 - P_2)T_3 \\ &= P_1(T_1 - T_3) + P_2(T_2 - T_3) + T_3 \end{aligned}.$$

The throughput increase compared with symmetric coded cooperation is

$$\begin{aligned} \Delta T &= T - T_3 = P_1(T_1 - T_3) + P_2(T_2 - T_3) \\ &= \frac{T_B(1 - P_e)(2P_1 + P_2)}{2(2R_p + 1)} \end{aligned}. \qquad (3)$$

In order to calculate type i probability P_i, we consider one BiCC process as two regular CC processes (upward transmission and downward transmission) as showed in Table I. The cases of CC are defined in Fig 2.

TABLE I. TYPE CLASSIFICATION BASED ON CC CASES

Upward trans / Downward trans	1	2	3	4
1	1	2	2	2
2	2	3	3	3
3	2	3	3	3
4	2	3	3	3

$$P_1 = P_{11}$$

$$P_2 = \sum_{i=2}^{3} P_{1i} + P_{i1} , \quad (4)$$

$$P_3 = 1 - P_1 - P_2$$

where P_{ij} is probability that the first set is in case i and the second set is in case j. Because these set are independent, let p_i is probability of case i in a single CC process, we have

$$P_{ij} = p_i p_j . \quad (5)$$

Probability for case 1 is evaluated in [8] with reciprocal inter-channels

$$p_1 \geq \int_0^\infty \left(1 - \min\left[1, \sum_{d=d_f}^{\infty} a(d) P(d \mid \gamma_{12})\right]\right)^{2N_B} p(\gamma_{12}) d\gamma_{12} ,$$

where N_B is the number of Trellis branches in the code word, d_f is the code free distance, a(d) is the number of error events of Hamming weight d, γ_{ij} is instantaneous SNR of the channel from node i to node j, and $p(\gamma_{ij})$ is probability density function of γ_{ij} that depends on fading type. Other cases can be similarly evaluated. PER for each case can be bounded as follows

$$P_{ei} \leq 1 - \int_0^\infty \int_0^\infty \left(1 - \min\left[1, \sum_{d=d_f}^{\infty} a(d) p(d \mid \gamma_{10}, \gamma_{10}, i)\right]\right)^{N_B}$$

$$\times p(\gamma_{10}) p(\gamma_{20}) d\gamma_{10} d\gamma_{10}$$

Consequently, PER for CC can be obtained:

$$P_{eCC} = \sum_{i=1}^{4} Per_i p_i . \quad (6)$$

It is also the same for BiCC. In conclusion, with (4), (5), and (6), throughput increase in (3) can be defined.

III. NUMERICAL RESULTS

We use computer simulations to compare BER and spectral efficiency of BiCC and CC as well as show BiCC case percentage. In the BiCC case, we assume that there are two wireless stations are communicating with an AP as in Fig. 1. The four packets are exchanged to follow the scheme in the Fig. 3. In the CC case, because downward transmissions are not supported, only upward transmissions are simulated (only X_U and Y_U are sent).

The instantaneous signal-to-noise ratio (SNR) of the wireless channel between node i and j (can be users or AP) is modeled as follows

$$\gamma_{i,j} = \Gamma_{i,j} \left| h_{i,j} \right|^2 = \frac{P}{N_0} K S_{i,j} d_{i,j}^{-\beta} \left| h_{i,j} \right|^2$$

Where P is the transmit power and N_0 is the additive white Gaussian noise power at the receivers, K = 1 is the path loss for an arbitrary reference distance, $S_{i,j}$ is a log-normal shadowing component with $E[10\log S_{i,j}] = 0$dB and $Var[10\log S_{i,j}] = 1$, $d_{i,j} = 0.5$ is the distance between node i and j, $\beta = 2$ is the path loss component and $|h_{i,j}|$ is fading magnitude. We investigate both quasi-static Rician ($\sigma = 1$, $\upsilon = 1$) and Rayleigh ($\sigma = 1$) fading, such that the fading coefficients $\{h_{i,j}\}$ are constant for a given transmitted block, or code word, but are i.i.d for different blocks. Packet length is 200 bits, 1/2 rate convolutional code is used with polynomial generator [15 17 13 15], 8PSK modulation is used and puncturing rate is 50% with puncturing table [1 0 1 0] for N_1 and [0 1 0 1] for N_2.

