Transmit Cooperation Versus Distributed Coordination in Interference Links

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***Abstract*—In this paper, we investigate whether using a simple form of power allocation and relaying at the transmitters has the same order of performance gain as transmit cooperation coupled with complex coding techniques. We consider two different interference channel scenarios: a cellular system with two neighboring cells and an ad-hoc network with two interfering communication links over a given area. For transmit cooperation, we propose simple and practical linear pre-coding schemes based on Zero-Forcing (ZF) algorithm. We also propose to exploit relaying with distributed power allocation schemes. We see that in the high interference regime, using transmit cooperation coupled with complex coding schemes outperforms pure power allocation and relaying schemes. On the other hand for the moderate to low interference regime, the performance of the simpler schemes become comparable to that of transmit cooperation.**

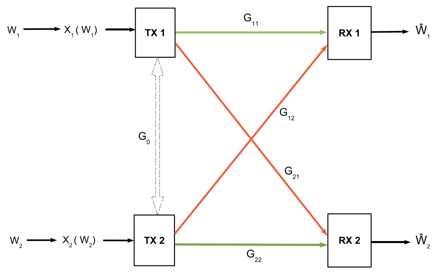

Figure 1. Interference channel with possible transmitter cooperation.

I. Introduction

Interference is a problematic issue in wireless communications as it has an adverse effect on the reliability of links. A number of ways exist to diminish its detrimental effects. The first method relies on performing resource allocation at the system level of the wireless network. In cellular networks for example, one way is to chop the available spectrum into smaller portions and allocate these to co-channel links so that transmissions are orthogonalized; a method called radio frequency planning. Similarly, an alternate method is to provide sufficient spatial separation to co-channel links so that the interfering signals decay enough to be negligible, e.g. as is done through multiple access control (MAC) protocols in ad-hoc networks. Power control is yet another way in which interference caused to others can be controlled and has been an extensively researched topic. In traditional voice-centric wireless networks, power control was found to be an effective method to enhance the reliability of the system [1]–[4]. The key idea here is to balance the transmit powers to achieve a minimum acceptable level of signal-to-interference-plus-noise ratio (SINR) for each user. Recently, power control has been investigated for future data wireless networks enabled with link adaptation protocols. These differ from voice networks due to the elastic nature of data traffic and thus guaranteeing a particular SINR requirement is not always the right strategy. The goal that is considered in [5] is to maximize the aggregate rate of the system through power allocation by exploiting binary power control [6]. Though the optimal solution entails centralized processing of network-wide channel state information, distributed solutions to this problem were presented with the goal of obtaining practical algorithms. This can be viewed as a form of cooperation as a link takes an action which benefits the overall system and not necessarily itself.

Another approach to combat interference has been innovating at the physical layer by employing interference cancellation techniques. Recently, for MIMO broadcast channels, it has been shown that Dirty Paper Coding (DPC) can be implemented at the transmitter side to cancel out interference terms seen at each receiving terminals with full channel state information (CSI) at the transmitter [7]. Although it has been shown that the capacity of MIMO broadcast channels can be achieved by DPC, it is a non-linear pre-coding technique and is difficult to implement [7]–[10]. Inspired by its capacity achieving performance, in [11]–[13] DPC has been exploited by means of transmitter cooperation in ad-hoc networks with simplified channel models where two transmitter nodes first share their transmit signals on an orthogonal channel, and then with full CSI assumption at each transmitter, they perform DPC to send their signals to their intended receivers. It has been shown that transmit cooperation using DPC provides capacity gain over the non-cooperative case when channel gain between the two transmitters is very good. The main drawbacks of transmit cooperation with DPC are the sum-power constraint and full CSI assumptions at the transmitter nodes, which are practically hard to implement in ad-hoc settings. In this paper, to judge the performance of more practical linear pre-coding schemes, we also consider both zero-forcing with a sum-power constraint (ZF-SPC), and zero-forcing with per-antenna power constraint (ZF-PAPC) which has been considered in [14].

