Capacity Bounds and Code Designs for Cooperative Diversity

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***Abstract*— Cooperative diversity is a novel technique for conveying information in wireless networks, where closely located single-antenna network nodes cooperatively transmit and/or receive by forming virtual antenna arrays. For the simplest cooperative setup with two transmitters and two receivers, we first present the latest advances made in determining the theoretical capacity bounds and point out the important roles of coding with side information in achieving the lower bounds on the capacity region. We then focus on practical code designs and describe two coding schemes: one for receiver cooperation based on Wyner-Ziv coding; another for transmitter cooperation based on dirty-paper coding. The two designs perform close to the theoretical bounds and show the gains of cooperative communications predicted by theory.**

I. Introduction

Cooperative diversity [1], [2] has recently been proposed for conveying information in wireless cellular, ad hoc, and sensor networks. It is based on grouping network nodes together into clusters, inside which the nodes cooperate when sending and/or receiving information. In this way, different clusters act as large transmit and/or receive antenna arrays achieving *spatial diversity* without the need for multiple antennas at any node. Hence, cheap and simple nodes can be employed to save power and at the same time mitigate the effects of interference and fading in the wireless links.

The simplest non-trivial setup of cooperative diversity is when the nodes form pairs, i.e., clusters of two, as shown in Fig. 1 (upper-left). The transmitter in Node 1 wants to send message $\omega_1 \in \{1, \ldots, M_1\}$ to the receiver in Node 3; likewise, the transmitter in Node 2 intends to send message $\omega_2 \in \{1, \ldots, M_2\}$ to the receiver in Node 4. Specifically, Node i ($i = 1, 2, 3, 4$) transmits a block $x_i[n]$ of N symbols at a time with $n = 1, \ldots, N$, while being subject to an average power constraint $\frac{1}{N}\sum_{n=1}^{N} |x_i[n]|^2 \le P_i$. The rate of the transmission from Node i is then $R_i = \frac{\log M_i}{N}$. We assume that the channel between Node i and Node j is a Rayleigh flat-fading channel with channel coefficient c_{ji}, which is an i.i.d. complex zero-mean Gaussian random variable.

At the symbol level, the received signals at Nodes 1, 2, 3, and 4 are given by

$$y_1[n] = c_{12}x_2[n] + z_1[n], \quad (1)$$

$$y_2[n] = c_{21}x_1[n] + z_2[n], \quad (2)$$

$$y_3[n] = c_{31}x_1[n] + c_{32}x_2[n] + c_{34}x_4[n] + z_3[n], \quad (3)$$

$$y_4[n] = c_{41}x_1[n] + c_{42}x_2[n] + c_{43}x_3[n] + z_4[n], \quad (4)$$

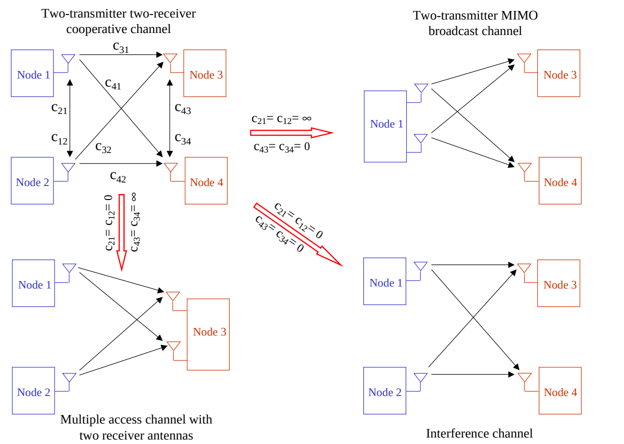

Fig. 1. The two-transmitter two-receiver cooperative channel together with its three special cases.

respectively, where z_i is an i.i.d. circular complex zero-mean Gaussian noise. To simplify the notation, without loss of generality, we assume that the noises are of unit power and $c_{31} = c_{42} = 1$.

