A Cooperative Three-Time-Slot Transmission in Asymmetric Two-Way Relay Channels

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***Abstract*— In a two-way relay system where two nodes exchange information via a half-duplex relay, the achievable data rates of both directions are limited by the weaker link. When the two-way channel is asymmetric due to relay positioning or channel fading, the sum rate of the two-way relay system will suffer from severe degradation. In this paper, we propose a novel three time-slot cooperative transmission strategy in order to transmit at the maximum rate of each link, and therefore, to improve the sum rate of the two-way relay system. We obtain capacity region for the new strategy and derive an achievable rate region. Time slot allocation and power allocation at the relay are optimized to achieve the maximum sum rate. Simulation results show that the proposed strategy significantly outperforms existing transmission strategies under asymmetric channel conditions both in AWGN and Rayleigh fading channels.**

I. Introduction

Relays assist in communication to extend coverage and increase data rates. It takes two time slots to transmit from source to destination in a one-way time-division duplex (TDD) relay system, and four time slots to exchange information between source and destination, while conventional two-way relay system completes the exchange of bi-directional information only in two time slots, thus doubles spectral efficiency [1]. Different forwarding protocols at the relay have been studied for the two-way relay system such as Amplify and Forward (AF), Decode and Forward (DF), and Compress and Forward (CF) or Denoise and forward (DNF) [2].

The simplest two-way relay network consists of three nodes: the relay node and two source nodes that intend to exchange information. A common strategy for two-way relay system is the Multiple Access and Broadcast (MABC) strategy. In the first time slot, two nodes transmit signals simultaneously to the relay, which is a Multiple Access (MA) phase. In the second slot, the relay broadcasts signals to the two nodes, which is a broadcasting (BC) phase. It has been shown that two-way relay system with MABC strategy doubles the sum rate with respect to the one-way relay system [3]. Another strategy is Time-Division and Broadcast (TDBC) with three time slots. In the first and second time slots, two source nodes take turns to transmit and relay receives. Relay then broadcasts in the third time slot. Compared with traditional four-phase transmission, TDBC improves throughout by 1/3 when receive signal-to-noise (SNR) ratios of bi-directional receive signals at the relay vary little [4]. These two strategies have been compared in terms of capacity bound and achievable rate regions in [5]. It is shown that MABC has a higher upper bound than TDBC in all circumstances but a lower achievable sum rate when the channel is symmetric. However, both strategies achieve much lower sum rates in asymmetric channel, where the link from one node to relay is much stronger than the other, than in symmetric scenario,

In practical systems such as cellular networks, asymmetric channels are frequently encountered due to terminal and relay locations and channel fading. Only a few papers now address the problem in two-way relay under asymmetric channel. The authors in [6] consider DF transmission for asymmetric channel only in BC phase of MABC strategy. The authors in [7] design codebook for CF MABC strategy with asymmetric data rates. However, these solutions are for MABC strategy and are not able to fully exploit channel resources.

In this paper, we propose a novel two-way relay strategy named Cooperative Multiple Access and Broadcast strategy (CoMABC). We introduce a third time slot after the MA and BC phase, in which one of the two source nodes cooperatively transmits with the relay. Compared with MABC and TDBC under same total transmission time, the CoMABC strategy significantly improves sum rate in asymmetric channels. We will study the capacity region upper bound of the strategy and derive an achievable rate region for DF protocol. Time slot allocation and power allocation are optimized to maximize the sum rate. Simulation results are provided in both additive white Gaussian noise (AWGN) and Rayleigh fading channels.

The rest of this paper is organized as follows: The system model and transmission process of CoMABC strategy is described in section II. In section III, we derive the capacity region upper bound and achievable rate region for the new strategy based on cut-set theorem [8], and formulate the optimization problem for resource allocation. Simulation results and analysis are presented in section IV. Section V gives the conclusion.

