Transmitter Cooperation in Ad-Hoc Wireless Networks: Does Dirty-Paper Coding Beat Relaying?

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Abstract — **We investigate capacity and achievable rates for transmitter cooperation schemes in ad-hoc wireless networks. In addition to cooperative dirty paper coding, we propose two new cooperative transmission techniques: time-division successive broadcasting and time-division relaying. We show that transmitter cooperation can significantly increase capacity, even if one of the cooperating nodes is halfway between the transmit and receive node clusters. However, the best form of cooperation depends on the relative geometry of the transmit and receive clusters. When the transmitters are close together, cooperative dirty paper coding achieves the highest rates. However, if one of the transmitters is relatively close to the receive cluster, cooperative broadcasting or relaying achieves higher rates than dirty paper coding. That is because, at large separations, the exchange of messages between the transmitters required for dirty paper coding consumes a substantial amount of power. We show that in most cases transmitter cooperation provides a substantial capacity improvement over noncooperative techniques, especially under an equal rate constraint.**

I. Introduction

Wireless ad-hoc networks typically consist of a large number of spatially dispersed nodes. Each node can communicate with any other node over the wireless channel. Thus, these nodes can cooperate to transmit and receive information via joint encoding, relaying, and/or joint decoding. The focus of this paper is to investigate cooperation strategies in such networks in terms of their capacity.

Transmitter and receiver cooperation between nodes has been investigated recently by several authors. In [1, 2], the achievable rate was considered for a CDMA system in which two transmitters cooperate by repeating detected symbols of the other to send to a single receiver. An information-theoretic achievable rate region for this channel was obtained in [3]. It was shown in [4] that transmitter cooperation can be incorporated within existing channel coding methods to improve bit error rates. In [5] transmitter relaying was studied for a two-transmitter two-receiver channel in terms of the level of diversity achieved based on outage behavior. Upper and lower bounds on information theoretic capacity were obtained in [6] for a channel with two cooperative transmitters and two independent receivers, and in [7] for a channel with two independent transmitters and two cooperative receivers.

The system we study is most similar to that of [8], where the effect of transmitter and receiver node cooperation on the capacity of a two-transmitter two-receiver ad-hoc wireless network was determined. In that work the capacity improvement from cooperation was characterized by capacity bounds of the corresponding broadcast (transmitter cooperation), multiple-access (receiver cooperation), and multiple-input-multiple-output (transmitter and receiver cooperation) channels. It was shown that cooperation among transmitters offers significant capacity improvement, while receiver cooperation does not substantially improve capacity. Thus, the focus of this paper is on transmitter cooperation only.

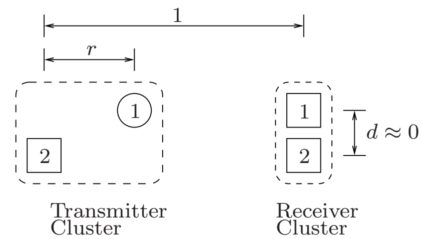

Fig. 1: System Model

We consider three different transmit cooperation strategies: dirty paper joint encoding, joint broadcasting and relaying, and pure relaying. We will see that the relative performance of these schemes depends on the network geometry and whether or not there is an equal rate constraint on the two transmitters. Our results indicate that cooperation can substantially increase capacity over noncooperative transmission.

The remainder of the paper is organized as follows. In Section II we present the system model. Section III gives the details of the three cooperative transmission strategies as well as that of noncooperative transmission. A comparison of the different strategies as a function of the network geometry is given in Section IV both with and without an equal rate constraint. Section V provides a summary and discussion of our results along with some potential extensions.

II. System Model

Consider a network with two pairs of interfering source-destination nodes as shown in Fig. 1. Transmitter 1 has a message intended for Receiver 1, and Transmitter 2, likewise, has a message intended for Receiver 2. The horizontal distance between Transmitter 2 and the receiver cluster is normalized to unity, and we let r denote the horizontal distance between Transmitter 1 and Transmitter 2, $0 \leq r \leq 1$. The vertical distance d between the transmitters and between the receivers is assumed to be small, $d \approx 0$, and the horizontal distance between the receivers is assumed to be zero. Thus, the receiver nodes are assumed to be very close together. Transmitter 2 and the receivers, denoted by square nodes, have a fixed position. Transmitter 1, denoted by the circular node, has a variable position that is restricted to the one-dimensional horizontal space between the transmitter and receiver clusters.

