Scalable and distributed transmitter cooperation in wireless networks

Team decision problems in wireless networks

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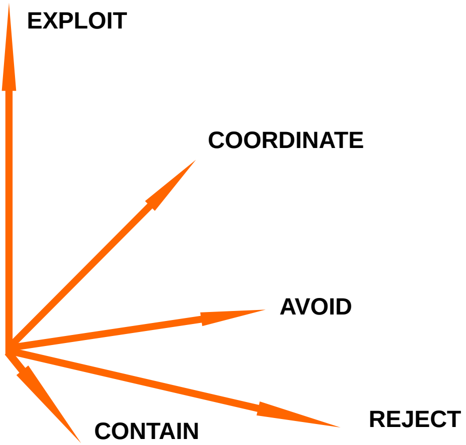
The Dimensions of Interference Management

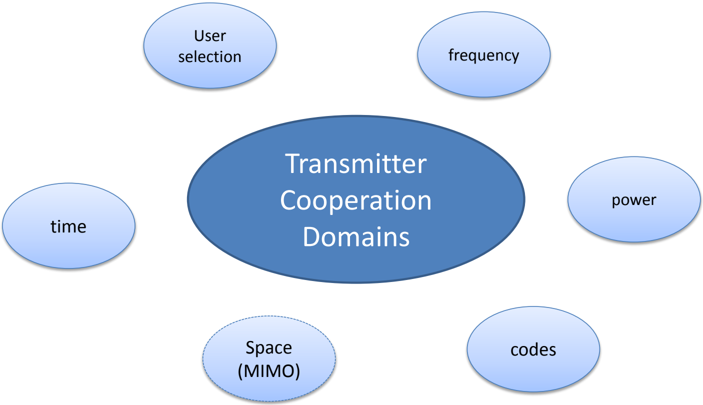


Outline

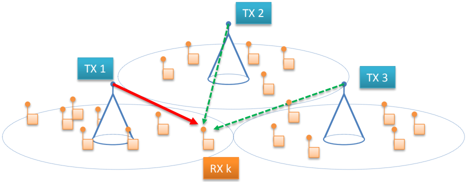
1. Fundamentals for Transmitter Coordination
2. Thinking Practical
3. Team Decisions Problems in Wireless Networks
4. Spatial Allocation of CSI in Multi-antenna Coordinated Networks
5. Team Decision for Multi-Antenna Precoding
6. Lessons learned and open problems

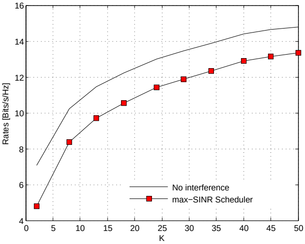
Outline

Transmitter Cooperation Domains



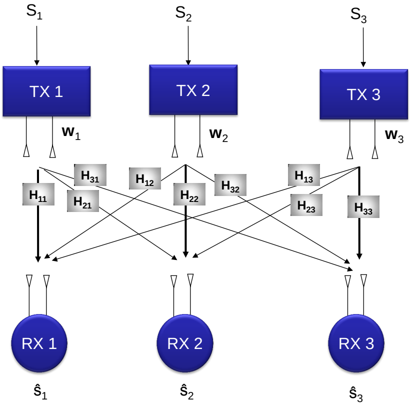
Example 1: Coordination using Scheduling, Power Co





- Picking the right user at any time/freq exploits the variability of interference
- Can be combined with power control/beamforming (will couple the decisions at all cells)
- Simple max-SINR scheduler is distributed and works beautifully

Example 2: Coordination using Alignment



Interference Alignment Conditions with N_r=2:

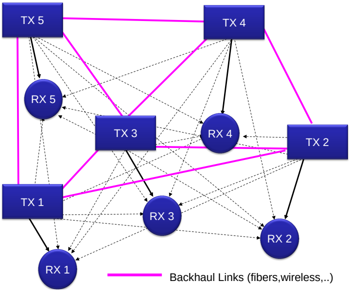
$$\mathbf{H}_{12}\mathbf{w}_2 \propto \mathbf{H}_{13}\mathbf{w}_3$$
$$\mathbf{H}_{21}\mathbf{w}_1 \propto \mathbf{H}_{23}\mathbf{w}_3$$
$$\mathbf{H}_{31}\mathbf{w}_1 \propto \mathbf{H}_{32}\mathbf{w}_2$$