II. Relaying Strategy

A. System Model

Consider a two-way relay system with a half-duplex relay node r and two source nodes a and b that intend to communicate with each other through the relay. Transmission is divided into M time slots or phases, the mth time slot is denoted as t_m. Let S_1 and S_2 denote the transmit node set and receive node set respectively. $s_i^{(m)}$ denotes the bits that node i in the

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transmission set S_1 wants to transmit in mth time slot. The bits are modulated to $x_{i,j}^{(m)} = \mathcal{M}_{i,j}^{(m)}(s_i^{(m)})$ and sent to node j in the receive node set S_2 with rate R_{ij}, where $\mathcal{M}_{i,j}^{(m)}$ denotes the modulation function applied to the signal from node i to node j. The modulated signal at each transmitter satisfies energy constraint $\mathbb{E}(x_{i,j}^2) = 1$, and the transmit power at node a, b and r are P_1, P_2 and P_3, respectively, see Fig.1.

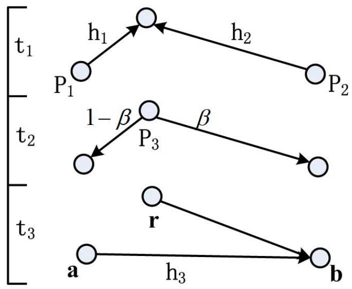

Fig. 1: System model

The relay is time division half-duplex and we assume channel reciprocity. We use h_1, h_2 and h_3 to denote the link between a and r, the link between b and r, and the direct link between a and b. n_j denotes the zero mean, unit variance white Gaussian noise at receiver j, and the received signal is

$$y_j^{(m)} = \sum_{i \in S_1} h_i \sqrt{P_i} x_{i,j}^{(m)} + n_j \tag{1}$$

B. Relaying Strategy

Without loss of generality, suppose that the link between a and r is stronger than the link between b and r, and assume channel reciprocity. In order to adapt to channel quality, different modulation and coding schemes should be applied in different phases. The relay receives signal from node a at a higher rate but forwards it to node b at a lower rate. The opposite happens to the signal from node b. By the time when node a has completed receiving data from node b, the relay has not yet finished forwarding data to b. If relay continues to forward, node a turns idle.

If we introduce a third slot in MABC strategy during which both the idle node a and relay transmit to the the other node, i.e., the relay continues to forward the signal it received in MA phase and node a transmits new information. In this way, the new strategy is able to increase the sum rate. When $b \leftrightarrow r$ link is stronger, we will only swap node a and node b in the third time slot and the strategy will still apply. The transmission process is depicted in Fig.1.

In time slot t_1, node a and node b simultaneously send modulated signals $x_{a,r}^{(1)} = \mathcal{M}_a^{(1)}(s_a^{(1)})$ and $x_{b,r}^{(1)} = \mathcal{M}_b^{(1)}(s_b^{(1)})$. The received signal at the relay is

$$y_r^{(1)} = h_1 \sqrt{P_1} x_{a,r}^{(1)} + h_2 \sqrt{P_2} x_{b,r}^{(1)} + n_r \tag{2}$$

The receive SNRs at the relay node from node a and node b differ significantly because of the asymmetric channel. The relay can decode the data from both sides by the successive interference cancelation (SIC) algorithm and obtain the estimate $\hat{s}_a^{(1)}$ and $\hat{s}_b^{(1)}$. The data are then remodulated based on channel conditions at the relay and to be sent in time slot t_2. The remodulated signals are $x_{r,b}^{(2)} = \mathcal{M}_{r,b}^{(2)}(\hat{s}_a^{(1)})$ and $x_{r,a}^{(2)} = \mathcal{M}_{r,a}^{(2)}(\hat{s}_b^{(1)})$.