The system assumes an additive white Gaussian noise (AWGN) environment: the receive signal is the transmit signal scaled by the channel gain, then corrupted by AWGN. Let x_1, x_2 denote the two transmit signals, and y_1, y_2 denote the received signals, respectively. The channel gain is inversely proportional to the distance between the transmitter-receiver nodes with a power fall-off exponent α. Hence, in matrix form, the channel between the transmitter and receiver cluster can be written as:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \mathbf{H} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}, \tag{1}$$

where

$$\mathbf{H} = \begin{bmatrix} \frac{e^{j\theta_1}}{\sqrt{(1-r)^\alpha}} & e^{j\theta_2} \\ \frac{e^{j\theta_3}}{\sqrt{(1-r)^\alpha}} & e^{j\theta_4} \end{bmatrix}, \tag{2}$$

and n_1, n_2 are independent zero-mean Gaussian noise. The channel gain phases θ_1, θ_2, θ_3 and θ_4 are uniformly distributed between 0 and 2π. For convenience, n_1, n_2 are normalized to have unit power, and the channel bandwidth is 1 Hz.

In addition to the main data channel, similar to [8], there is also an orthogonal cooperation channel between the transmitters. The transmitters are assumed to be able to simultaneously send and receive on this cooperation channel. Let x_i', y_j' denote, respectively, the signal sent by Transmitter i and the signal received by Transmitter j. Then the cooperation channels are given by:

$$y_1' = \frac{1}{\sqrt{r^\alpha}}\, x_2' + n_3 \qquad\qquad y_2' = \frac{1}{\sqrt{r^\alpha}}\, x_1' + n_4, \tag{3}$$

where n_3, n_4 are again zero-mean independent Gaussian noise with unit variance and the cooperation channel has a bandwidth of 1 Hz. There is an average total power constraint P for all transmitters, i.e., $E[x_1^2 + x_2^2 + x_1'^2 + x_2'^2] \leq P$.

To isolate the effect of transmitter cooperation on capacity gain, even though the receiver nodes are close together, it is assumed that no receiver cooperation is allowed. The transmitters can cooperate using various cooperation schemes, and the goal is to maximize the sum-rate $R_1 + R_2$, where R_1 is the rate at which Transmitter 1 sends information to Receiver 1 and R_2 is the rate at which Transmitter 2 sends to Receiver 2. We refer to the channel between Transmitter 1 and Receiver 1 as Channel 1, and the channel between Transmitter 2 and Receiver 2 as Channel 2.

To fully characterize the benefits of our node cooperation strategies, we would need to find their entire achievable rate region. However, in our analysis we focus on obtaining the sum-rate point $R_1 + R_2$. This point provides a simple metric to compare the different strategies. We also consider the sum-rate point with an equal rate constraint. Under this constraint, we find the maximum achievable sum-rate $R_1 + R_2$ for each cooperation strategy with the added restriction that $R_1 = R_2$. We shall see that this constraint imposes a fairness condition on the cooperation strategies that favors dirty paper coding.

III. Transmitter Cooperation

A. Time-Division

Without transmitter cooperation and without an equal rate constraint, the main data channel is a Gaussian interference channel. If fact, it is a strong interference channel, defined as an interference channel for which the channel gain along the interference path is at least as strong as that along the desired signal path. To see the data channel satisfies this criterion, the scaling transformation described in [10] can be used to scale Transmitter 1's codewords and its power constraint. Suppose a fraction of sum power uP and $(1-u)P$ are allocated to Transmitters 1 and 2, respectively, for $u \in [0, 1]$. Then the equivalent channel becomes

$$\begin{bmatrix} \tilde{y_1} \\ \tilde{y_2} \end{bmatrix} = \begin{bmatrix} e^{j\theta_1} & e^{j\theta_2} \\ e^{j\theta_3} & e^{j\theta_4} \end{bmatrix} \begin{bmatrix} \tilde{x_1} \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}, \tag{4}$$

where $\tilde{x_1} = x_1/\sqrt{(1-r)^\alpha}$, and the scaled power constraint for Transmitter 1 becomes $uP/(1-r)^\alpha$.

