Transmitter Cooperation in Wireless Networks: Potential and Challenges

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Shameless (but useful) Self-references

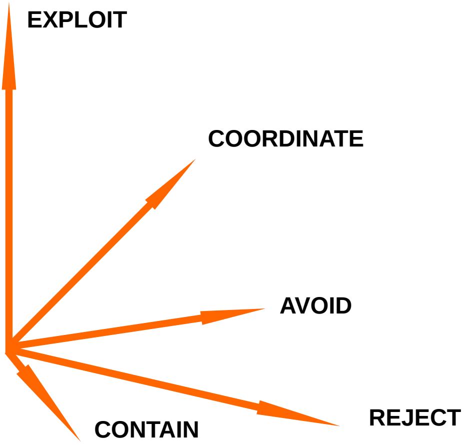
- Multi-cell MIMO cooperative networks : A new look at interference
  D. Gesbert, S. Hanly, H. Huang, S. Shamai, O. Simeone, and W. Yu,
  IEEE Journal on Selected Areas in Communications, December 2010.
- CSI sharing strategies for transmitter cooperation in wireless networks, P. de Kerret and D. Gesbert, in IEEE Wireless Communications Magazine, Feb. 2013.

The Essence of this Talk

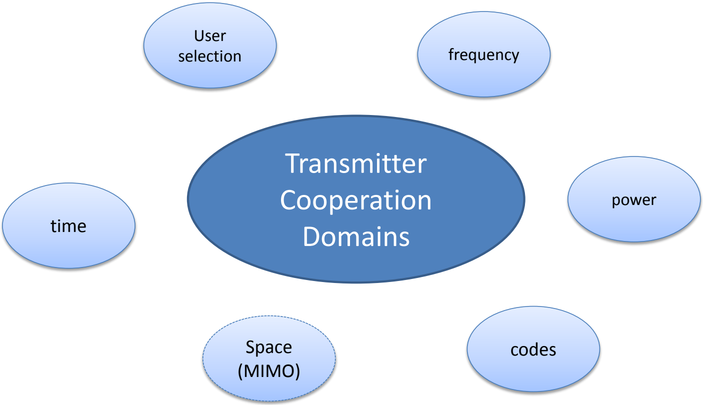
Outline

Outline

The Dimensions of Interference Management



Transmitter Cooperation Domains



Example 1: Interference Coordination using Scheduling and Power Control

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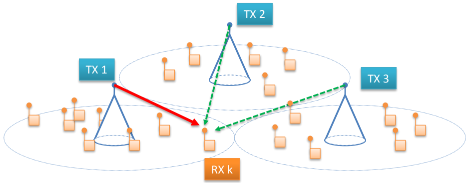
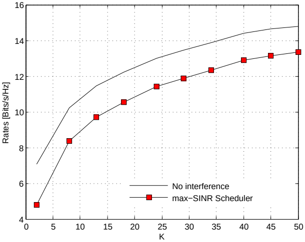
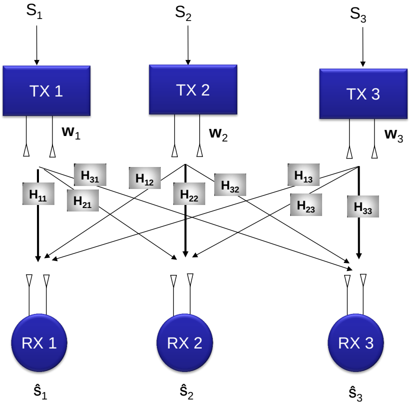




- Distributed max-SINR scheduler exploits the variability (fading) of interference
- Power control/beamforming couples the decisions at all cells

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]

Interference Alignment: Algorithm Design

Exploiting uplink downlink duality of alignment [Gomadam et al., 2011, TIT]