In time slot t_2, we allocate βP_3 to the data $x_{r,b}^{(2)}$ that is destined to node b and $(1-\beta)P_3$ to $x_{r,a}^{(2)}$, where β is the power allocating factor. The relay then combines two signals by analog network coding [9]. The transmitted signal at the relay in BC phase is

$$x_r^{(2)} = \sqrt{\beta P_3} x_{r,b}^{(2)} + \sqrt{(1-\beta) P_3} x_{r,a}^{(2)} \tag{3}$$

Node a and node b receive the combined signals. At node a, the received signal is

$$\begin{aligned} y_a^{(2)} &= h_1 x_r^{(2)} + n_a \\ &= h_1 \sqrt{\beta P_3} x_{r,b}^{(2)} + h_1 \sqrt{(1-\beta) P_3} x_{r,a}^{(2)} + n_a \end{aligned} \tag{4}$$

and node b receives

$$\begin{aligned} y_b^{(2)} &= h_2 x_r^{(2)} + n_b \\ &= h_2 \sqrt{\beta P_3} x_{r,b}^{(2)} + h_2 \sqrt{(1-\beta) P_3} x_{r,a}^{(2)} + n_b \end{aligned} \tag{5}$$

Each node has its own transmitted data s_a or s_b, which can be subtracted from the received signal first [9], and then the exchanged information can be demodulated without self-interference.

In time slot t_3, relay node continues forwarding the rest of the data and node a begins to transmit new information. By the end of this transmission, node b will receive

$$y_b^{(3)} = h_3 \sqrt{P_1} x_a^{(3)} + h_2 \sqrt{P_3} x_r^{(3)} + n_b \tag{6}$$

After SIC, receiver b will finally obtain the desired data from node a.

This transmission can provide high sum rate and is feasible. In next section, we will derive the achievable rate regions. The upper bound of capacity region will be derived by applying cut-set theorem [8] for half-duplex systems. We will compare the sum rates of the three strategies: CoMABC, MABC and TDBC, where the upper bound and achievable rate region of MABC and TDBC are given in [5].

III. Performance Analysis and Resource Allocation Optimization

A. Capacity Bound and Achievable Rate Region

The cut-set theorem for networks with multiple phases provides an upper bound on the half-duplex relay capacity, which is proved in [5] and [10]. We restate it here for the convenience of readers and for defining some important notations in later proofs.

Cut-set Theorem [8]: Consider a general network with M phases and N nodes, where M and N are finite. The nodes are divided into two sets S and S^C(the complement of S) by a cut C. If the rates $\{R_{ij}\}$ are achievable, the sum rate of information transfer from transmit node set S_1 to a disjoint receive node set S_2, $i \in S_1$, $j \in S_2$, $S_1, S_2 \subset \{1, 2, ..., N\}$, and for any choice of network phase sequence $(m_k)_{k=1}^{\infty}$, is bounded by,

$$\sum_{i \in S_1, j \in S_2} R_{ij} \leq \sup_{t_m} \min_{S} \sum_{m=1}^{M} t_m I(X_S^{(m)}; Y_{S^C}^{(m)} | X_{S^C}^{(m)}) \tag{7}$$

when the minimization is taken over all sets $S \subset \{1, 2, ..., N\}$ subject to $S \cap S_1 = S_1, S \cap S_2 = \emptyset$ and the supremum is over all non-negative t_m subject to $\sum_{m=1}^{M} t_m = 1$.

The conditional mutual information $I(X_S^{(m)}; Y_{S^c}^{(m)}|X_{S^c}^{(m)})$ is the maximum achievable rate between transmit nodes in set S and receive nodes in set S^C, given the transmit signal from set S^C.

Applying the cut-set theorem for half-duplex relays, the following proposition give the upper bound for the CoMABC strategy.