The capacity region of the strong interference channel is known [9]. Moreover, TD achieves the sum-rate capacity of the strong interference channel by allocating all power over all time to just one of the transmitters. Thus, we will use the time-division (TD) scheme as a capacity benchmark for non-cooperative transmission. With an equal rate constraint TD no longer achieves the sum-rate capacity of the strong interference channel, so in this case TD serves as a lower bound to the capacity of non-cooperative transmission.

Suppose Transmitter 1 sends for a fraction u of time using power $\frac{a}{u}P$, with $u, a \in [0, 1]$. To satisfy the average total power constraint, Transmitter 2 sends in the remaining $1-u$ fraction of time with power $\frac{1-a}{1-u}P$. Let R_{T1} and R_{T2} denote the rates of Channel 1 and Channel 2, respectively. Then the TD sum-rate capacity R_T can be obtained by maximizing over u, a:

$$R_T = \max_{u,\,a}\ R_{T1} + R_{T2}, \tag{5}$$

where

$$R_{T1} = u \log\left(1 + \frac{aP}{u(1-r)^\alpha}\right) \tag{6}$$

$$R_{T2} = (1-u) \log\left(1 + \frac{(1-a)P}{1-u}\right). \tag{7}$$

Since Channel 1 always has an equal or higher signal-to-noise ratio (SNR) than Channel 2, the sum-rate is maximized when only Channel 1 is used (i.e., $u = 1$, $a = 1$):

$$R_T = \log\left(1 + \frac{P}{(1-r)^\alpha}\right). \tag{8}$$

The TD sum-rate capacity with an equal rate constraint R_T' can be written as

$$R_T' = \max_{u,\,a:\, R_{T1} = R_{T2}} R_{T1} + R_{T2}. \tag{9}$$

Numerical results for the TD sum-rate capacity with and without an equal rate constraint are shown in Fig. 2 for different values of the power fall-off exponent α. The average total power constraint for these curves is $P = 10$ W, so the SNR is 10 dB. We see from these curves that without an equal rate constraint, the sum-rate grows rapidly as Transmitter 1 approaches the receiver cluster. That is because for large r Transmitter 1 has a high gain to its receiver, resulting in a large rate R_{T1} for Channel 1, and this rate equals the sum-rate without an equal rate constraint. However, with an equal rate constraint, the sum-rate is limited by the rate R_{T2} associated with the weaker Channel 2 between Transmitter 2 and

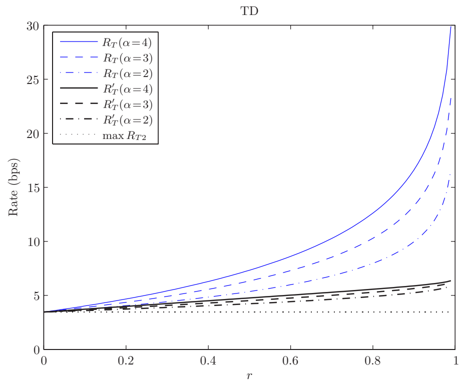

Fig. 2: Time-division (TD) cooperation scheme.

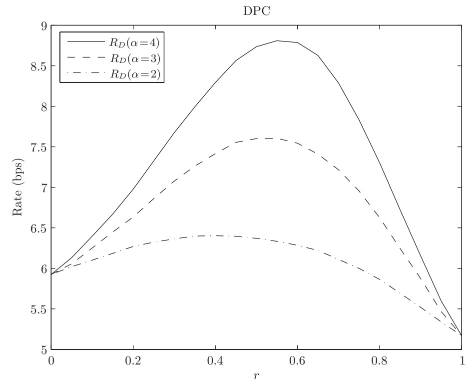

Fig. 3: Dirty paper coding (DPC) cooperation scheme.

its receiver. The rate R_{T2} is shown by the dotted line in Fig. 2, and we see that since this rate does not change appreciably with r, the corresponding sum-rate under an equal rate constraint does not either.