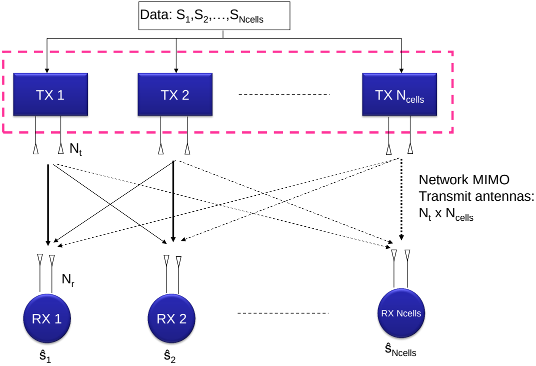
- Alignment can be carried out in space, frequency, time domains
- A optimal DoF of 1/2 can be achieved (everyone gets half the cake)

  [Maddah-Ali et al., 2008, TIT] [Cadambe and Jafar, 2008, TIT]

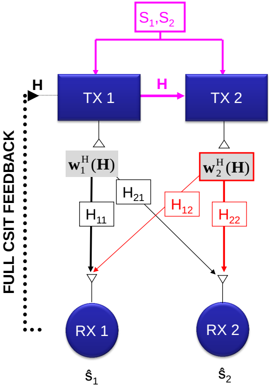
Example 3: Cooperation with Joint MIMO Precoding

- Joint MIMO Precoding [Hanly, 1993] [Shamai and Zaidel, 2001, VTC]





How does Joint MIMO Precoding Work?



Ideal Network MIMO

$$\mathbf{T} = [\mathbf{t}_1(\mathbf{H}) \quad \mathbf{t}_2(\mathbf{H})] = \begin{bmatrix} \mathbf{w}_1^H(\mathbf{H}) \\ \mathbf{w}_2^H(\mathbf{H}) \end{bmatrix}$$

$$\text{e.g.}\ \mathbf{T} = \frac{\mathbf{H}^{-1}}{\|\mathbf{H}^{-1}\|_F}$$

Modify standard MU-MIMO schemes to reflect per base power constraint (ZF, MMSE, non-linear precoding: Dirty Paper Coding, vector perturbation, ..)

Figures-of-Merit

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- Average rate of user i given by [Cover and Thomas, 2006]

$$R_i \triangleq \mathrm{E}\left[\log_2\left(1+\frac{|\mathbf{g}_i^{\mathrm{H}}\mathbf{H}_i^{\mathrm{H}}\mathbf{t}_i|^2}{1+\sum_{j\neq i}|\mathbf{g}_i^{\mathrm{H}}\mathbf{H}_i^{\mathrm{H}}\mathbf{t}_j|^2}\right)\right]$$

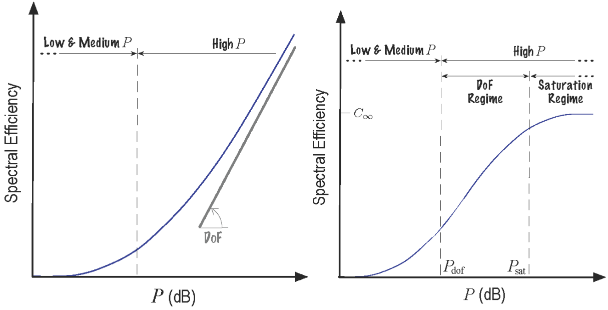
- Number of Degrees-of-Freedom (DoF) at user i –or prelog factor– defined as [Tse and Viswanath, 2005]

$$\mathrm{DoF}_i \triangleq \lim_{P\to\infty}\frac{R_i}{\log_2(P)}.$$

- Sum DoF over K TX-RX pairs:

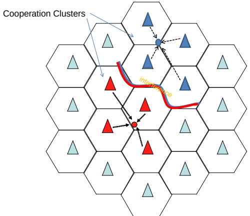
$$\mathrm{DoF} \triangleq \sum_{i=1..K}\mathrm{DoF}_i$$

Myth and Reality of Transmitter Cooperation



* *A. Lozano et al, "Fundamental limits of cooperation", IEEE Trans. On Information Theory, Sept. 2013.*

Is this a fundamental clustering limitation?