- Notations:
  - Let $\mathbf{U}_i$ be the RX filter at RX i
  - Let $\mathbf{W}_j$ be the TX precoder at TX j
  - Let I_i be the total noise summed at RX i, with covariance $\mathbf{Q}_i$
- Algorithm:
  1. Take $\mathbf{U}_i$ as minimum eigenvector of $\mathbf{Q}_i$, $\forall i$
  2. Use $\mathbf{U}_i$ as TX precoder from RX i, on reciprocal channel
  3. Take $\mathbf{W}_i$ as RX vector at TX i, on reciprocal channel
  4. Find $\mathbf{W}_i$ as minimum eigenvector of noise covariance matrix at base i
  5. iterate

Interference Alignment: Finite SNR

- IA is optimal at infinite SNR case only
- At finite SNR, key is to balance interference canceling with desired signal enhancement
  - Maximum SINR [Gomadam et al., 2011, TIT]
  - Minimum MSE [Peters and Heath, 2011, TVT]
  - Maximum sum rate [Santamaría et al., 2010, GLOBECOM]
  - Game theoretic approach (Altruism vs. Egoism) [Ho and Gesbert, 2010, ICC]
  - ...

Example 3: Cooperation with Joint MIMO Precoding

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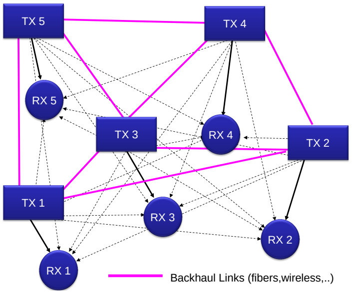
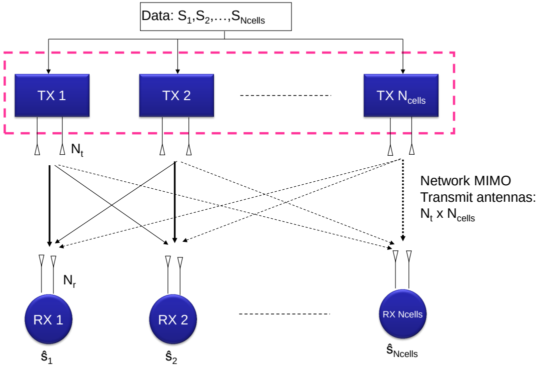
- Joint MIMO Precoding [Hanly, 1993] [Shamai and Zaidel, 2001, VTC]





How does Joint MIMO Precoding Work?

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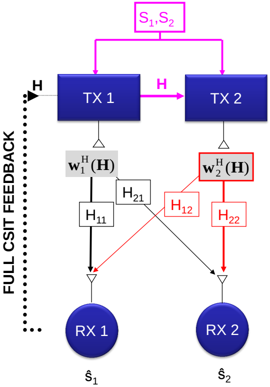

Ideal Network MIMO

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

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

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

Performance Modeling of Joint Precoding

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- Transmission from K TXs to K RXs where the ith TX and the ith RX are equipped respectively with M_i and N_i antennas

$$N_{\text{tot}} \triangleq \sum_{i=1}^{K} N_i, \qquad M_{\text{tot}} \triangleq \sum_{i=1}^{K} M_i$$

- Multi-user channel $\mathbf{H}^{\mathrm{H}} \in \mathbb{C}^{N_{\text{tot}} \times M_{\text{tot}}}$
- $\mathbf{H}_{ik}^{\mathrm{H}} \in \mathbb{C}^{N_i \times M_k}$ channel matrix from TX k to RX i with its elements i.i.d. as $\mathcal{CN}(0, \rho_{ik}^2)$
- Perfect CSI at the RXs treating interference as noise
- Linear precoding and filtering