Proposition 1: The capacity region of the half-duplex two-way relay channel with CoMABC strategy is upper bounded by

$$\begin{aligned} R_a \leq \min\{&t_1 I(X_a^{(1)}; Y_r^{(1)}|X_b^{(1)}) + t_3 I(X_a^{(3)}; Y_b^{(3)}|X_r^{(3)}), \\ &t_2 I(X_r^{(2)}; Y_b^{(2)}) + t_3 I(X_a^{(3)}, X_r^{(3)}; Y_b^{(3)})\} \end{aligned} \tag{8a}$$

$$R_b \leq \min\{t_1 I(X_b^{(1)}; Y_r^{(1)}|X_a^{(1)}), t_2 I(X_r^{(2)}; Y_a^{(2)})\} \tag{8b}$$

Proof: According to the cut-set theorem, there are three phases in CoMABC strategy as shown in Fig.1 and Fig.2, the MA phase in t_1, the BC phase in t_2 and the cooperative transmission phase in t_3, respectively.

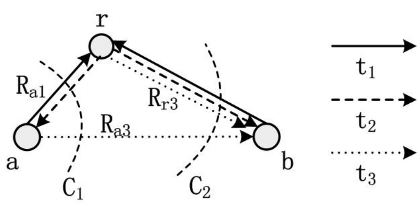

Fig. 2: Cut-set of the network

First we determine the data rate from node b to node a. Data are transmitted in the first two phases from b to a. The transmit set is $S_1 = \{b\}$, and receive node set is $S_2 = \{a\}$. Set S should satisfy $S \cap S_1 = S_1, S \cap S_2 = \emptyset$. In t_1 slot when b transmits and relay receives, cut C_2 determines $S = \{b\}$, and in t_2 slot, cut C_1 determines $S = \{r, b\}$. According to the theorem, the minimization is taken over S and hence the rate from node b to node a is given by (8b).

The data rate from node a to node b can be derived in a similar way but with an additional time slot t_3. Data flows from transmit set $S_1 = \{a\}$ to receive set $S_2 = \{b\}$, and the cut C_1 and C_2 correspond to $S = \{a\}$ and $S = \{a, r\}$. Then by directly applying the cut-set theorem, the rate from node a to node b follows (8a). ■

We can derive the capacity upper bound for CoMABC strategy in terms of point-to-point channel capacity $C(x) = \log_2(1 + x)$ under current system model, that is

$$\begin{aligned} R_a \leq \min\{&t_1 C(P_1|h_1|^2) + t_3 C(P_1|h_3|^2), \\ &t_2 C(P_3|h_2|^2) + t_3 C(P_3|h_2|^2 + P_1|h_3|^2)\} \\ R_b \leq \min\{&t_1 C(P_2|h_2|^2), t_2 C(P_3|h_1|^2)\} \end{aligned} \tag{9}$$

In AWGN channel, channel coefficient h reflects path loss, while in Rayleigh fading channel, it includes both large-scale and small-scale fading. We can obtain ergodic capacity of Rayleigh fading channel by averaging over each channel realization, for here and after.

Next we give the achievable rate region for DF CoMABC strategy in the following proposition.

Proposition 2: An achievable region of the half-duplex two-way relay channel with DF CoMABC strategy is the union of

$$\begin{aligned} R_a \leq \min\{&t_1 I(X_a^{(1)}; Y_r^{(1)}|X_b^{(1)}) + t_3 I(X_a^{(3)}; Y_b^{(3)}|X_r^{(3)}), \\ &t_2 I(X_r^{(2)}; Y_b^{(2)}) + t_3 I(X_a^{(3)}, X_r^{(3)}; Y_b^{(3)})\} \end{aligned} \tag{10a}$$

$$R_b \leq \min\{t_1 I(X_b^{(1)}; Y_r^{(1)}|X_a^{(1)}), t_2 I(X_r^{(2)}; Y_a^{(2)})\} \tag{10b}$$

$$R_a + R_b \leq t_1 I(X_a^{(1)}, X_b^{(1)}; Y_r^{(1)}) + t_3 I(X_a^{(3)}; Y_b^{(3)}|X_r^{(3)}) \tag{10c}$$

Proof: Compared with proposition 1, (10c) is added to reflect the DF nature of the first MA phase.