Outline

Thinking practical

A number of issues arise in the implementation of cooperation mechanisms:

- Hardware impairments
- Channel estimation and tracking
- Channel State information (CSI) Feedback limitation
- Inter-transmitter information sharing limitation

Inter-transmitter Information Sharing Limitation

- Perfect sharing of CSIT is not scalable in large networks
- CSIT sharing is:
  - Latency limited (often)
  - Capacity limited (sometimes) as in wireless mmw backhauling
  - Privacy limited (cognitive radios)

$\rightarrow$ TX-dependent CSIT noise

A Distributed Channel State Information Model

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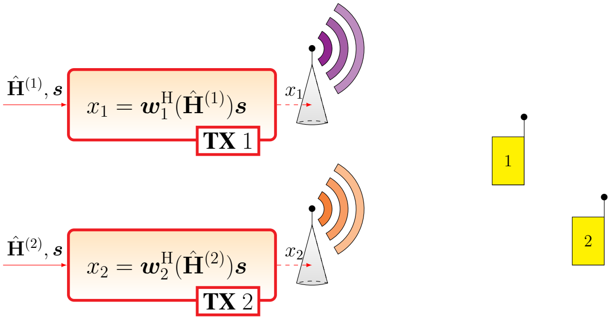
- CSIT imperfection at TX j modeled as Local quantization noise

$$\{\hat{\mathbf{H}}^{(j)}\}_{i,k} = \sqrt{1-2^{-B_{i,k}^{(j)}}}\sigma_{i,k}\{\mathbf{H}\}_{i,k} + \sqrt{2^{-B_{i,k}^{(j)}}}\sigma_{i,k}\{\mathbf{\Delta}\}_{i,k}^{(j)}, \qquad \forall i,k$$

where $\{\mathbf{\Delta}\}_{i,k}^{(j)} \sim \mathcal{CN}(0,1)$

- CSIT allocation $\mathbf{B}^{(j)}$ at TX j defined as $\{\mathbf{B}^{(j)}\}_{i,k} = B_{i,k}^{(j)}, \qquad \forall i,k$

Joint Precoding with Distributed CSIT

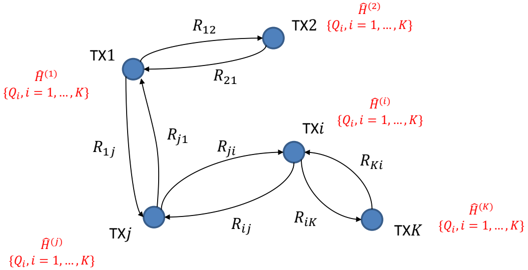


Key questions (assuming single-shot coordination):

1. What kind of CSI should over-the-air feedback convey?
2. What should be exchanged over the signaling links?
3. Assuming TX 1 finally has $\mathbf{H}^{(1)}$ and TX 2 has $\mathbf{H}^{(2)}$, how should precoders $\mathbf{w}_1(\mathbf{H}^{(1)})$ and $\mathbf{w}_2(\mathbf{H}^{(2)})$ be designed?

Outline

One-shot coordination problems



A priori information:

$\hat{H}^{(.)}$: local CSI

Q_i: Error covariance

Coordination link rates:

From i to j: R $_{ij}$

- Problem 1: Channel state information allocation (what should $\hat{\mathbf{H}}^{(i)}$ be?
- Problem 2: Signaling (what to send over R_{ij} bits?)
- Problem 3: Team decision making

Problem 1: Channel State Information Allocation

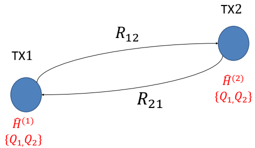
- The nodes to be coordinated are initially assigned *some* CSIT-related data. The spatial distribution of CSIT is called the information structure.
  - A CSI structure is *perfect* if $\hat{\mathbf{H}}^{(i)} = \mathbf{H}$, $\forall i$.
  - A CSI structure is *centralized* if $\hat{\mathbf{H}}^{(i)} = \hat{\mathbf{H}}^{(j)}$, $\forall i, j$.
  - A CSI structure is *distributed* if there exist i and j such that $\hat{\mathbf{H}}^{(i)} \neq \hat{\mathbf{H}}^{(j)}$.