The main goal of node cooperation is to achieve spatial diversity and rate multiplexing without increasing the number of antennas at a single node. If $c_{43} = c_{34} = 0$, we have *transmitter cooperation*. On the other hand, if $c_{21} = c_{12} = 0$, we speak of *receiver cooperation*. Note that, if cooperation is perfect, then transmitter cooperation leads to a two-antenna multiple-input multiple-output (MIMO) broadcast channel [10] ($c_{21}, c_{12} \to \infty$), receiver cooperation reduces to a two-user multiple-access channel (MAC) with two receive antennas ($c_{43}, c_{34} \to \infty$), and the general setup with both transmitter and receiver cooperation becomes a single MIMO channel with two transmit and two receive antennas ($c_{21}, c_{12}, c_{43}, c_{34} \to \infty$). On the other hand, when cooperation is not allowed, i.e., $c_{21} = c_{12} = c_{43} = c_{34} = 0$, the channel degenerates to the interference channel [4]. See Fig. 1 for three of these four simplifications.

We consider a quasi-static channel, thus all channel coefficients are constant during transmission of each block. In the *synchronous model* of (1)-(4), the nodes are perfectly synchronized and have full channel state information (CSI), i.e., each node knows instantaneous values of all channel coefficients and their statistics. While it is relatively simple to achieve symbol/time synchronization between nodes, carrier synchronization is challenging in practice. Therefore, we also consider the *asynchronous model*, where random phase offsets are added to the transmitted signals. We include these random phases in the channel coefficients, so that the model stays the same as (1)-(4). Under the asynchronous model for receiver cooperation, the transmitters do not have any CSI, whereas the receivers need to know only the magnitudes of all channel coefficients, not their phases. Thus, receiver cooperation is suitable in the systems with simple transmitters. On the other hand, under the asynchronous model for transmitter cooperation, the transmitters must know the magnitudes of all channel coefficients.

In this paper, we consider the diversity and data rate gains of node cooperation, while focusing on the high SNR regime, where the data rates are mainly limited by interference. The *diversity gain* defined as $d = -\lim_{\text{SNR}\to\infty} \frac{\log P_e(\text{SNR})}{\log \text{SNR}}$, shows how fast the probability of decoding error P_e decays with SNR. The data rate gain is usually decoupled into a *multiplexing gain* and an *additive gain*. The multiplexing gain shows how fast the rate increases with SNR and is given by $r = \lim_{\text{SNR}\to\infty} \frac{R(\text{SNR})}{\log \text{SNR}}$, where R(SNR) denotes the sum of data rates of transmitting nodes for a given SNR. The additive gain is a shift of the R(SNR) function from the origin at high SNRs, i.e., $a = \lim_{\text{SNR}\to\infty} R(\text{SNR}) - r\log(\text{SNR})$. If all the limits exist, then R(SNR) in the high SNR regime can be approximated by a line of slope r and SNR-offset a, i.e., $R(\text{SNR}) \approx r\log(\text{SNR}) + a$.

Perfect cooperation achieves a diversity gain of $d = 2$ and a multiplexing gain of $r = 2$. On the other hand, the interference channel provides no diversity or multiplexing gain (i.e., $d = 1$ and $r = 1$). In Section II, we first present capacity bounds for cooperative diversity, indicating a multiplexing gain of only one at high SNRs, which is a somewhat negative result. However, the main message of Section II is that node cooperation **can** provide a large additive gain and a diversity gain of two. In Section III we describe two practical code designs, one for receiver cooperation and another for transmitter cooperation, which aim at achieving these additive and diversity gains.

II. Capacity Bounds

Since a cooperative channel can be viewed as a combination of a relay channel [3] and an interference channel [4], its best achievable rate regions are obtained by combining decode-forward (DF) or compress-forward (CF) coding techniques developed for the relay channel [3] with coding for the interference channel [4]. In DF, the relay decodes the received source message, re-encodes it, and forwards the resulting signal to the destination. In CF, on the other hand, the relay merely forwards a compressed version of its received source signal. The results in [5] on capacity bounds of the wireless relay channel indicate that DF outperforms CF when the link between the source and relay is good (e.g., the relay is close to the source), whereas CF is desirable when the link between the relay and destination is clean (e.g., the relay is close to the destination).

