Transmit Cooperation Versus Distributed Coordination in Interference Links

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Outline

- The Interference Channel
- An Outer Bound on Achievable Sum-of-Rates
- Optimal Power Allocation (OPA) for Sum-of-Rates Maximization
- Distributed Power Allocation (DPA)
  - DPA + 1-bit Feedback (DPA-F)
  - DPA + 1-bit Feedback + Relaying (DPA-F-R)
- Transmit Cooperation with Full Channel State Information at the Transmitters (CSIT)
  - Dirty Paper Coding (DPC) Cooperation
  - Zero-Forcing (ZF) Cooperation
    - ZF with Sum-Power Constraint (ZF-SPC)
    - ZF with Per-User Power Constraint (ZF-PAPC)
- Numerical Results
- Summary & Outlook

The Interference Channel

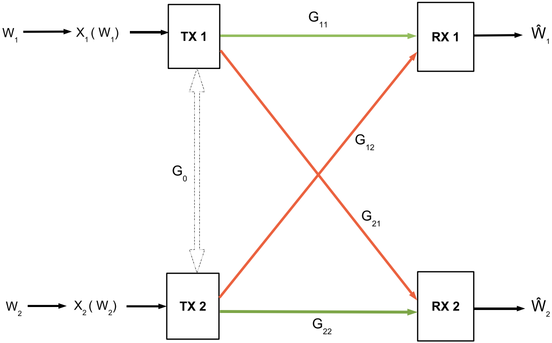
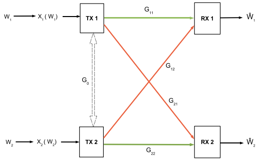


Figure: The interference channel with possible transmitter cooperation.

Signal Model (1/2)

- A simple two-link wireless network in which each transmitter wants to communicate with its respective receiver.
- Each transmitter sends a message to its intended receiver only.
- Due to full spectral resource reuse, the receiver is interfered by the other active link (Interference Channel)
- Single-User decoder at each Receiving node: Treating interference as noise.
- Practically can be Ad-Hoc network or Cellular network (e.g. downlink with Access-Points (APs) being transmitters)

Signal Model (2/2)



- Signal Model for receiver of link j:

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

  - X_i is the signal from transmitter i.
  - $G_{ji} \in \mathbb{R}^+$ is random channel gain between any arbitrary transmitter i and receiver j (assumed constant over access slot).
  - Z_j is circularly symmetric complex Gaussian noise $Z_j \sim \mathcal{CN}(0, \sigma^2)$
- Denote the random channel gain between transmitter nodes as $G_0 \in \mathbb{R}^+$ not including fast fading component
- Each Transmitter has power constraint: $0 \leq P_j \leq P_{\max}$.

An Outer Bound on Sum-of-Rates: MIMO interpretation

- Assume that both the transmitters and the receivers form clusters
  - TX & RX Cooperation $\rightarrow$ without any resources consumption
  - TX powers add up
  - Mimics 2×2 MIMO
- Equivalent 2×2 MIMO input-output relation:

$$\begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \underbrace{\begin{bmatrix} X_1 \\ X_2 \end{bmatrix}}_{\mathbf{X}} + \begin{bmatrix} Z_1 \\ Z_2 \end{bmatrix}$$

- where $\mathbb{E}\|\mathbf{X}\|^2 \leq 2P_{max}$.

OPA for Sum-of-Rates Maximization

- The SINR at the j-th RX is given by

$$\Gamma_j(P_j, P_i) = \frac{G_{jj}P_j}{\sigma^2 + \sum_{i \neq j}^{2} G_{ji}P_i}, \quad \text{where} \quad 0 \leq P_j \leq P_{\max}, \forall j \qquad (1)$$

- Assuming full CSIT we have the following sum-of-rates:

$$\mathscr{C}(P_j, P_i) \triangleq \sum_{j=1}^{2} \log_2 \Big(1 + \Gamma_j(P_j, P_i)\Big) \quad [\text{bits/sec/Hz}]. \qquad (2)$$

- The sum-rate maximizing PA for 2 interfering links is [1, Ebrahimi06], [2, Anders07]

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

- That is either the link will transmit with full power or remain inactive and this is termed binary power control.
- A centralized solution is required for finding the optimal power allocation vector for given instantaneous channel realizations.