$$\text{maximize objective}\left(\{\mathbf{H}^{(j)}\}_{j=1}^{K}, \mathbf{H}\right) \text{ subject to } \mathrm{size}(\{\mathbf{B}^{(j)}\}_{j=1}^{K}) \leq \tau$$

Some Distributed Information Structures

- **Incomplete CSIT**: A CSI structure is *incomplete* if $\hat{\mathbf{H}}^{(i)}$ takes the form $\forall i\ \hat{\mathbf{H}}^{(i)} = \{\mathbf{H}_{kl}, k \in \mathcal{S}_{tx},\ l \in \mathcal{S}_{rx}\}$, where $\mathcal{S}_{tx}$ (resp. $\mathcal{S}_{rx}$) are subsets of the transmitter set (resp. receiver set).
- **Hierarchical CSIT**: A CSI structure is *hierarchical* if there exists an order of transmitter indices i_1, i_2, i_3.. such that $\hat{\mathbf{H}}^{(i_1)} \subset \hat{\mathbf{H}}^{(i_2)} \subset \hat{\mathbf{H}}^{(i_3)} \subset \ldots$
  - **Master Slave**: Hierarchical where $\hat{\mathbf{H}}^{(i_1)} = []$, and $\hat{\mathbf{H}}^{(i_2)} = \mathbf{H}$ (can be extended to $K > 2$.)

Problem 2: Signaling for Coordination



- Heuristic strategies:
  1. Local decision W_i based on $\hat{\mathbf{H}}^{(i)}$ and $\mathbf{Q}_i, i = 1, .., K$, exchange quantized decisions over R_{ij} bits
     - But poorly informed nodes make bad decisions !
  2. Exchange quantized CSI $\hat{\mathbf{H}}^{(i)}$ over R_{ij} bits
     - But this ignores $\mathbf{Q}_i$!
- Optimal strategy (source coding with side-information): Create locally optimal codebooks, that are function of local CSI and neighbor CSI qualities [Li et al., 2014]

Problem 3: Team Decision

- Several network agents wish to cooperate towards maximization of a common utility
- Each agent has its own limited view over the system state
- All need to come up with consistent actions
- Introduced first in economics and control [Ho, 1980, IEEE], recently in wireless [Zakhour and Gesbert, 2010, ITA]

Team Decision Theory: Buying a Baguette or not?

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In 1936, a couple returns separately from work and wants baguette for dinner. Personal cost for stopping at the baker is ci . Each person knows its own cost c_i,. We assume that the c_i are uniformly distributed over $[0, 1]$.

Goal: maximize expectation of joint utility given by:

Person 2\Person 1	Buy bread	Go home
Buy bread	$a-c_1-c_2$	$1-c_1$
Go home	$1-c_2$	0

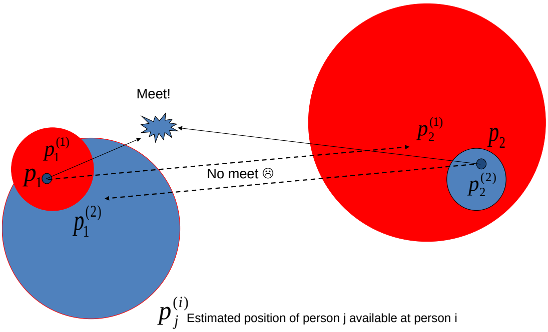
When should each person buy bread?

Optimal decision $\gamma_i^*(c_i)$ *of threshold form*

$$\boxed{\gamma_i^*(c_i) = \begin{cases} \text{Buy bread if } c_i \le c_i^{th} \\ \text{Go home if } c_i > c_i^{th} \end{cases}}$$

The Distributed Rendez-vous Problem

- Two visitors arrive independently in Hammamet and seek to meet as quickly as possible.
- They have different and imprecise information about their own and each other's position.
- **Problem**: *Pick a direction to walk into*



Games vs. Teams

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- Team agents (network nodes) are not conflicting players
- Agents seek maximization of the same network utility
- It is the lack of shared information which hinders cooperation, not selfishness
- Connections to Bayesian games (see work by 1994 Nobel Prize winner John Harsanyi [Harsanyi, 1967])