Received Signal

- Received signal

$$\begin{bmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_K \end{bmatrix} = \mathbf{H}^{\mathrm{H}} \boldsymbol{x} + \boldsymbol{\eta} = \begin{bmatrix} \mathbf{H}_1^{\mathrm{H}} \\ \vdots \\ \mathbf{H}_K^{\mathrm{H}} \end{bmatrix} \begin{bmatrix} \boldsymbol{t}_1 & \dots & \boldsymbol{t}_K \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_K \end{bmatrix} + \begin{bmatrix} \boldsymbol{\eta}_1 \\ \vdots \\ \boldsymbol{\eta}_K \end{bmatrix}$$

with $\|\boldsymbol{t}_i\|^2 = P, \forall i$, s_i i.i.d. $\mathcal{N}_{\mathbb{C}}(0,1)$ and $\boldsymbol{\eta}_i$ i.i.d. $\mathcal{N}_{\mathbb{C}}(\mathbf{0}, \mathbf{I}_{N_i})$

Received Signal

- Received signal

$$\begin{bmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_K \end{bmatrix} = \overbrace{\mathbf{H}^{\mathrm{H}}}^{\text{Channel matrix } (N_{\text{tot}} \times M_{\text{tot}})} \boldsymbol{x} + \boldsymbol{\eta} = \overbrace{\begin{bmatrix} \mathbf{H}_1^{\mathrm{H}} \\ \vdots \\ \mathbf{H}_K^{\mathrm{H}} \end{bmatrix}}^{\text{Channel matrix } (N_{\text{tot}} \times M_{\text{tot}})} \begin{bmatrix} \boldsymbol{t}_1 & \dots & \boldsymbol{t}_K \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_K \end{bmatrix} + \begin{bmatrix} \boldsymbol{\eta}_1 \\ \vdots \\ \boldsymbol{\eta}_K \end{bmatrix}$$

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with $\|\boldsymbol{t}_i\|^2 = P, \forall i$, s_i i.i.d. $\mathcal{N}_{\mathbb{C}}(0,1)$ and $\boldsymbol{\eta}_i$ i.i.d. $\mathcal{N}_{\mathbb{C}}(\mathbf{0}, \mathbf{I}_{N_i})$

Received Signal

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- Received signal

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with $\|\boldsymbol{t}_i\|^2 = P, \forall i$, s_i i.i.d. $\mathcal{N}_{\mathbb{C}}(0,1)$ and $\boldsymbol{\eta}_i$ i.i.d. $\mathcal{N}_{\mathbb{C}}(\mathbf{0}, \mathbf{I}_{N_i})$

Received Signal

EURECOM

- Received signal

Noise at the RXs ($N_{\text{tot}} \times 1$)

$$\begin{bmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_K \end{bmatrix} = \mathbf{H}^{\mathrm{H}} \boldsymbol{x} + \boldsymbol{\eta} = \begin{bmatrix} \mathbf{H}_1^{\mathrm{H}} \\ \vdots \\ \mathbf{H}_K^{\mathrm{H}} \end{bmatrix} \begin{bmatrix} \boldsymbol{t}_1 & \dots & \boldsymbol{t}_K \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_K \end{bmatrix} + \overbrace{\begin{bmatrix} \boldsymbol{\eta}_1 \\ \vdots \\ \boldsymbol{\eta}_K \end{bmatrix}}$$

with $\|\boldsymbol{t}_i\|^2 = P, \forall i$, s_i i.i.d. $\mathcal{N}_{\mathbb{C}}(0,1)$ and $\boldsymbol{\eta}_i$ i.i.d. $\mathcal{N}_{\mathbb{C}}(\mathbf{0}, \mathbf{I}_{N_i})$

Figures-of-Merit

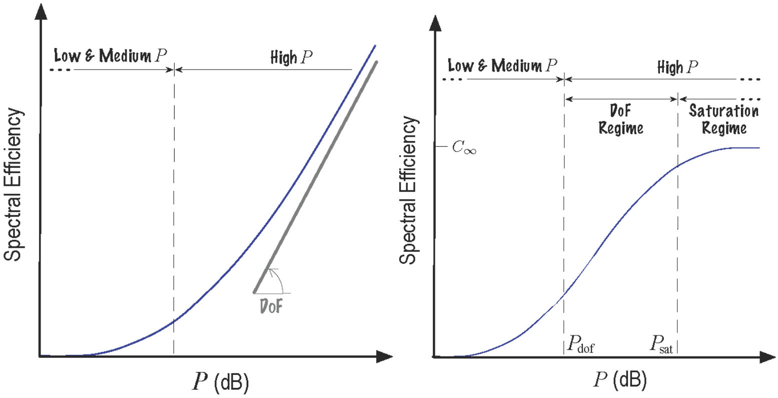
- Average rate of user i given by [Cover and Thomas, 2006]