Distributed Power Allocation (DPA)

- Each transmitter has only local knowledge of channel gains defined as $\mathscr{G}_j^{\text{local}} = \{G_{ji}\ \forall\ i\}$
- The unknown information at the transmitter can be represented by $\tilde{\mathscr{G}}_j = \mathscr{G} \setminus \mathscr{G}_j^{\text{local}}$
- Each transmitter tries to maximize the expected network capacity which is defined as follow for the j-th transmitter

$$\begin{aligned} \overline{\mathscr{C}}_j(P_j, P_i) &= \log_2\left(1 + \frac{G_{jj}P_j}{\sigma^2 + G_{ji}P_i}\right) \\ &+ \mathbb{E}_{G_{ii},G_{ij}}\left\{\log_2\left(1 + \frac{G_{ii}P_i}{\sigma^2 + G_{ij}P_j}\right)\right\}. \end{aligned} \tag{4}$$

- By exploiting the optimality of binary power allocation a link will either transmit at $P_j = P_{\max}$ or remain inactive ($P_j = 0$).
- In [3, Kiani07] simple conditions were derived on the link SINR and SNR to determine if it should be active or not.

DPA + 1-bit Feedback (DPA-F)

- The distributed algorithm requires no real-time information exchange between the links
- The undesirable condition of both links being inactive: $(P_1^*, P_2^*) = (0, 0)$
- In order to avoid this undesirable effect:
  - **1-bit** message passing can be used to inform the action of one link to the other.
  - This 1-bit information significantly enhances the performance as with the **1-bit** signal 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 what is more beneficial for the system based on the activity conditions.

DPA + 1-bit Feedback + Relaying (DPA-F-R) (1/2)

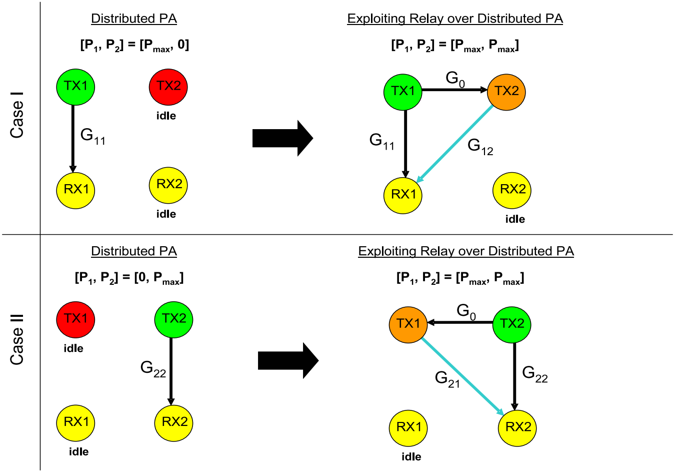


Figure: Two cases for which relaying mechanism is used after DPA.

DPA + 1-bit Feedback + Relaying (DPA-F-R) (2/2)

- In the case of the DPA algorithm each link takes independent decisions!
- In strong interference case (**!**) most likely to have one TX being active while the other inactive!
- If a link decided to be inactive, then that inactive transmitter can act as a **relay** for the active link.
- Additional diversity (more reliable communication)!
- For Case-I in Figure-2 with **Full-Duplex** **AF** relaying, the achievable rate is

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

where $\alpha = \sqrt{\frac{P_{\max}}{P_{\max}G_0 + \sigma^2}}$.