Team Decision Making

Distributed coordination = team decision making = A difficult problem in general! (functional optimization).

$$\max_{\mathbf{W}_i(\hat{\mathbf{H}}^{(i)}), i=1..K} E\left\{\sum_i u_i(\mathbf{W}_1(\hat{\mathbf{H}}^{(1)}), \ldots, \mathbf{W}_K(\hat{\mathbf{H}}^{(K)}), \mathbf{H})\right\}$$

Solving the Problem

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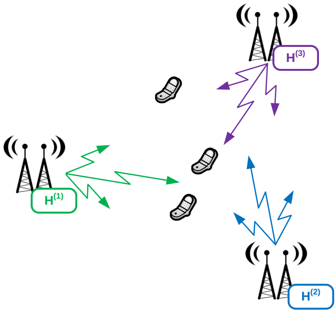
Some pragmatic approaches:

- Model based decision
- Hierarchical (nested) CSI structure
- High SNR regime
- Large scale analysis

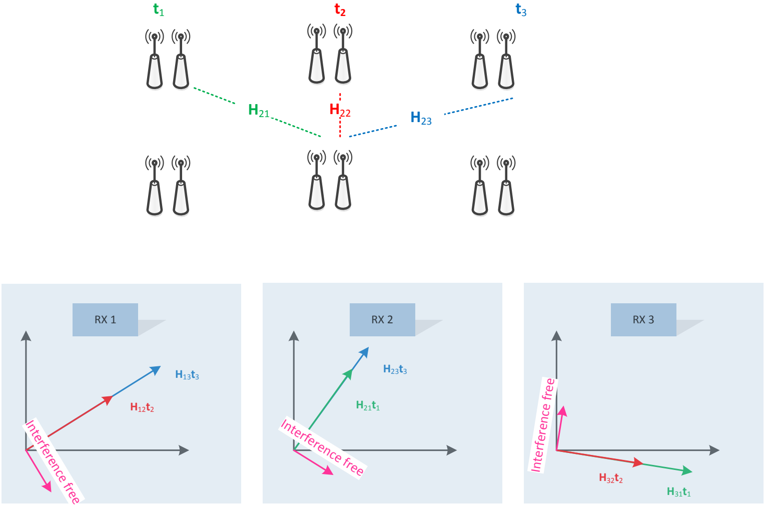
Outline

spatial Allocation of CSIT

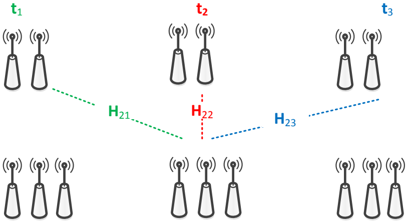


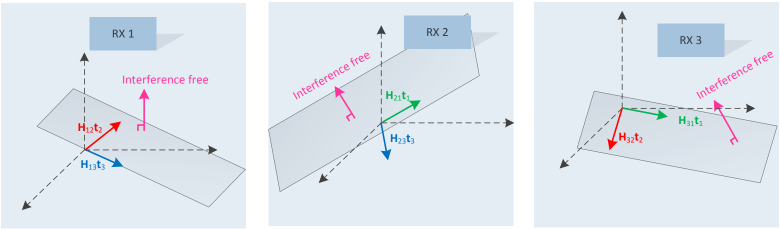
- Is it optimal for each TX to receive the same information?
- How can we save on sharing overhead?

CSIT vs. antennas in interference alignment



CSIT vs. antennas in interference alignment





Modeling the CSIT sharing overhead

- $\mathbf{H}_{ik}$ either known perfectly or not at all at TX j
- $\mathbf{F}^{(j)} \in \{0,1\}^{N_{\text{tot}} \times M_{\text{tot}}}$ the CSIT index matrix
- $\mathrm{Size}(\mathcal{F})$ the size of a CSIT allocation $\mathcal{F} = \{\mathbf{F}^{(j)} | j = 1, \dots, K\}$

$$\mathrm{Size}(\mathcal{F}) = \sum_{j=1}^{K} \|\mathbf{F}^{(j)}\|_{\mathrm{F}}^2$$

- One question: How can we reduce CSIT allocation size while preserving alignment?