In this paper, we try to address the following question: can the same order of performance gain be obtained by using a simple form of cooperation rather than resorting to complex coding techniques? To this end, we first propose a simple scheme for cooperation involving power allocation capacity maximization coupled with relaying to obtain an added diversity benefit. This technique is based on the distributed power allocation algorithms proposed in [5] by taking advantage of inactive nodes in the network. An alternate and more complex cooperation technique is based on DPC where each transmitter tries to cancel out the interference seen from the other node. This basically involves cooperation at the transmitter. In the end numerical results are presented and show that at high interference regime using transmit cooperation coupled with complex coding schemes outperforms pure power allocation and relaying schemes while for low interference regime the roles change.

II. System Model

We consider a very simple two-link wireless network in which each transmitter wants to communicate with its respective receiver. In this network, the transmitter sends a message to its intended receiver only. However, due to full spectral resource reuse, the receiver is interfered by the other active link. We assume single user decoding and thus interference from the other link is treated as noise, as depicted in Figure-1. This setup can be seen as an instance of the interference channel, the analysis of which is a famously difficult problem in information theory [15].

A. Signal Model

Denoting the random channel gain between any arbitrary transmitter i and receiver j by $G_{j,i} \in \mathbb{R}^+$, the received signal Y_j can be written as

$$Y_j = \sqrt{G_{j,j}} X_j + \sum_{i \neq j}^{2} \sqrt{G_{j,i}} X_i + Z_j,$$

where X_j is the intended signal from the transmitter, $\sum_{i \neq j}^{2} \sqrt{G_{j,i}} X_i$ is the sum of interfering signals from other transmitters and Z_j is the noise. For convenience, Z_j is modeled as circularly symmetric complex Gaussian noise with power $\mathbb{E}|Z_j|^2 = \sigma^2$ and zero mean. We denote the random channel gain between transmitter nodes as $G_0 \in \mathbb{R}^+$ which does not include fast fading component.

III. Optimal Power Allocation (OPA) for Sum-Rate Maximization

We are interested in maximizing the sum-rate of the above network. Denoting the power used by transmitter j to communicate with its respective receiver by P_j, the signal to interference-plus-noise ratio (SINR) at the receiver of link j is then given by

$$\Gamma_j(P_j, P_i) = \frac{G_{j,j} P_j}{\sigma^2 + \sum_{i \neq j}^{2} G_{j,i} P_i}. \tag{1}$$

As in all realistic networks, we impose a power constraint on each transmitter such that $0 \leq P_j \leq P_{\max}$. Assuming an ideal link adaptation protocol and perfect CSI at the transmitter, we define the sum-rate in bits/sec/Hz using the Shannon capacity as

$$\mathcal{C}(P_j, P_i) \triangleq \sum_{j=1}^{2} \log_2 \Big(1 + \Gamma_j(P_j, P_i)\Big). \tag{2}$$

The sum-rate maximizing power allocation for two interfering links has been characterized in [6] where it has been shown that

$$(P_1^*, P_2^*) \in \{(P_{\max}, 0), (0, P_{\max}), (P_{\max}, P_{\max})\} \tag{3}$$

This result substantially decreases the optimization complexity from a continuous search space to 2 discrete values for each link. That is either the link will transmit with full power or remain inactive and this is termed binary power control. However, as the network capacity is coupled with the network-wide transmit powers, finding the optimal power allocation vector for given instantaneous channel realizations still requires a centralized solution.

IV. Distributed Power Allocation (DPA)

From a practical point of view centralized processing might not be feasible and to address this issue distributed power allocation was studied in [5] under statistical knowledge of unknown information. In this approach, each transmitter has only local knowledge of channel gains defined as $\mathcal{G}_j^{\text{local}} = \{G_{j,i} \ \forall \ i\}$. The convenience of such a choice is that a transmitter has knowledge of the link SINR. Thus, the unknown information at the transmitter can be represented by $\tilde{\mathcal{G}}_j = \mathcal{G} \setminus \mathcal{G}_j^{\text{local}}$. A transmitter j then tries to maximize the expected network capacity defined as