BER of BiCC and CC are showed in Fig 4 when there is Rayleigh or Rician fading. Figure 5 shows the throughputs of BiCC and CC. When SNR is higher, the probability of full-bidirectional relaying is higher and throughput is higher. The percentage of BiCC types are shown in Fig 6.

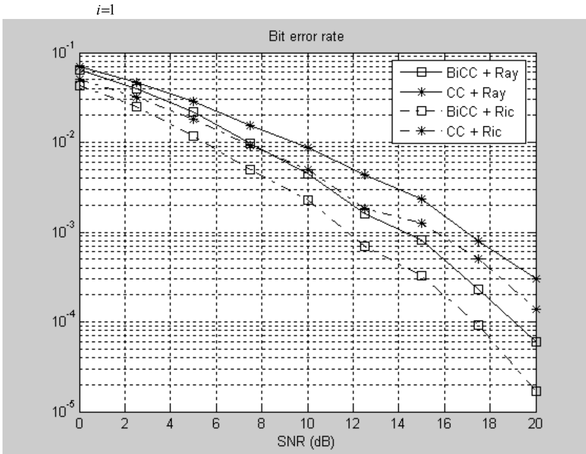

Figure 4. BER performance comparisons of BiCC and regular CC for Rayleigh (Ray) and Rician (Ric) channels models.

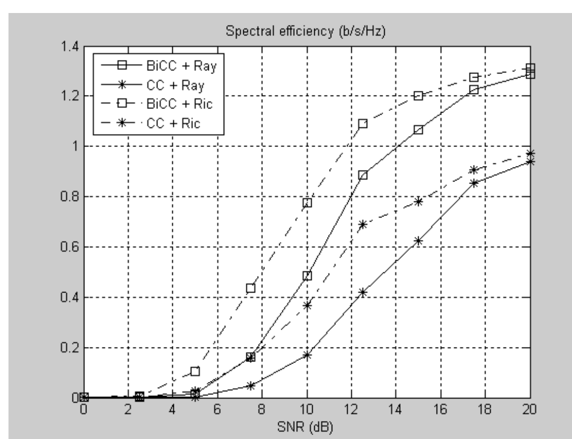

Figure 5. Spectral efficiency comparisons of BiCC and regular CC for Rayleigh (Ray) and Rician (Ric) channels model.

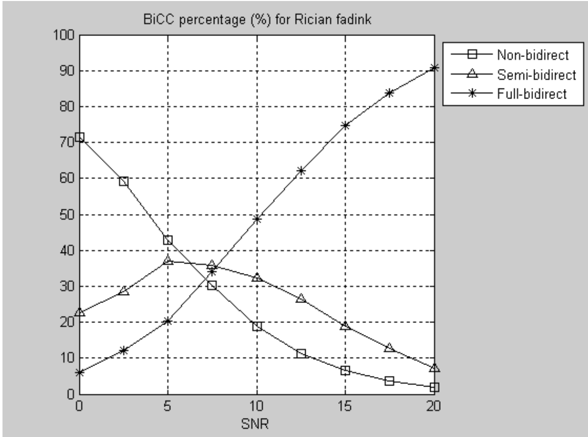

Figure 6. BiCC percentage

IV. CONCLUSION

Taking advantage of bi-directional flow property and openness of radio channels, a novel approach is proposed to increase the throughput transmission without degrading any of quality. Instead of sending all packets in the second phase of regular coded cooperation, respective packets are XOR together and broadcasted. Some problems of CC were also analyzed and solve. We showed the throughput increase in mathematical analysis and computer simulations.

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