An efficient CSI allocation result

Theorem

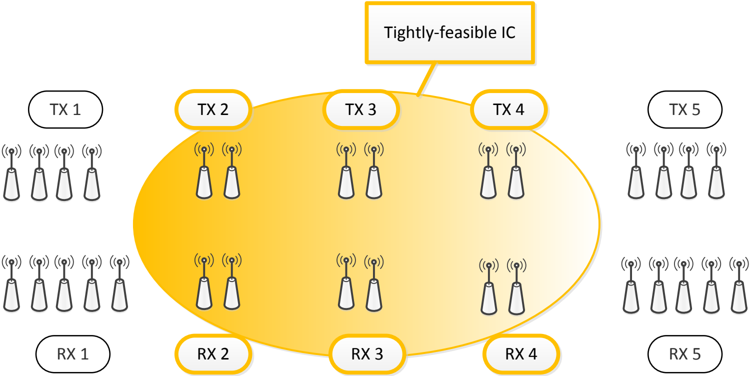
[de Kerret and Gesbert, 2014b, TWC] In a tightly-feasible $[\prod_{k=1}^{K}(N_k, M_k)]$ *IC, if there exists a tightly-feasible sub-IC formed by the set of TXs* $\mathcal{S}_{\text{TX}}$ *and the set of RXs* $\mathcal{S}_{\text{RX}}$*, i.e.,*

$$\mathcal{N}_{\text{var}}(\mathcal{S}_{\text{RX}}, \mathcal{S}_{\text{TX}}) = \mathcal{N}_{\text{eq}}(\mathcal{S}_{\text{RX}}, \mathcal{S}_{\text{TX}}),$$

then the incomplete CSIT allocation $\mathcal{F} = \{\mathbf{F}^{(j)} | j \in \mathcal{K}\}$ *preserves IA feasibility, if*

$$\begin{aligned} \mathbf{F}^{(j)} &= \mathbf{F}_{\mathcal{S}_{\text{RX}},\mathcal{S}_{\text{TX}}}, & \forall j \in \mathcal{S}_{\text{TX}} \\ \mathbf{F}^{(j)} &= \mathbf{F}_{\mathcal{K},\mathcal{K}} = \mathbf{1}_{N_{\text{tot}} \times M_{\text{tot}}}, & \forall j \notin \mathcal{S}_{\text{TX}}. \end{aligned}$$

Example (IC $(5,4),(2,2),(2,2),(2,2),(5,4)$)



Random Antenna Settings

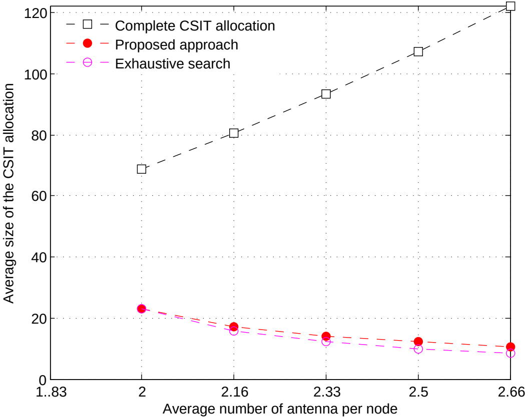
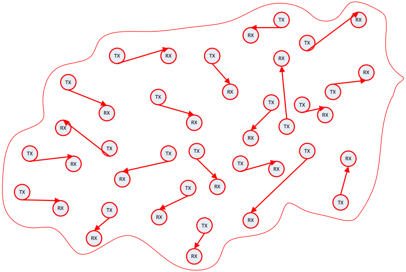


Figure: Average feedback size for $K = 3$ users with the antennas allocated uniformly at random to the TXs and the RXs

A result for joint MIMO precoding

- Goal is to find a frugal spatial CSIT allocation giving same DoF as perfect CSIT.
- Intuition: Two far away nodes should exchange little (or no) CSI



Generalized DoF and Interference Level Matrix

- Define the generalized DoF

$$\mathrm{DoF}_i(\mathbf{\Gamma}) \triangleq \lim_{P \to \infty} \frac{R_i}{\log_2(P)} \quad \text{, subject to } \sigma_{i,j}^2 = P^{-\{\mathbf{\Gamma}\}_{i,j}}, \quad \forall i, j$$