$$\begin{aligned} \overline{\mathcal{C}}_j(P_j, P_i) \;&=\; \log_2 \left(1 + \frac{G_{j,j} P_j}{\sigma^2 + G_{j,i} P_i}\right) \\ &+\; \mathbb{E}\left\{\log_2 \left(1 + \frac{G_{i,i} P_i}{\sigma^2 + G_{i,j} P_j}\right)\right\}, \end{aligned} \tag{4}$$

where the expectation is taken over the other link's channel gains, namely $G_{i,i}$ and $G_{i,j}$. By exploiting the optimality of binary power allocation a link will either transmit at $P_{\max}$ (assumed as 1) or remain inactive (i.e. link power will be 0). Simple conditions were derived on the link SINR and SNR to determine if it should be active or not and these can be found in [5].

A. Performance Enhancement with 1-bit Message Passing (DPAF)

The distributed algorithm requires no real-time information exchange between the links and this can sometimes lead to the undesirable condition of both links being inactive. In order to avoid this undesirable effect 1-bit message passing was used to communicate the action of one link to the other. The most natural choice of information to send would be the result of a link's power optimization solution. This algorithm significantly enhanced the performance as with the 1-bit signal

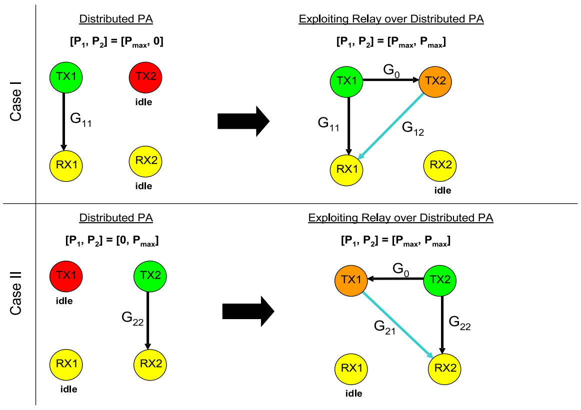

Figure 2. Two cases for which relaying mechanism is used after DPA.

from link 1, a more *informed* decision can be made by link 2. Clearly, if link 1 sends a 0 then link 2 will be active. If a 1 is sent then link 2 needs to consider if what it is more beneficial for the system based on the activity conditions.

V. Distributed Power Allocation and Relaying (DPAFR)

As expressed in (3), there are three possibilities for the optimal power allocation. The distributed algorithm exploits this result to reduce complexity. However, one advantage that is not exploited is the fact that the nodes of an inactive link are available to help the communication of the link which is active. If both links are active then there is no cooperation and each transmitter communicates with its respective receiver. However, when one of the link is inactive, the most simple way to cooperate in this case is for the inactive transmitter to act as a relay for the communicating link. This is explained in Figure-2 where Case-I corresponds to the power allocation case $(P_{\max}, 0)$, i.e. transmit node 2 is inactive, and Case-II corresponds to the power allocation case $(0, P_{\max})$, i.e. transmit node 1 is inactive.

In the case of the distributed power allocation algorithm, each link takes independent decisions. If a link decided to be inactive, it will listen for the signal from the active transmitter and then relay this signal in the second phase. Note that when transmitter decide to act as relay it needs to send acknowledgment to the destination of active link for coherent combination at the destination.

For relaying although there are adaptive relaying strategies [16], we simply consider amplify-and-forward (AF) relaying strategy where the relay node scales its received signal according to its transmit power constraint and sends it to the destination. Moreover, we assume that relay node operates in full-duplex mode.

If we consider Case-I in Figure-2, the achievable network instantaneous rate is given by

$$R = \log_2\left(1 + \frac{P_{\max} G_{11}}{\sigma^2} + \frac{P_{\max}^2 G_0 G_{12}}{\sigma^2(\sigma^2 + P_{\max} G_0 + P_{\max} G_{12})}\right). \quad (5)$$

VI. Transmit Cooperation with Full CSI at the Transmitters

In this section we look at two transmit cooperation schemes where the transmit nodes first exchange their messages and than they jointly utilize DPC or ZF pre-coding techniques which are commonly used in multi-user down-link communications. Here all nodes assumed to have full CSI. Depending on power constrains we look at two ZF pre-coding schemes: sum-power constraint and per-user power constraint schemes. Note by means of practicality second ZF scheme makes more sense.