B. Dirty Paper Coding Cooperation

We consider the same dirty paper coding (DPC) transmit cooperation scheme analyzed in [8]. In this scheme, the transmitters first use a fraction of their transmit power $P_t/2$ to exchange transmit messages on an orthogonal cooperation channel. The cooperation rate R_t each way between the transmitters is thus $R_t = \log\left(1 + \frac{P_t}{2\, r^{\alpha}}\right)$. After receiving each other's transmit message, the transmitters jointly encode the transmit messages, effectively forming a two-antenna broadcast channel with two single-antenna receivers. The sum-rate capacity and, in fact, the entire capacity region of this broadcast channel is achieved using dirty paper coding [11, 12, 13]. The sum-rate point is typically calculated from the dual multiple-access channel [11] with power $P - P_t$ corresponding to the total transmit power P minus that used for cooperation. This sum-rate point is thus given by

$$R_{dpc} = \max_{P_1:\, 0 \le P_1 \le P - P_t} \log \left| I + H_1^{\dagger} P_1 H_1 + H_2^{\dagger} (P - P_t - P_1) H_2 \right|, \tag{10}$$

where H_1, H_2 are the first and second row, respectively, of the channel matrix $\mathbf{H}$. Note that the DPC of the cooperating transmitters assumes perfect channel state information (CSI). In particular, it is assumed that the channel state $\mathbf{H}$ given in (2) is completely known. Furthermore, it is required that the cooperation rate R_t be at least equal to the maximum message rate of each transmitter to its intended receiver, so that the intended message of each transmitter can be learned by the other through the cooperation channel in order to perform the joint encoding. Therefore the transmitter cooperation sum-rate is the minimum of the cooperation rates and the dirty paper coding rate:

$$R_D = \max_{P_t:\, 0 \le P_t \le P} \min(2R_t, R_{dpc}). \tag{11}$$

For transmitter cooperation using DPC, since each transmitter knows the message of the other, the sum-rate can be allocated freely to carry information for Transmitter 1 or Transmitter 2. Therefore, the sum-rate R_D is not affected by the equal rate constraint. Fig. 3 shows the sum-rate achieved using the DPC cooperation scheme. The numerical results are obtained by averaging over samples of the random channel realization. Note that at $r = 0$, when the transmitters are close together and the cooperation overhead is zero, the sum-rate achieved corresponds to the multiple-input-single-output (MISO) broadcast capacity upper bound described in [8]:

$$R_D|_{r=0} = \log \left| I + \frac{P}{2}(H_1^{\dagger} H_1 + H_2^{\dagger} H_2) \right|. \tag{12}$$

Conversely, at $r = 1$, the sum-rate is entirely limited by the cooperation rate at which the transmitters can exchange messages:

$$R_D|_{r=1} = 2 \log \left(1 + \frac{P}{2}\right). \tag{13}$$

We see from Fig. 3 that the sum-rate achieved by the DPC cooperation scheme first increases with r, reaches a maximum, and then decreases. This is because as Transmitter 1 moves away from Transmitter 2, even though the transmitters have to spend more power exchanging messages, nonetheless, Transmitter 1 is closer to the receiver cluster and hence able to achieve a higher DPC rate. Beyond a certain distance r, however, significant power is spent on exchanging messages between the transmitters and the sum-rate begins to fall.

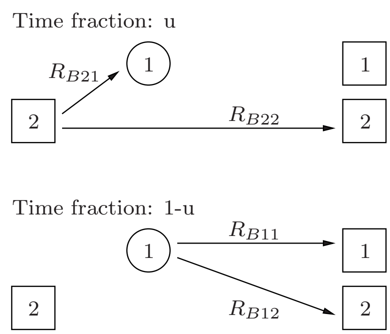

Fig. 4: Time-division successive broadcast (TDSB) cooperation scheme.