- Define $\mathbf{\Gamma} \in [0, \infty]^{K \times K}$ the interference level matrix
- $\mathbf{\Gamma}$ results from the network topology

Conventional CSIT Allocation

Proposition

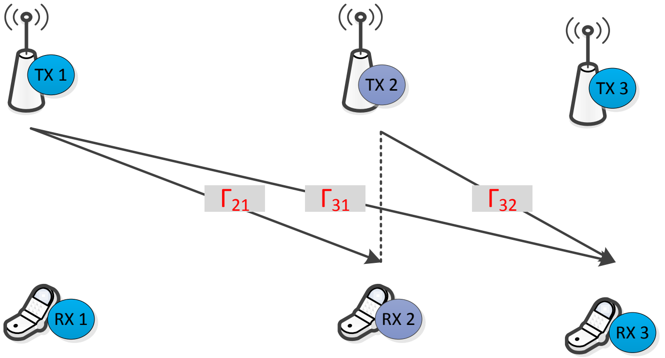
The following "conventional" CSIT allocation $\{\mathbf{B}^{\text{conv},(j)}\}_{j=1}^{K}$ such that

$$\begin{aligned}\{\mathbf{B}^{\text{conv},(j)}\}_{k,i} &= [\lceil \log_2(P\sigma_{k,i}^2)\rceil]^+, \qquad \forall k,i,j \\ &= \lceil [1-\Gamma_{k,i}]^+ \log_2(P)\rceil\end{aligned}$$

is DoF achieving, i.e., $\{\mathbf{B}^{\text{conv},(j)}\}_{j=1}^{K} \in \mathbb{B}_{\text{DoF}}$.

Shortest Path: Example

Example



$$\Gamma_{1\to 3} = \min\left(\Gamma_{2,1} + \Gamma_{3,2}, \Gamma_{3,1}\right).$$

CSIT Allocation for regular networks

Theorem ([de Kerret and Gesbert, 2014a, TIT])

If

- *Symmetry:* $\Gamma_{k,i} = \Gamma_{i,k}, \forall i, k$
- *Triangular inequality:* $\Gamma_{i \to k} = \Gamma_{k,i}, \forall k, i$ $(\Leftrightarrow \Gamma_{k,i} \leq \Gamma_{k,\ell} + \Gamma_{\ell,i}, \forall k, i, \ell)$

then the distance based CSIT allocation simplifies to

$$\{\mathbf{B}^{\mathrm{dist},(j)}\}_{k,i} = \left\lceil [1 - \Gamma_{k,i} - \min\left(\Gamma_{i,j}, \Gamma_{k,j}\right)]^{+} \log_2(P) \right\rceil, \qquad \forall k, i, j$$

Outline

The Naive Zero Forcing in the distributed setting

- TX j computes $\mathbf{T}^{(j)} = [\mathbf{t}_1^{(j)}, \dots, \mathbf{t}_K^{(j)}] \in \mathbb{C}^{K \times K}$ where

$$\mathbf{t}_i^{(j)} \triangleq \frac{\left(\hat{\mathbf{H}}_i^{(j)}\right)^{-1} \mathbf{e}_i}{\| \left(\hat{\mathbf{H}}_i^{(j)}\right)^{-1} \mathbf{e}_i \|} \sqrt{P}, \qquad \forall i$$

Applying the Naive ZF in distributed CSI setting

Define CSIT scaling coefficients $A_i^{(j)}$ at TX j such that

$$A_i^{(j)} \triangleq \lim_{P\to\infty} \frac{\sum_{k=1}^{K} B_{i,k}^{(j)}}{K\log(P)}$$