Transmit Cooperation with full CSIT

- Full CSI at the transmitters (CSIT)
- The transmitters first exchange their messages
  - Resource consumption: Time + Power
  - If the channel gain between two transmitters G_0 is not good then time and/or power required for data exchange will be more!
- and then jointly transmit to the receivers (broadcasting)
- We look at DPC and ZF pre-coding techniques

Transmit Cooperation + DPC

- DPC is complex and *non-linear* pre-coding technique
- DPC TX cooperation has been studied in [4, Vishwanath], [5, NG08]:
  - First TXs exchange their signals on an orthogonal channel in Full-Duplex mode by using a fraction of power $P_t/2$ each:

$$R_t = \log_2(1 + \frac{G_0 P_t}{2\sigma^2})$$

  - TXs jointly encode both messages using DPC under SPC with the remaining power, $P = 2P_{\max} - P_t$
- By using the duality between BC and MAC [4, Vishwanath]:

$$R_{DPC} = \max_{\substack{P_1+P_2 \leq P \\ P_1 \geq 0, P_2 \geq 0}} \log_2 \left| \mathbf{I} + P_1 \mathbf{f}_1^H \mathbf{f}_1 + P_2 \mathbf{f}_2^H \mathbf{f}_2 \right|$$

  where $\mathbf{f}_1 = [\sqrt{G_{11}} \; \sqrt{G_{12}}]$ and $\mathbf{f}_2 = [\sqrt{G_{21}} \; \sqrt{G_{22}}]$.
- The network instantaneous sum-of-rates of the DPC cooperation scheme:

$$R = \max_{0 \leq P_t \leq 2P_{\max}} \min\{2R_t, R_{DPC}\}.$$

Transmit Cooperation + ZF

- ZF is a *linear* pre-coding scheme as opposed to DPC which is a non-linear pre-coding technique
- The TXs first exchange their messages by using P_t power
- Then with remaining power, $P = 2P_{\max} - P_t$, the TXs jointly perform ZF and power allocation
- Define the channel matrix from the TXs to the RXs as

$$\mathbf{H} = [\mathbf{f}_1^T \ \mathbf{f}_2^T]^T = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix}$$

- The corresponding ZF matrix:

$$\mathbf{G} = \mathbf{H}^H (\mathbf{H}\mathbf{H}^H)^{-1}$$

- After ZF pre-coder the transmitted signal vector is

$$\mathbf{t} = \mathbf{G}\,\mathbf{x} = [\mathbf{g}_1 \mathbf{g}_2]\mathbf{x}$$

  where $\mathbf{x} = [x_1 \ x_2]^T$ with $\mathbb{E}[|x_1|^2] = v_1$ and $\mathbb{E}[|x_2|^2] = v_2$
- Assume that $\mathbb{E}[|t_1|^2] = P_1$ and $\mathbb{E}[|t_2|^2] = P_2$
- We look at two different power constraint policies: SPC and PAPC

Transmit Cooperation + ZF

ZF with SPC

- we have the following simple sum-of-rates optimization problem

$$R_{SPC} = \max_{v_i \; i=1,2} \sum_{i=1}^{2} \log_2(1+v_i) \tag{6}$$

$$\text{subject to } \mathbb{E}[||\mathbf{t}||^2] = \sum_{i=1}^{2} ||\mathbf{g}_i||^2 v_i \leq P_1 + P_2 = P \quad \text{and} \quad v_i \geq 0 \quad i = 1,2$$

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

ZF with PAPC

- Assume symmetric powers at the TXs: $P_1 = P_2 = P/2$
- The sum-of-rates is given by [6, Boccardi06]

$$R_{PAPC} = \max_{v_i \; i=1,2} \sum_{i=1}^{2} \log_2(1+v_i) \tag{7}$$

$$\text{subject to } \sum_{i=1}^{2} |g_{mi}|^2 v_i \leq P_m \quad m = 1,2 \quad \text{and} \quad v_i \geq 0 \quad i = 1,2.$$

Overall instantaneous network capacities for the above ZF schemes are calculated in the same way as in DPC.