Node b sends data to relay node r with rate R_b in time slot t_1. Relay remodulates the data according to the channel quality of link $r \rightarrow a$ and forwards it to node a in t_2. After canceling self interference, node a obtains its desired information from b. R_b depends on the minimal rate of the two transmissions as (10b) indicates.

Node a also sends information to relay in time slot t_1 with rate R_{a1}. Part of the data is remodulated and forwarded to node b in t_2 and the remaining data is sent to node b in t_3. R_{a1} satisfies

$$R_{a1} \leq \min\{t_1 I(X_a^{(1)}; Y_r^{(1)}|X_b^{(1)}), t_2 I(X_r^{(2)}; Y_b^{(2)}) + R_{r3}\} \tag{11}$$

where R_{r3} denotes the maximum rate that the relay can support in t_3. The first term represents the transmission rate in t_1, and the second term represents the total data rate that the relay can forward in both t_2 and t_3.

The relay implements SIC to separate signals at the end of t_1, so R_{a1} and R_b are constrained by the capacity of multiple access channel

$$R_{a1} + R_b \leq t_1 I(X_a^{(1)}, X_b^{(1)}; Y_r^{(1)}) \tag{12}$$

In time slot t_3, relay and node a simultaneously transmit to node b and node b decodes both signals. The rate R_{r3} from r to b and R_{a3} from a to b in t_3 is constrained by

$$R_{r3} + R_{a3} \leq t_3 I(X_a^{(3)}, X_r^{(3)}; Y_b^{(3)}) \tag{13}$$

where R_{a3} and R_{r3} should also respectively satisfy

$$R_{a3} \leq t_3 I(X_a^{(3)}; Y_b^{(3)}|X_r^{(3)}) \tag{14}$$

and

$$R_{r3} \leq t_3 I(X_r^{(3)}; Y_b^{(3)}|X_a^{(3)}) \tag{15}$$

The data rate from node a to node b is the sum of R_{a1} and R_{a3}, i.e., $R_a = R_{a1} + R_{a3}$. (10a) can be obtained if we replace R_{a1} with (11), R_{a3} with (14) and together with the constraint (13). Finally, since $R_a + R_b = R_{a1} + R_{a3} + R_b$ and considering (12), (14), we can derive (10c).

■

The achievable rate region for CoMABC strategy of AWGN and Rayleigh fading channel is then given as follows

$$\begin{aligned} R_a &\le \min\{t_1 C(P_1|h_1|^2) + t_3 C(P_1|h_3|^2), \\ &\qquad t_2 C(\beta P_3|h_2|^2) + t_3 C(P_3|h_2|^2 + P_1|h_3|^2)\} \\ R_b &\le \min\{t_1 C(P_2|h_2|^2), t_2 C((1-\beta)P_3|h_1|^2)\} \\ R_a + R_b &\le t_1 C(P_1|h_1|^2 + P_2|h_2|^2) + t_3 C(P_1|h_3|^2) \end{aligned} \tag{16}$$

Note that power allocation is performed in the second time slot, so the transmit power of two signals are βP_3 and $(1-\beta)P_3$ respectively which is revealed in the first two inequations of (16).

B. Resource Allocation Optimization

We formulate optimization problem with the aim to maximize the sum rate. Objective function is the sum of R_a and R_b. For maximizing upper bound, time slots should be optimized. (9) is transformed into the constraint conditions. So the optimization problem is

$$\begin{aligned} &\max_{t_1,t_2,t_3} R_a + R_b \\ &s.t. R_a - t_1 C(P_1|h_1|^2) - t_3 C(P_1|h_3|^2)) \le 0 \\ &\quad R_a - t_2 C(P_3|h_2|^2) - t_3 C(P_3|h_2|^2 + P_1|h_3|^2) \le 0 \\ &\quad R_b - t_1 C(P_2|h_2|^2) \le 0 \\ &\quad R_b - t_2 C(P_3|h_1|^2) \le 0 \\ &\quad t_1 + t_2 + t_3 = 1 \\ &\quad 0 \le t_1, t_2, t_3 \le 1 \end{aligned} \tag{17}$$

This is a linear programming problem with t_1, t_2 and t_3 as the optimization parameter and can be easily solved.