Theorem

The DoF achieved with conventional ZF for user i is equal to [de Kerret and Gesbert, 2012, TIT]

$$\mathrm{DoF}^{\mathrm{ZF}} = K \min_{i,j\in\{1,\ldots,K\}} A_i^{(j)}.$$

- Feedback quality of RX i impacts all RXs!
- Cost of distributedness

Conventional Robust Design

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- Classical robust designs target CSI imperfection but not CSI inconsistencies [Shenouda and Davidson, 2006, ICASSP]

$$\mathbf{t}_i^{\mathrm{rZF}(j)} \triangleq \sqrt{\frac{P}{2}} \frac{(\mathbf{R}_{\boldsymbol{\Delta}}^{(j)} + \mathbf{H}^{(j)\mathrm{H}}\mathbf{H}^{(j)})^{-1}\mathbf{H}^{(j)\mathrm{H}}\mathbf{e}_i}{\left\|(\mathbf{R}_{\boldsymbol{\Delta}}^{(j)} + \mathbf{H}^{(j)\mathrm{H}}\mathbf{H}^{(j)})^{-1}\mathbf{H}^{(j)\mathrm{H}}\mathbf{e}_i\right\|}$$

with $\mathbf{R}_{\boldsymbol{\Delta}}^{(j)}$ the covariance matrix of the multiuser channel estimation error at TX j

Theorem

Conventional robust ZF precoder achieves the same number of DoFs as conventional ZF.

Hierarchical Feedback

- Introduce Hierarchical/Layered Quantization [Ng et al., 2009, TIT]
- CSI encoded such that each TX decodes up to a number of bits depending on the quality of the feedback link
- If $\mathbf{h}_i^{(j_1)}$ more accurate than $\mathbf{h}_i^{(j_2)}$, then TX j_1 has also knowledge of $\mathbf{h}_i^{(j_2)}$

Remark: If $A_i^{(j_1)} = A_i^{(j_2)}$, then $\mathbf{h}_i^{(j_1)} = \mathbf{h}_i^{(j_2)}$

Degrees of Freedom with Hierarchical Feedback

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Theorem

The number of DoFs achieved by user i with Conventional ZF and hierarchical feedback is

$$\mathrm{DoF}^{\mathrm{cZF}} = \sum_{i=1}^{K} \min_{j\in\{1,\ldots,K\}} A_i^{(j)}.$$

- Strong improvement of the number of DoFs achieved
- CSI scaling of user i impacts solely number of DoFs of user i

➥ Hierachical quantifization enforces coordination between TXs

Active-Passive Zero Forcing (two user case)

- Assume w.l.o.g. that $A_{\bar{i}}^{(2)} \geq A_{\bar{i}}^{(1)}$, then

$$\mathbf{t}_i^{\mathrm{APZF}} \triangleq \sqrt{\frac{P}{2\log_2(P)}} \begin{bmatrix} 1 \\ -\frac{\{\tilde{\mathbf{h}}_{\bar{i}}^{(2)}\}_1}{\{\tilde{\mathbf{h}}_{\bar{i}}^{(2)}\}_2} \end{bmatrix}$$

Theorem

Active-Passive ZF achieves the number of DoFs at user i

$$\mathrm{DoF}^{\mathrm{APZF}} = \max_{j\in[1,2]} A_1^{(j)} + \max_{j\in[1,2]} A_2^{(j)}$$

Simulations

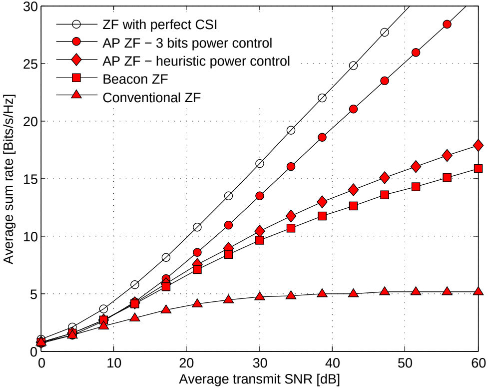

Figure: Sum rate in terms of the SNR with a statistical modeling of the error from RVQ using $[A_1^{(1)}, A_1^{(2)}] = [1, 0.5]$ and $[A_2^{(1)}, A_2^{(2)}] = [0, 0.7]$.

Outline

Lessons learned

- Coordination a powerful method to optimize wireless networks
- Nodes may not (must not) share a common channel state information
- Team decision methods allow dealing with lack of consistency in CSI at various users
- Some solutions for certain regimes (high nb users, SNR) but a general optimal strategy remains elusive.

Some interesting future work:

- Sequential coordination
- Connections with many-shot coordination (Convergence speed vs timeliness)
- Implicit coordination [Larrousse and Lasaulce, 2013, ISIT]


thanks

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