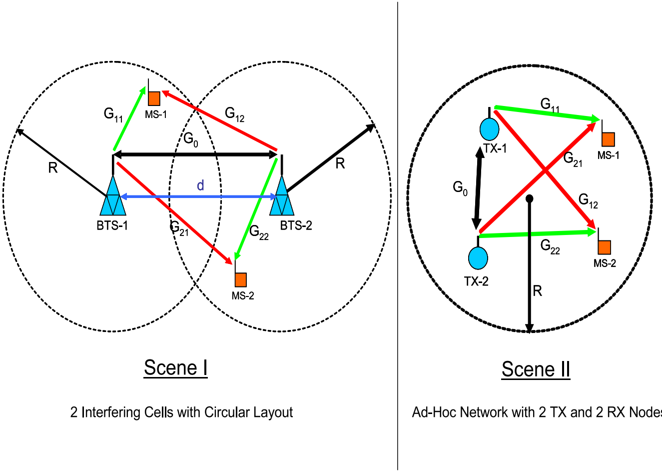


Figure: Two Simulation Scenes considered: Scene-I is 2 interfering cells with circular layout and Scene-II is Ad-Hoc network.

Table: Simulation Parameters

R	1 km
P_{max}	1 [Watt]
G_0	Includes only Path-Loss + Shadowing
Antenna Gains ([dBi])	$G_{TX} = 16$, $G_{RX} = 4$
Operating Band-width	2 MHz
Boltzmann constant	$k_B = 1.38\ 10^{-23}$
Operating temperature	$T = 290$ Kelvin
Log-normal Shadowing	0[dB] mean and standard deviation 10[dB]
Path-Loss in [dB]	$138 + 39.6 \log_{10}(d)$, d in [km]

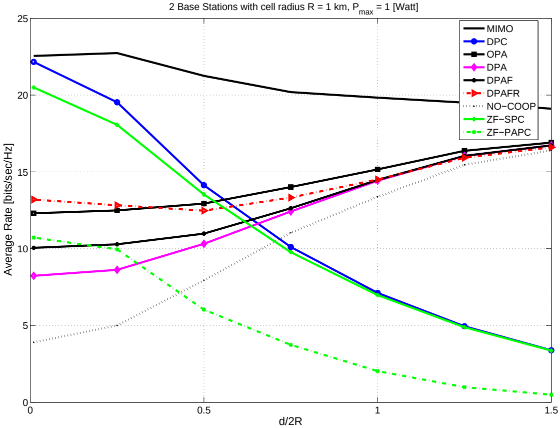


Figure: Average sum-of-rates vs. $d/2R$ for Circular cell layout.

Numerical Results (4/4)

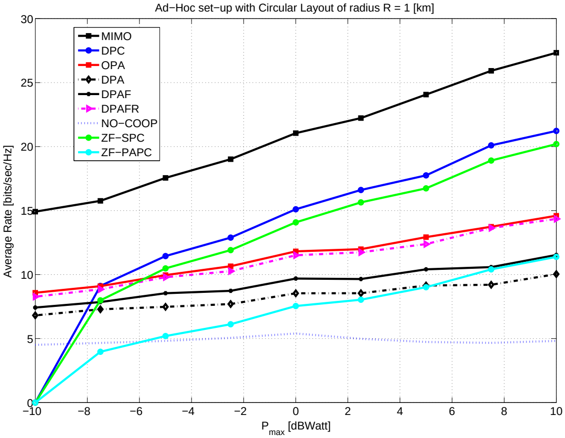


Figure: Average sum-of-rates vs. $P_{\max}$ for Ad-Hoc Network.

Summary & Outlook

Summary:

- Centralized processing Oriented Transmission Schemes
  - DPC, ZF-SPC, ZF-PAPC and OPA schemes fall in this group
  - TXs first exchange their messages and jointly transmit to the RXs with the specified pre-coding policy
- Distributed processing Oriented Transmission Schemes
  - DPA, DPA-F and DPA-F-R schemes fall in this group
  - TXs individually decide their transmission policies
- At high interference regime DPC, ZF-SPC and ZF-PAPC schemes outperform OPA, DPA, DPA-F and DPA-F-R schemes
- For moderate to low interference regime the roles change
- By exploiting Relaying at the TXs on the top of the DPA policy we come very close to the OPA scheme performance

Outlook:

- Interference Channel with Multiple TX-RX pairs
- The effects on network sum-of-rates of
  - Selfish behavior: Create interference to other links
  - Cooperative behavior: Broke your link and act as a relay to help others

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Thanks...