Building upon works on relay and interference channels, two main ideas arise in obtaining achievable rates for cooperative channels. The first idea is based on nodes decoding messages from other nodes and re-encoding them. The second lies in exploiting the joint statistics between the data at cooperating nodes by means of *coding with side information*, i.e., Wyner-Ziv coding (WZC) [6] or dirty-paper coding (DPC) [7]. Specifically, it turns out that WZC achieves the capacity of receiver cooperation asymptotically as the interference and SNR approach infinity, while DPC approaches the capacity of transmitter cooperation for weak interference and high SNR.

A. Receiver cooperation

In receiver cooperation, two single-antenna receivers cooperate to decode messages from two remote transmitters. The channel model is shown in Fig. 1 with $c_{21} = c_{12} = 0$.

Based on "transforming" a receiver cooperative channel to one with the same or higher capacity, tighter upper bounds on capacity than the standard max-flow-min-cut bound are derived in [8], yielding

$$\begin{aligned} R_1 + R_2 \quad \leq \quad & \log(1 + |c_{41}|^2 P_1 + P_2 + |c_{43}|^2 P_3) + \\ & \log \frac{1 + (1 + |c_{41}|^2) P_1}{1 + |c_{41}|^2 P_1} \end{aligned}$$

in the asynchronous case, and

$$\begin{aligned} R_1 + R_2 \quad \leq \quad & \log(1 + |c_{41}|^2 P_1 + P_2 + |c_{43}|^2 P_3 + \\ & 2\sqrt{|c_{43}|^2 P_2 P_3 + |c_{43}|^2 |c_{41}|^2 P_1 P_3}) + \\ & \log \frac{1 + (1 + |c_{41}|^2) P_1}{1 + |c_{41}|^2 P_1} \end{aligned}$$

in the synchronous case. We get a symmetric set of rate bounds if Nodes 1 and 2 are exchanged with Nodes 3 and 4.

It follows from the above bounds that, in the high SNR regime, receiver cooperation gives a multiplexing gain of only $r = 1$ as opposed to the two-user MAC with two receive antennas which results in $r = 2$. However, the additive gain, which is upper bounded by

$$\begin{aligned} a \leq \min\{&\log(|c_{41}|^2 P_1 + P_2 + |c_{43}|^2 P_3) + \log(1 + |c_{41}|^{-2}), \\ &\log(P_1 + |c_{32}|^2 P_2 + |c_{34}|^2 P_4) + \log(1 + |c_{32}|^{-2})\} \qquad (5) \end{aligned}$$

can be very high.

Receiver cooperation is based on communication between the receivers to facilitate decoding messages. Thus, since the distance between the two receivers is expected to be much smaller than that between a transmitter and a receiver, CF with WZC provides the highest achievable rates. CF can be used with *forward-decoding*, where the decoder starts by decoding the first received block of symbols, or *backward-decoding*, where the decoder proceeds backwards. In [8], forward-decoding is combined with either joint or individual decoding technique [4] and backward-decoding is used with joint decoding, giving three different decoding choices. Since Nodes 3 and 4 can use three different decoding methods each, there are nine possibilities, each providing a different rate bound. To obtain the best achievable CF rate bound, the maximum of all nine rate bounds should be taken. All these bounds together with those of DF are given in [8].

It is shown in [8], that for $|c_{41}|, |c_{32}| > 1$ CF gives a maximum additive gain of

$$a = \min\{\log(|c_{41}|^2 P_1 + P_2 + |c_{43}|^2 P_3), \log(P_1 + |c_{32}|^2 P_2 + |c_{34}|^2 P_4)\}. \quad (6)$$

Note that the gain in (6) is identical to that in (5) except for the $\log(1 + |c_{41}|^{-2})$ and $\log(1 + |c_{32}|^{-2})$ terms, which are small for large $|c_{41}|$ and $|c_{32}|$. Thus, CF with WZC achieves capacity asymptotically as $|c_{41}|$, $|c_{32}|$, and the SNR go to infinity. An interesting conclusion from [8] is that the gain from exploiting full synchronization in receiver cooperation is very limited. Thus, in practice, it is enough to resort to the asynchronous cooperation, which significantly saves the hardware cost. However, as pointed out in [9], optimal power allocation is essential in achieving the full additive gain.