C. Time-Division Successive Broadcast

We next consider a time-division successive broadcast strategy that combines broadcasting and relaying, as illustrated in Fig. 4. In this scheme, for a fraction u of the time, Transmitter 2 uses power $\frac{a}{u}P$ to broadcast independent messages to Transmitter 1 and Receiver 2, with rates R_{B21} and R_{B22}, respectively. In the remaining $1-u$ fraction of time, Transmitter 1 uses power $\frac{1-a}{1-u}P$ to broadcast to Receiver 1 and Receiver 2 with respective rates R_{B11} and R_{B12}. Note that R_{B12} is the rate at which Transmitter 1 relays messages from Transmitter 2 to Receiver 2. Channel 1 has rate R_{B11}, while Channel 2 achieves rate R_{B22} plus the rate at which Transmitter 1 relays Transmitter 2's messages. Since Transmitter 1 cannot forward faster than it receives messages from Transmitter 2, the forwarding rate is limited to $\min(R_{B21}, R_{B12})$. The sum-rate capacity of this time-division successive broadcast (TDSB) cooperation scheme can be obtained by maximizing over $u, a \in [0, 1]$:

$$R_B = \max_{u,\,a}\; R_{B1} + R_{B2}, \tag{14}$$

where

$$R_{B1} = R_{B11} \tag{15}$$

$$R_{B2} = R_{B22} + \min(R_{B21}, R_{B12}). \tag{16}$$

The capacity region of an AWGN broadcast channel with one transmitter and two receivers is given by the set of rate pairs (r_1, r_2) such that [14]

$$r_1 \le \log\left(1 + \frac{\mu g_1 P}{N}\right) \quad r_2 \le \log\left(1 + \frac{(1-\mu) g_2 P}{\mu g_2 P + N}\right), \tag{17}$$

for some $\mu \in [0, 1]$, where N is the receiver noise, g_1 is the channel gain between the transmitter and the first receiver, g_2 is the channel gain between the transmitter and the second receiver, and we assume $g_2 \le g_1$. Substituting the channel gains from (2) in (17), the rates R_{B21}, R_{B22} can be readily obtained as

$$R_{B21} = u\,\log\left(1 + \frac{\mu_1 a P}{u\, r^{\alpha}}\right) \tag{18}$$

$$R_{B22} = u\,\log\left(1 + \frac{(1-\mu_1) a P}{\mu_1 a P + u}\right), \tag{19}$$

for some $\mu_1 \in [0, 1]$. For Transmitter 1, since the channel gain to Receiver 1 and Receiver 2 are the same, the broadcast capacity is achievable using time-division:

$$R_{B11} = \mu_2 (1-u) \log\left(1 + \frac{(1-a)P}{(1-u)(1-r)^{\alpha}}\right) \tag{20}$$

$$R_{B12} = (1-\mu_2)(1-u) \log\left(1 + \frac{(1-a)P}{(1-u)(1-r)^{\alpha}}\right), \tag{21}$$

for some $\mu_2 \in [0, 1]$.

Similar to the TD scheme described in Section III.A, since Channel 1 always has an equal or higher SNR than Channel 2, the sum-rate R_B is maximized when only Channel 1 is used (i.e., $u = 0$, $a = 0$):

$$R_B = \log\left(1 + \frac{P}{(1-r)^{\alpha}}\right). \tag{22}$$

When an equal rate between Channel 1 and Channel 2 is desired, the TDSB sum-rate with constraint $R_{B1} = R_{B2}$ can be defined:

$$R'_B = \max_{u,\,a:\, R_{B1} = R_{B2}} R_{B1} + R_{B2}. \tag{23}$$

Fig. 5 shows the TDSB sum-rate capacity with and without an equal rate constraint. Similar to the TD scheme, when an equal rate constraint is present the achievable sum-rate is

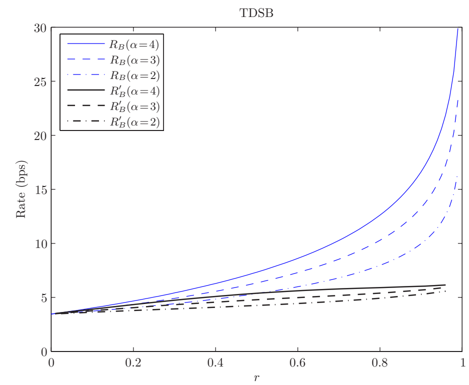

Fig. 5: Time-division successive broadcast (TDSB) scheme.