A. DPC Cooperation

In this section, we explain how DPC cooperation works and comment on how practical DPC cooperation is. DPC cooperation has been proposed in [11], [12], [13], [10] under simplified channel models. First transmitters exchange their signals on an orthogonal channel and then they both implement DPC under sum-power constraint and each transmitter sends corresponding pre-coded signal to the channel. It has been shown that under low channel gain between the two transmitters, the sum-of-rates performance achieved by DPC is worse then non-cooperative transmission for low SNR case [9]. Note that DPC is complex and non-linear pre-coding technique which makes it being an impractical scheme.

To have the complete picture of DPC cooperation, we give the achievable sum-of-rates expressions here. First, the transmitters exchange their signals by using a fraction of power $P_t/2$ each. And then with the remaining power, $P = 2P_{\max} - P_t$, they jointly encode both messages using DPC. Assuming the transmitters operate in full-duplex mode, the transmission rate from one transmitter to the other is $R_t = \log_2(1 + \frac{G_0 P_t}{2\sigma^2})$. After message exchanging with remaining power transmitters implement DCP as if they were a single transmitter. Using the duality between broadcast and multiple-access channels [10], we achieve the following DPC transmission rate

$$R_{DPC} = \max_{\substack{P_1 + P_2 \le P \\ P_1 \ge 0, P_2 \ge 0}} \log_2 \left| \mathbf{I} + P_1 \mathbf{f}_1^H \mathbf{f}_1 + P_2 \mathbf{f}_2^H \mathbf{f}_2 \right| \quad (6)$$

where $\mathbf{f}_1 = [\sqrt{G_{11}}\ \sqrt{G_{12}}]$ and $\mathbf{f}_2 = [\sqrt{G_{21}}\ \sqrt{G_{22}}]$. Note that in [8] some iterative solutions are given for the optimization problem (6).

After all, the network instantaneous sum-of-rates of the DPC cooperation scheme is given by

$$R = \max_{0 \le P_t \le 2P_{\max}} \min\{2R_t, R_{DPC}\}. \quad (7)$$

B. Zero-Forcing (ZF) Cooperation

In this section, we look at ZF pre-coder at the transmitters for both sum power and per-user power constraint cases. Note that ZF is a linear pre-coding scheme as opposed to DPC which is a non-linear pre-coding technique. As in DPC case, the transmitters first exchange their messages by using P_t power, and then with remaining power, $P = 2P_{\max} - P_t$, the transmitters jointly perform ZF and power allocation. Assuming $\mathbf{H} = [\mathbf{f}_1^T\ \ \mathbf{f}_2^T]^T$ is the channel matrix from the

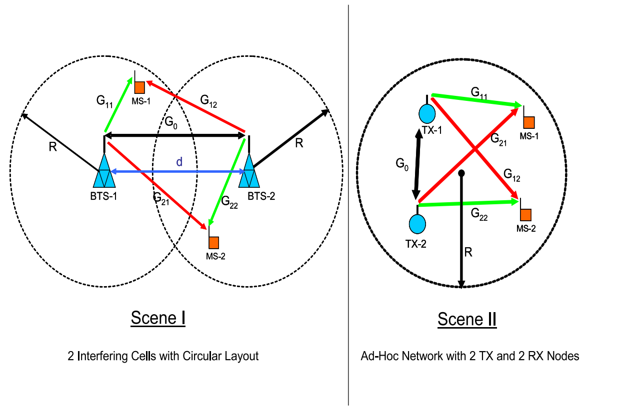

Figure 3. Two Simulation Scenes considered: Scene I is 2 interfering cell with circular layout and Scene II is Ad-Hoc network.

transmitters to the receivers, the corresponding ZF matrix is given by

$$\mathbf{G} \quad = \quad \mathbf{H}^H(\mathbf{H}\mathbf{H}^H)^{-1}. \tag{8}$$

Assuming x_1 and x_2 are the messages of the transmitters with $E[|x_1|^2] = v_1$ and $E[|x_2|^2] = v_2$, respectively, after ZF precoder the transmitted signal vector is given by

$$\mathbf{t} \quad = \quad \mathbf{G}\,\mathbf{x} \tag{9}$$

where $\mathbf{x} = [x_1 \ \ x_2]^T$. We assume that $E[|t_1|^2] = P_1$ and $E[|t_2|^2] = P_2$. In the following sections we look at two different power constraint policies.