Fig. 2 shows the sum-rate $R_1 + R_2$ vs. the received SNR on the direct link between Nodes 1 and 3. The received SNR at the link between Nodes 3 and 4 is 30 dB higher than that from the direct link – an indication that the cooperating nodes are close together. It is seen from Fig. 2 that CF gives an additive gain that can be up to 20 dB higher than no cooperation, CF always performs close to the upper bound, and there is no gain from synchronization. Interestingly, receiver cooperation performs close to using two receive antennas at low and medium SNRs, thus providing a multiplexing gain of two. However, at the high SNRs, the multiplexing gain drops to one, and the rate gain over the non-cooperative case boils down to a high additive gain.

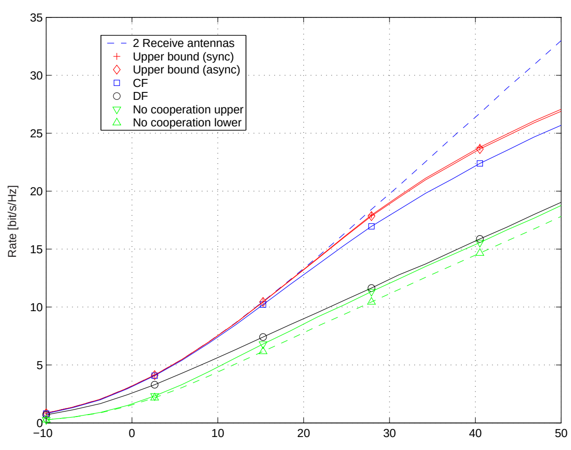

Fig. 2. Receiver cooperation: Bounds on the sum-rate $R_1 + R_2$ as a function of the received SNR from the direct link between Nodes 1 and 3. The received SNR at the link between Nodes 3 and 4 is 30 dB higher than that at the direct link. The average powers of all four nodes are the same.

B. Transmitter cooperation

In transmitter cooperation, two single-antenna transmitters collaborate in communicating to two remote receivers. The channel model is depicted in Fig. 1 with $c_{43} = c_{34} = 0$.

Based on channel transformations, the following upper bounds on capacity are derived in [8]. For $|c_{41}| < 1$, the upper bound is

$$R_2 \le \log \frac{1 + |c_{41}|^2 P_1 + P_2}{|c_{41}|^2 2^{R_1} \frac{1+P_1}{1+(1+|c_{21}|^2)P_1} + 1 - |c_{41}|^2},$$

in the asynchronous case, and

$$R_2 \le \log \frac{1 + (|c_{41}|\sqrt{P_1} + \sqrt{P_2})^2}{|c_{41}|^2 2^{R_1} \frac{1+P_1}{1+(1+|c_{21}|^2)P_1} + 1 - |c_{41}|^2}$$

in the synchronous case, and the sum-rate bound $R_1 + R_2$ is an increasing function of R_1. If $|c_{41}| > 1$, the upper bound is

$$R_1 + R_2 \le \log(1 + |c_{41}|^2 P_1 + P_2) + \log \frac{1 + (|c_{41}|^2 + |c_{21}|^2)P_1}{1 + |c_{41}|^2 P_1}$$

in the asynchronous case, and

$$R_1 + R_2 \le \log(1 + (|c_{41}|\sqrt{P_1} + \sqrt{P_2})^2) + \log \frac{1 + (|c_{41}|^2 + |c_{21}|^2)P_1}{1 + |c_{41}|^2 P_1}$$

in the synchronous case. There is also a symmetric set of rate bounds by exchanging Nodes 1 and 3 with Nodes 2 and 4.