predominantly limited by Channel 2's capacity. A comparison of the achievable rates of the TDSB and TD schemes can be found in Fig. 9. At $r = 0$ (when Transmitter 1 is close to Transmitter 2), Transmitter 1's broadcast channel has the same SNR as that of Channel 2; therefore, joint broadcasting and relaying offers no additional benefit and the capacity reduces to that of TD at $r = 0$, i.e., $R_B|_{r=0} = R_T|_{r=0}$. Similarly, at $r = 1$, it requires as much power for Transmitter 2 to broadcast to Transmitter 1 for relaying as it does to send directly to its receiver; hence the capacity reduces to that of TD at $r = 1$, i.e., $R_B|_{r=1} = R_T|_{r=1}$. However, when Transmitter 1 is between the transmitter and receiver nodes, joint broadcasting and relaying can take advantage of sending independent messages to the receivers simultaneously, and thus achieves a higher sum-rate capacity then the TD scheme. Note that the higher the power fall-off exponent α, the greater capacity improvement TDSB yields over the TD scheme.

D. Time-Division Relay

The time-division relay (TDR) scheme is an alternate scheme where the transmitters cooperate as follows. For a fraction u of the time, Transmitter 1 sends directly to Receiver 1 with power $P_1 = \frac{a}{u}P$, with $u, a \in [0, 1]$. For the remaining time fraction $1-u$, Transmitter 2 sends to Receiver 2 using Transmitter 1 as a relay under the total power constraint $P_2 = \frac{1-a}{1-u}P$. Let the relay node send with power $P_{21} = \lambda P_2$, and let Transmitter 2 send with power $P_{22} = (1-\lambda)P_2$, with $\lambda \in [0, 1]$. Similar to the TD scheme, Channel 1 is able to achieve the rate $R_{R1} = u\,\log\left(1 + \frac{P_1}{(1-r)^{\alpha}}\right)$. Channel 2 with Transmitter 1 as a relay is a general AWGN relay channel and its capacity is not known. However a max-flow min-cut (MFMC) upper bound and a block-Markov (BM) lower bound for the general relay channel were derived in [15] as

$$C \le \max_{p(x_1,x_2)} \min\{I(X_1, X_2; Y), I(X_1; Y, Y_1 | X_2)\}, \tag{24}$$

$$C \ge \max_{p(x_1,x_2)} \min\{I(X_1, X_2; Y), I(X_1; Y_1 | X_2)\}, \tag{25}$$

where X_1 is the symbol transmitted from the transmitter, Y_1 is the received symbol at the relay, which encodes it as X_2 for transmission to the receiver, and Y is the received symbol at the receiver. Let R_{R2} denote the capacity of Channel 2 with Transmitter 1 as a relay. Given the channel model of Fig. 1, it can be shown that the mutual information bounds (24) and

(25) become

$$R_{R2} \leq (1-u) \max_{0 \leq \rho \leq 1} \min(C_1, C_2) \triangleq R^u_{R2} \tag{26}$$

$$R_{R2} \geq (1-u) \max_{0 \leq \rho \leq 1} \min(C_1, C_3) \triangleq R^l_{R2}, \tag{27}$$

where

$$C_1 = \log(1 + (1 + g_b^2 \gamma + 2 g_b \rho \sqrt{\gamma}) P_{22}) \tag{28}$$

$$C_2 = \log(1 + (1 + g_a^2)(1 - \rho^2) P_{22}) \tag{29}$$

$$C_3 = \log(1 + g_a^2 (1 - \rho^2) P_{22}), \tag{30}$$

where $g_a = 1/\sqrt{r^\alpha}$, $g_b = 1/\sqrt{(1-r)^\alpha}$ are the channel gains, and $\gamma = \lambda/(1-\lambda)$ is the ratio of the transmission power of the relay to that of Transmitter 2. The corresponding TDR sum-rate capacity upper and lower bounds R^u_R and R^l_R, respectively, can be obtained by further maximizing over u, a, and λ:

$$R^u_R = \max_{u,a,\lambda} R_{R1} + R^u_{R2} \tag{31}$$

$$R^l_R = \max_{u,a,\lambda} R_{R1} + R^l_{R2}. \tag{32}$$

Similarly, the TDR sum-rate capacity with an equal rate constraint upper and lower bounds are:

$$R'^u_R = \max_{u,a,\lambda:\, R_{R1} = R^u_{R2}} R_{R1} + R^u_{R2} \tag{33}$$

$$R'^l_R = \max_{u,a,\lambda:\, R_{R1} = R^l_{R2}} R_{R1} + R^l_{R2}. \tag{34}$$

The bounds without and with an equal rate constraint are illustrated in Fig. 6 and Fig. 7, respectively. For TDR without an equal rate constraint, we see that the bounds are tight; however, with an equal rate constraint, the bounds are only tight for $r \ll 0.5$. Beyond $r \approx 0.5$ the lower bound begins to decrease, or level off, which suggests that the relay node is most beneficial in increasing capacity when it is approximately halfway between the transmitter and receiver clusters.

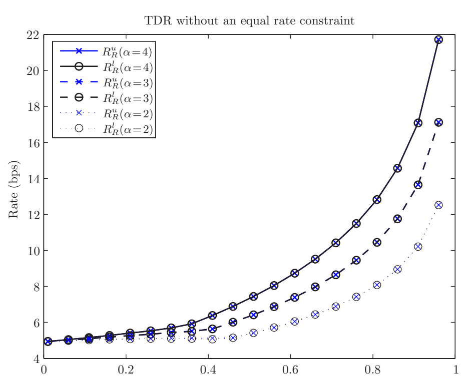

Fig. 6: Upper and lower bounds for the time-division relay (TDR) sum-rate capacity without an equal rate constraint.

IV. Comparison of Transmission Schemes

The sum-rate capacity achieved by the different transmitter cooperation schemes without an equal rate constraint are shown in Fig. 8 for a power fall-off exponent α of 4. Other values of α exhibit similar trends. Note that the capacity

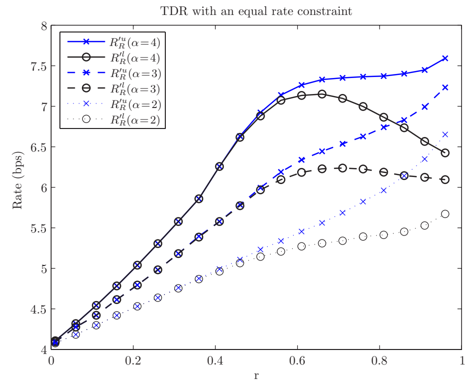

Fig. 7: Upper and lower bounds for the time-division relay (TDR) sum-rate capacity with an equal rate constraint.

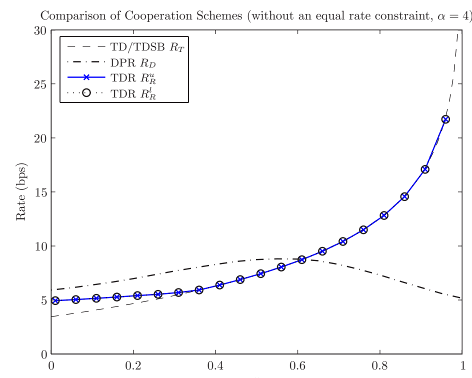

Fig. 8: Comparison of transmitter cooperation schemes (without an equal rate constraint, $\alpha = 4$).

achieved by the TDSB and TD schemes are the same, since in TDSB the achievable sum-rate is maximized when only Channel 1 is used over all time. For TDR, the upper and lower bounds are tight. We see from the figure that for small r, due to the dirty paper coding gain, the DPC capacity R_D exceeds the TDR capacity R_R, which in turn exceeds the capacity of the other schemes. However, for large r, DPC wastes significant power on exchanging messages and its capacity is not as high as the TD strategy of sending information using only the good channel (Channel 1). In TDR, as r increases, the relay channel offers diminishing capacity improvement over TD and, for large enough r, the capacity reduces to that of noncooperative TD.