1) ZF with Sum-Power Constraint (ZF-SPC): In this case, we have the following simple sum-of-rates optimization problem

$$\begin{aligned} R_{SPC} \quad &= \quad \max_{v_i \ i=1,2} \sum_{i=1}^{2} \log_2(1+v_i) \qquad (10) \\ \text{subject to} \quad & \sum_{i=1}^{2} ||\mathbf{g}_i||^2 v_i \leq P_1 + P_2 = P \\ & v_i \geq 0 \quad i = 1,2 \end{aligned}$$

where $\mathbf{g}_i$ is the i-th column of $\mathbf{G}$. The solution to this problem can be found by water-filling.

2) ZF with Per-User Power Constraint (ZF-PAPC): In this case, we assume symmetric powers at the users that is $P_1 = P_2 = P/2$. Then the sum-of-rates is given by the following optimization problem [14]

$$\begin{aligned} R_{PAPC} \quad &= \quad \max_{v_i \ i=1,2} \sum_{i=1}^{2} \log_2(1+v_i) \qquad (11) \\ \text{subject to} \quad & \sum_{i=1}^{2} |g_{mi}|^2 v_i \leq P_m \quad m = 1,2 \\ & v_i \geq 0 \quad i = 1,2. \end{aligned}$$

Overall instantaneous network capacities corresponding to the above ZF schemes are calculated in the same way as in DPC cooperation case, which is given in (7).

VII. Numerical Results

In this section, we give some numerical results for achievable networks capacities for the schemes described above. We look at two different system scenarios. The first scenario is that of a cellular network with two interfering cells having circular layout and in each cell, users are randomly positioned with uniform distribution. In this case, to see the interference effect on the system sum-of-rates performance, we vary the distance between the two BTSs which is parameterized as $d/2R$. The second scenario is an ad-hoc network with 2 TX-RX pairs in a circular area of radius 1 km. In this case, we vary with average transmit powers to see the power loading effect on interference and cooperation for bounded user positions. These two scenarios are depicted in Figure-3. For each case cell radius is taken as $R = 1$ km.

We assume that channel gains, $G_{i,j} \forall i, j \in \{1, 2\}$, include path-loss, shadowing, antenna gain terms and fast-fading with Rayleigh distribution. On the other hand, the link between transmitter nodes, G_0, includes only large scale fading effects: path-loss, shadowing. It is assumed that each link undergoes path-loss according to simplified COST-231 model [17], which is given by

$$\mathrm{PL(dB)} \quad = \quad 138 + 39.6 \log_{10}(d)$$

where d is the distance between communicating links. The transmitter and receiver antenna gains are $G_{TX} = 16$[dB] and $G_{RX} = 4$[dB], respectively, and the log-normal shadowing is taken to be normal distributed random variable with mean of 0[dB] and standard deviation 10[dB]. We assume that operation band-width is 2 MHz.

In Figure-4, we plot the achievable network sum-of-rates as a function of normalized distance between two BTSs, $d/2R$. We take $P_{\max} = 1$ [Watt] for all of the schemes. For the MIMO scheme, which serves as outer bound, we assume co-located transmit antennas with total power $2P_{\max}$. In this figure, we see that if two cells coincide, i.e. $d/2R = 0$, there is maximum interference for which DPC, ZF-SPC and ZF-PAPC cooperation schemes have very good performance. With increasing $d/2R$, we see that the performance of the transmit cooperation schemes decreases due to increasing power expenditure on the message exchanging phase. After $d/2R \approx 0,65$, OPA and DPAFR schemes outperform DPC, ZF-SPC and ZF-PAPC transmit cooperation schemes. And at $d/2R \approx 0,75$, even DPA and DPAF and non-cooperative schemes reaches the same performance as the transmit cooperation schemes have.