Similar to receiver cooperation, in the high SNR regime, transmitter cooperation only gives a multiplexing gain of $r = 1$ (in contrast to the two-antenna broadcast channel which results in $r = 2$ [10]). The additive gain can be high. For example, when $|c_{41}| < 1$, in the synchronous case it is bounded by

$$a \le \log((|c_{41}|\sqrt{P_1} + \sqrt{P_2})^2) + \log\left(\frac{1 + |c_{21}|^2}{|c_{41}|^2}\right). \quad (7)$$

It is shown in [8], [9] that, in contrast to receiver co-operation, synchronization helps a lot when the transmitters cooperate. That is, if the two transmitters are synchronized, they can completely cancel out the interference using DPC [7]. DPC was already exploited in [10], [11] to find the capacity of the Gaussian MIMO broadcast channel. For the two-antenna broadcast channel with two receivers [10], the main idea is to decompose the MIMO channel into two interference channels and perform successive encoding, in which the message for the second receiver is dirty-paper encoded while assuming the previously encoded message for the first receiver as known interference (the side information). In this way, the second receiver can completely cancel out the interference from the signal for the first receiver. The coding strategy of [10] is extended to transmitter cooperation in [8], [12]. In [8], a coding scheme that achieves the best lower bounds is described. However, the scheme of [8] suffers high complexity as it requires **three** independent dirty-paper codes. In many scenarios, a similar performance can be achieved using **one** DPC at the transmitter nodes.

In the asynchronous case, DPC cannot be exploited, and the resulting achievable rates are strictly below those in the synchronous case. (However, so far there exist no upper bounds that actually prove that the gains cannot be obtained without synchronization.) All achievable bounds can be found in [8]. Although it is possible to use WZC in transmitter cooperation, since the two transmitters are closely located, DPC always dominates. This is why WZC is not considered in this setup.

Besides the multiplexing gain of $r = 1$, DPC achieves a high-SNR additive gain of

$$a = \log\left((|c_{41}||t_{12}| + |t_{22}|)^2\right) + \log \frac{|c_{21}|^2}{|c_{41}|^2}, \qquad (8)$$

where t_{ij}'s are scaling factors that control power allocation. Comparing (7) and (8), we see that the additive gain of using DPC is approximately equal to that from the upper bound when $|t_{12}|^2 \approx P_1$ and $|t_{22}|^2 \approx P_2$, which corresponds to the scenario with weak interference, i.e., $|c_{41}|, |c_{32}| << 1$. In this case, the gain compared to no cooperation can be significant. This is illustrated in Fig. 3, which shows the high-SNR additive gain for a symmetric cooperative channel ($|c_{41}| = |c_{32}|, |c_{21}| = |c_{12}|$). Note that, under strong interference, i.e., $|c_{32}|, |c_{41}| >> 1$, there is no gain from cooperation, which is somewhat surprising and is in contrast to receiver cooperation.

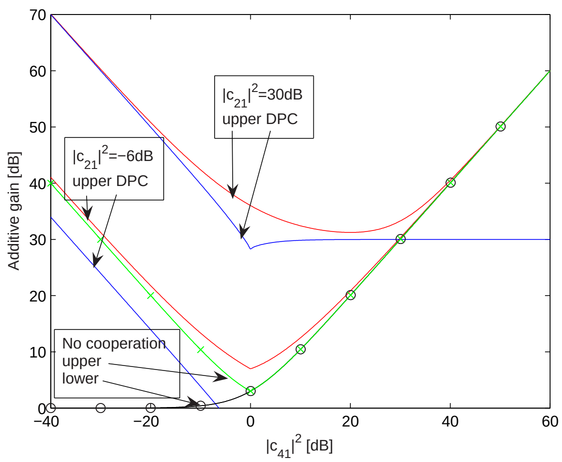

Fig. 3. The bounds on the additive gain for a symmetric transmitter cooperative channel ($|c_{41}| = |c_{32}|, |c_{21}| = |c_{12}|$), averaged over the relative phases of c_{41} and c_{32}.

Fig. 4 shows the sum-rate bounds $R_1 + R_2$ as functions of the received SNR on the direct link between Nodes 1 and 3. The simulation setup is similar to that for receiver cooperation with the received SNR at the cooperative link (between Nodes 1 and 2) being 30 dB higher than that at the direct link, again indicating that the cooperating transmitters are close together.

The achievable bounds of the synchronous system with DPC is usually close to the upper bound, although noticeable gaps exist in certain SNR ranges. There is almost no performance loss if only one DPC is used instead of three. The additive gain compared to the non-cooperative case is up to 15 dB in the high SNR regime. Transmitter cooperation with DPC performs close to using two transmit antennas at low and medium SNRs, giving a multiplexing gain of two. However, at high SNRs, the multiplexing gain is only one.