In order to achieve the maximum achievable sum rate, time slot t_1, t_2 and t_3 as well as power allocation factor β at the relay should be jointly optimized. (16) gives the constraints and the optimization problem is formulated as follows,

$$\begin{aligned} &\max_{t_1,t_2,t_3,\beta} R_a + R_b \\ &s.t. R_a - t_1 C(P_1|h_1|^2) - t_3 C(P_1|h_3|^2)) \le 0 \\ &\quad R_a - t_2 C(\beta P_3|h_2|^2) - t_3 C(P_3|h_2|^2 + P_1|h_3|^2) \le 0 \\ &\quad R_b - t_1 C(P_2|h_2|^2) \le 0 \\ &\quad R_b - t_2 C((1-\beta)P_3|h_1|^2) \le 0 \\ &\quad R_a + R_b - t_1 C(P_1|h_1|^2 + P_2|h_2|^2) - t_3 C(P_1|h_3|^2) \le 0 \\ &\quad t_1 + t_2 + t_3 = 1 \\ &\quad 0 \le \beta, t_1, t_2, t_3 \le 1 \end{aligned} \tag{18}$$

This is a nonlinear constraint programming problem and can be solved by the active-set algorithm (also known as a projection method) [11]. Numerical results of optimal t_1, t_2, t_3 and β under various channel conditions will be given in the next section.

IV. Numerical and Simulation Results

In this section, we compare capacity upper bound of three two-way relay transmission strategies: CoMABC, MABC and TDBC, and compare their achievable sum rates under DF protocol. For simplicity, suppose node a and b are fixed and relay r moves between them, as shown in Fig. 3. We assume the distance between a and r as d, the channel gains $h_1 = d^{-\alpha/2}$, $h_2 = (1-d)^{-\alpha/2}$ and $h_3 = 1$, where α is the path loss exponent. As d varies from 0 to 1, the relay moves from a to b. Assume that all nodes have the same transmit power, *i.e.*, $P_1 = P_2 = P_3 = P$, and are interfered by white Gaussian noise with variance $\sigma^2 = 1$. In the following simulations, transmit SNR at each node is $P/\sigma^2 = 10$dB.

In our simulations, time slot allocation is optimized for the upper bound of MABC and TDBC strategies similar to the optimization problem of CoMABC in (17). Both time slot and power allocation are optimized for the achievable sum rates of MABC and TDBC with DF protocol similar to (18).

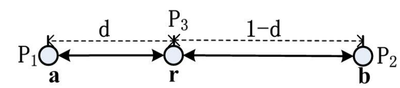

Fig. 3: Simplified system model.

Capacity upper bound and achievable sum rate in AWGN channel for CoMABC, MABC and TDBC are given in Fig.4. We can see from the figure that the upper bound of CoMABC is higher than the other two under all circumstances and CoMABC is always superior to MABC. When the relay is close to node a ($d < 0.3$) or close to node b ($d > 0.7$), the CoMABC outperforms MABC and TDBC significantly which demonstrates the advantage of the proposed strategy in asymmetric channels.

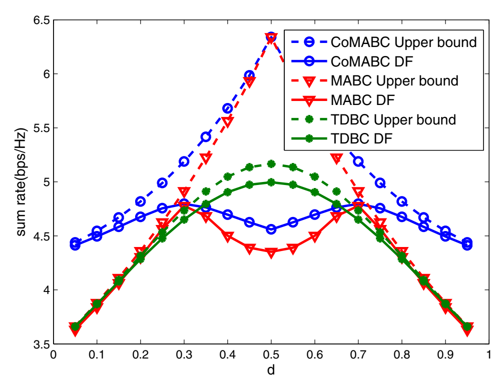

Fig. 4: Sum rates in AWGN channel.