The sum-rate capacities of the different cooperation schemes under an equal rate constraint are shown in Fig. 9, also for a power fall-off exponent α of 4. The figure indicates that the sum-rate R_D associated with DPC outperforms every other transmitter cooperation schemes for most values of r. We also see that TDSB has a sum-rate capacity R'_B that outperforms that achieved by the non-cooperative TD scheme R'_T for all r. The TDR achievable rate, as represented by the lower bound R'^l_R, in turn outperforms TDSB, with the most significant capacity improvement for $r \approx 0.5$. Beyond $r \approx 0.5$, the TDR capacity with an equal rate constraint either decreases or offers little additional improvement. The upper bound of TDR continues to increase beyond $r \approx 0.5$; however, it is not known if the upper bound rate is achievable. These bounds

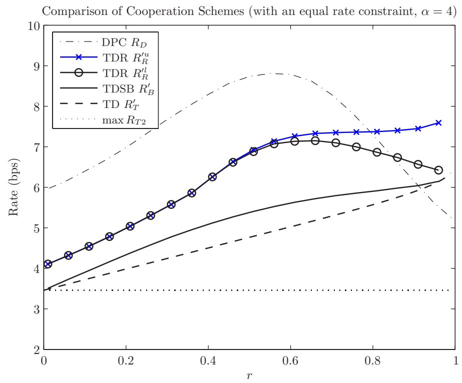

Fig. 9: Comparison of cooperation schemes (with an equal rate constraint, $\alpha = 4$).

indicate that under an equal rate constraint, using a transmitter in the transmit cluster as a relay node is most beneficial when this potential relay is about halfway between the transmit and receive clusters. Different values of the power fall-off exponent α indicate the same trend.

Our DPC strategy assumes an orthogonal cooperation channel and the bandwidth cost of this channel was not taken into account in the capacity calculation. This cost can be included by assuming a frequency-division scheme that optimally allocates bandwidth between the cooperation channel and the main data channel. This optimization problem is non-convex, and the large search space and slow convergence of the random channel samples make it computationally intensive to find the resulting capacity. The capacity reduction associated with the bandwidth cost of cooperation was investigated in [8]: this reduction was relatively modest for DPC joint encoding with no receiver cooperation. Thus, even with the bandwidth cost of cooperation factored in, we still expect DPC to outperform the other transmitter cooperation strategies over a range of r values, although this range will be somewhat reduced from that indicated in Figures 8 and 9.

V. Conclusion

We have proposed several new strategies for transmitter cooperation in ad-hoc wireless networks and investigated their relative performance in terms of their sum-rate capacity. The schemes exploit different techniques for cooperation, including dirty paper, broadcast, and relay coding strategies. When the transmitters in the transmit cluster are relatively close together, all of our proposed schemes outperform a non-cooperative TD strategy. In particular, with or without an equal rate constraint, DPC provides the largest capacity when transmitters are close together. However, as one of the transmitters moves closer to the receive cluster, the capacity advantage of DPC deteriorates due to the need for the transmitters to reliably exchange messages. Thus, when one of the transmitters is close to the receive cluster, it is more advantageous for that transmitter to act as a relay for the transmitter that is farther away, especially when the system operates under an equal rate constraint. Intuitively, this result can be interpreted as the transmitters performing joint data transmission and routing: cooperation not only allows joint encoding between the transmitters, but also forwards the message to a node closer to the destination.

There are several interesting extensions for our model. Our results only consider sum-rate capacity, and it would be valuable to extend the comparison to the entire capacity or achievable rate region for each scheme. Another interesting extension is the case of partial CSI. DPC is not possible without perfect channel information, and it is not clear how the different cooperation schemes would compare under more realistic assumptions about channel CSI. Finally, the benefits of transmitter cooperation when there is a hard energy constraint on each node requires investigation. It was shown in [16] that for transmission of a single message, transmitter cooperation can lead to reduced energy consumption. However, it's not clear if that result will still apply when different nodes have independent messages to transmit.

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