III. Code Designs

In this section we describe code designs for receiver cooperation based on CF with WZC and for transmitter cooperation based on DF with one DPC.

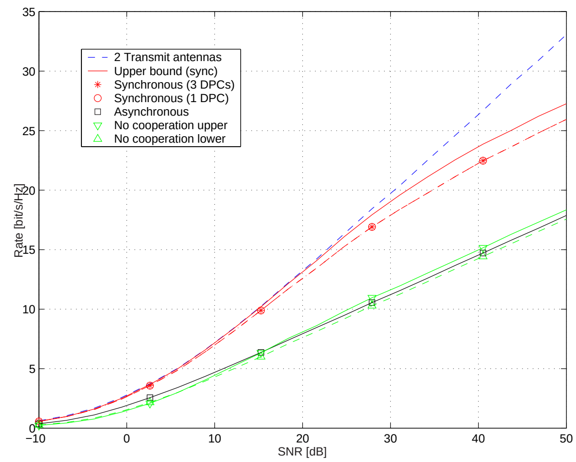

Fig. 4. Transmitter cooperation: Bounds on the sum-rate $R_1 + R_2$ as a function of the received SNR at the direct link between Nodes 1 and 3. The received SNR at the link between Nodes 1 and 2 is 30 dB higher than that at the direct link. The average powers of all four nodes are the same.

A. CF with WZC for receiver cooperation

Our code design for receiver cooperation follows closely asymptotically optimal CF with forward-decoding of [8]. Thus, the receiver at Node 3 employs WZC to compress the signal $y_3[n] - c_{34}\hat{x}_4[n]$ (with $\hat{x}_4[n]$ being the reconstruction of $x_4[n]$), before passing the resulting codeword $x_3[n+1]$ to the collaborating receiver in Node 4. Node 4 starts by decoding $x_3[n+1]$ from the received $y_4[n+1]$, while treating $x_2[n+1] + c_{41}x_1[n+1]$ as part of the background noise. The reconstructed signal $\hat{x}_3[n+1]$ is then Wyner-Ziv decoded using $y_4[n] - c_{43}\hat{x}_3[n]$ as the decoder side information, resulting in an estimate of $y_3[n] - c_{34}x_4[n]$. Next, the individual decoding via maximum ratio combining is employed to reconstruct $x_2[n]$ from the estimates $y_4[n] - c_{43}\hat{x}_3[n] = x_2[n] + c_{41}x_1[n] + z_4[n]$ and $\hat{y}_3[n] - c_{34}x_4[n] = c_{32}x_2[n] + x_1[n] + z_3[n]$. A similar procedure is performed at Node 3 to reconstruct $x_1[n]$.

Each transmitter performs one channel encoding using an LDPC code, and each receiver realizes WZC via nested scalar quantization followed by syndrome-based Slepian-Wolf coding [13] and error protection. Slepian-Wolf coding and error protection are performed jointly bitplane by bitplane, using irregular repeat-accumulate (IRA) codes. Note that, since the scheme exploits forward individual decoding only, it loses in performance compared to the bound of CF which is obtained in [8] as the maximum of nine cases.

Simulation results are shown in Fig. 5, which represents the only code design results reported so far for receiver cooperation. The performance loss is about 2 dB, which can be reduced by employing stronger source codes.

B. DF with DPC for transmitter cooperation

In contrast to the scarcity of WZC-based CF designs for receiver cooperation, there have been more code designs for transmitter cooperation [14], [15]; however neither of them exploits DPC, which provides the highest achievable rates over a transmitter cooperative channel.