In Figure-5, we plot the achievable network sum-of-rates as a function of maximum transmit power, P_{max}, at the transmitting nodes. At low transmit power, which means interference free regime, we see that the transmit cooperation schemes has inferior performance than the power allocation schemes, and the non-cooperative scheme which means it is better not to cooperate at low transmit power case. After $P_{\max} = -8$[dB] we see that the cooperation schemes outperform both power allocation and non-cooperative schemes. Note that the most

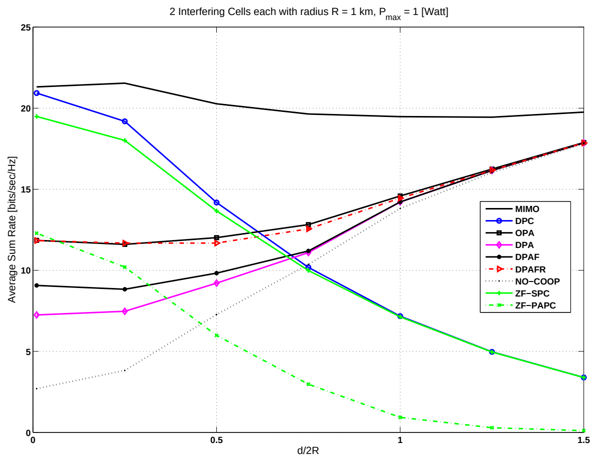

Figure 4. Average sum of rates versus $d/2R$ for circular cell layout.

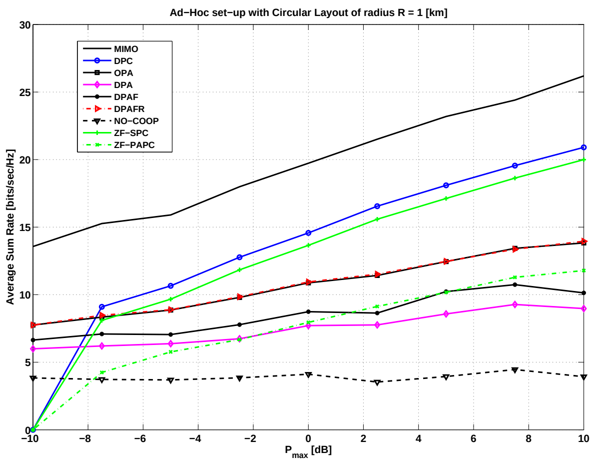

Figure 5. Average sum of rates versus $P_{\max}$ for Ad-Hoc Network.

practical cooperation scheme, ZF-PAPC scheme, is always inferior to both OPA and DPAFR schemes, and at low $P_{\max}$ has even worse performance than DPA and DPAF schemes. As mentioned before, in ad-hoc settings assuming sum-power constraints is not as realistic as assuming individual power constraints. Hence, in Figure-5, ZF-PAPC transmitter cooperation scheme gives us more insight on the system performance and on the comparisons with power allocation schemes. In this plot, we also see that OPA and DPAFR schemes have nearly the same performance. So exploiting relaying functionality on the transmitter nodes we come close to the OPA scheme performance.

VIII. Conclusions

In this paper, we look at achievable network sum rates performances of different transmission schemes. The schemes considered in this paper can be categorized as centralized processing oriented and distributed processing oriented. OPA, DPC, ZF-SPC and ZF-PAPC schemes fall in the first group where transmitter nodes first exchange their messages and jointly transmit to the receivers with the specified pre-coding policy. While DPA, DPAF and DPAFR schemes fall in the second group where the transmitting nodes individually decide their transmission policies.

We considered two different interference channel scenarios, one of which was a cellular system with two neighboring cells and the second was an ad-hoc network with two interfering communication links. We see that at high interference regime DPC, ZF-SPC and ZF-PAPC schemes outperforms OPA, DPA, DPAF and DPAFR schemes. On the other hand, for moderate to low interference regime, it is the opposite. Also, we see that by exploiting relaying functionality at the transmitters on the top of the distributed power allocation policy we come very close to the OPA scheme performance.

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