In the middle region, where d is around 0.5, both CoMABC and MABC suffer from sum rate loss due to the DF protocol. Signals from a and b interfere severely with each other at the relay when the receive SNRs are nearly the same and transmission rate is limited by (12). For TDBC, since multiple access is implemented in two time slots, the sum rate does not degrade and we can see from the figure that TDBC outperforms the other two in symmetric channels.

Table I gives the optimal time slots and power allocation factors of the three strategies with $d = 0.2$ and $d = 0.4$. We can see from the table that more power is allocated to the weaker link in BC phase so as to maximize the two-way sum rate. In our strategy, the idle node and relay cooperate in the third time slot to improve sum rate. The more asymmetric the channel is, the longer duration of the third time slot in CoMABC.

TABLE I: Optimal time slots and power allocation factor when $d = 0.2$ and $d = 0.4$.

Strategy	β	t_1	t_2	t_3
CoMABC	0.8(0.6)	0.25(0.46)	0.13(0.20)	0.62(0.34)
MABC	0.9(0.5)	0.62(0.59)	0.38(0.41)	-
TDBC	0.9(0.7)	0.07(0.26)	0.83(0.53)	0.10(0.20)

Sum rates of three strategies under Rayleigh fading channel are shown in Fig.5. Simulation results are obtained by averaging over 1000 channel realizations. For each realization, optimization parameters are re-computed. We can see from the figure that in asymmetric Rayleigh fading channels, sum rate of the proposed strategy is higher than MABC and TDBC.

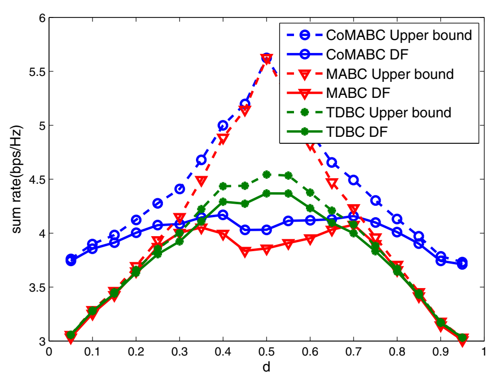

Fig. 5: Sum rates in Rayleigh fading channel.

Computing the optimal parameters for each channel realization will cause high complexity, which is not feasible in practice. To reduce the complexity and relax the requirement of site planning of the relay, we can obtain the optimal power and slot allocation based on the large scale fading factor, which varies slowly and only depends on the positions of the nodes.

In Fig.6 we show the capacity upper bound and achievable sum rates with the large scale fading based power allocation factor and time slots in Rayleigh fading channel. It shows that the CoMABC performs closely to the case when the optimization is for each channel realization.

V. Conclusion

In this paper, we proposed a new three time-slot cooperative transmission strategy for half-duplex two-way relay systems to

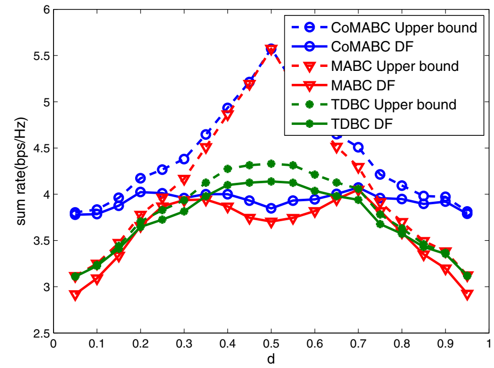

Fig. 6: Sum rates in Rayleigh fading channel with fixed factors.

improve the sum rate under asymmetric channels. We studied the capacity upper bound and achievable rate regions of the proposed strategy and optimized the time slots and power allocation factor. We compared the new strategy with existing ones in both AWGN and Rayleigh fading channels. Simulation results showed remarkable performance gain of the proposed strategy in asymmetric channels.

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