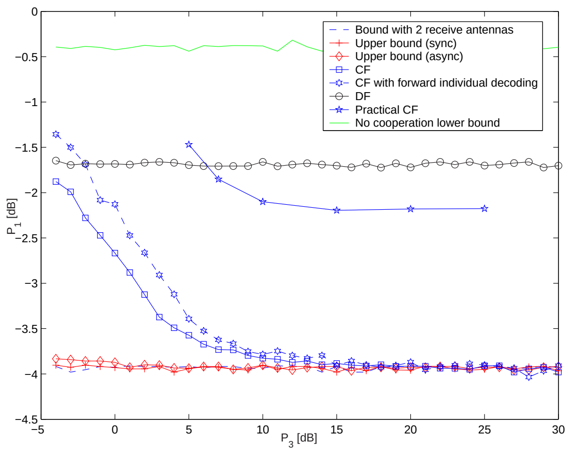

Fig. 5. Receiver cooperation: The average transmitter power $P_1 = P_2$ vs. the average cooperation power $P_3 = P_4$. BPSK signaling is used. The received SNR at the link between the two receivers is 15 dB higher than that at the direct link.

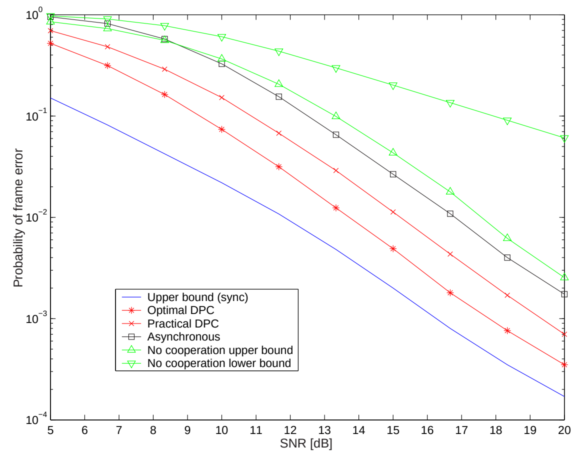

Fig. 6. Transmitter cooperation: Frame error rate vs. the received SNR at the direct link together with various theoretical bounds.

By extending the coding strategy proposed in [10] for the two-user Gaussian MIMO broadcast channel, we develop a code design for transmitter cooperation in which one DPC with backward-decoding is performed at the transmitter nodes. During the i-th time instant, the transmitter in Node j, $j = 1, 2$, sends $x_j[i] = A_j U_j(\omega_j[i]) + t_{j1} U_1^0(\omega_1[i-1], U_2^0(\omega_2[i-1])) + t_{j2} U_2^0(\omega_2[i-1])$, where U_2^0, U_1, and U_2 are Gaussian codebooks (e.g., standard channel codes in practice) of unit power. U_1 and U_2 are used for exchanging messages between the transmitters and appear as part of the background noise at the receivers. Assuming correct decoding of $U_1(\omega_1[i-1])$ and $U_2(\omega_2[i-1])$ in time instant $i-1$, the two transmitters can now act as a single two-antenna broadcast transmitter; thus, the transmitter in Node 1 can use codebook U_1^0 to dirty-paper encode $\omega_1[i-1]$ with $U_2^0(\omega_2[i-1])$ as the side information. The scaling factors A_i and t_{ij} are selected to maximize the rate while satisfying the input power constraints.

For DPC, we use the capacity-approaching scheme of [16] based on trellis coded quantization and turbo trellis coded modulation. Practical design results under the same channel condition as in Fig. 4 and $R_1 = R_2 = 1$ bit per channel use are shown in Fig. 6, indicating a loss of 1.5 dB from the achievable bound at 2% frame error rate.

IV. Conclusions

Due to its low-complexity and decentralized nature, cooperative diversity arises as a strong candidate for conveying information in emerging wireless networks. For a two-transmitter two-receiver cooperative channel, the theory shows that in contrast to a two-antenna MIMO system, cooperative diversity cannot achieve the full multiplexing gain of two. However, cooperative diversity does offer high additive rate gains when compared to the non-cooperation case, and the key in achieving these gains lies in coding with side information (e.g., DPC and WZC).

We described two practical code designs: one for receiver cooperation based on WZC; another for transmitter cooperation based on DPC. Future work will contain reducing the performance loss of the practical schemes to the theoretical limits with stronger code designs while staying at acceptable complexity. The practical designs proposed so far are only for two-transmitter two-receiver cooperative channels. Substantial research efforts are needed to construct practical systems based on cooperative diversity for larger wireless networks.

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