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

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

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

Myth and Reality of Transmitter Cooperation



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

Outline

Thinking practical

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

- Hardware impairments
- Channel estimation and tracking
- Feedback limitation
- Inter-transmitter signaling limitation

Channel Estimation

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- Usually relying on a pilot training phase [Hassibi and Hochwald, 2003, TIT],[Caire et al., 2010, TIT]
  - TX transmits α pilots per antenna ($\alpha \geq 1$)
  - Received signals
$$\boldsymbol{y} = \sqrt{\alpha P}\boldsymbol{h} + \boldsymbol{\eta}$$
  - MSE channel estimate
$$\hat{\boldsymbol{h}} = \frac{\sqrt{\alpha P}}{N_0 + \alpha P}\boldsymbol{y}$$
  - This yields [Caire et al., 2010, TIT]
$$\boldsymbol{h} = \hat{\boldsymbol{h}} + \tilde{\boldsymbol{h}}$$

with $\tilde{\boldsymbol{h}} \sim \mathcal{N}_{\mathbb{C}}(0, \frac{1}{1+\frac{\alpha P}{N_0}})$ being independent of $\hat{\boldsymbol{h}}$

➥ Challenging in massive MIMO [Jose et al., 2011, TWC]

Hardware Impairments

- Transceiver impairments leads to a modified RX signal model [Studer et al., 2010, WSA],[Bjornson et al., 2012, WSA]

$$\boldsymbol{y} = \sqrt{P}\mathbf{H}\left(\boldsymbol{x} + \eta\right) + \boldsymbol{n}$$

  with $\boldsymbol{\eta} \propto \mathrm{tr}(\mathrm{E}[\boldsymbol{x}\boldsymbol{x}^{\mathrm{H}}])$ (radiated power)
- DoF is shown to be 0
- Need for robust signal processing taking the imperfections into accounts [Bjornson et al., 2012, GLOBECOM]

Modeling Feedback Limitation in TX Cooperation

- Quantized feedback
- Noisy analog feedback
- Delayed feedback

Imperfect Centralized CSIT

- Imperfect CSIT at the TX modeled as [Wagner et al., 2012, TIT]

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

  where $\{\mathbf{\Delta}\}_{ik} \sim \mathcal{CN}(0, 1)$
- CSIT allocation $\mathbf{B}$ defined as

$$\{\mathbf{B}\}_{ik} = B_{ik}, \qquad \forall i, k$$

Quantized Feedback in MU-MIMO

Assume a total of M antennas across all cooperating BS, single antenna users

- No feedback

Theorem ([Jafar and Goldsmith, 2005, TIT])

With no CSIT, then DoF $\to 1$

- Quantized feedback

Theorem ([Jindal, 2006, TIT])

Assume Random Vector Quantization with B bits used to encode the channel of one user. Then $B \geq \alpha(M-1)\log(\mathrm{SNR})$ *is sufficient to achieve DoF of* $M\alpha$.

Crucial assumption: The quantized feedback is ideally shared across all transmit antennas.

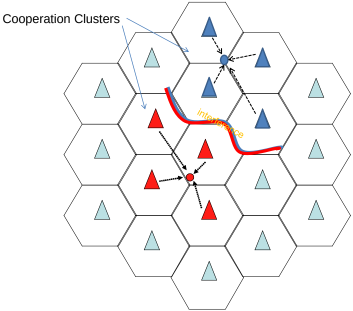
CSIT in Interference Alignement

- Current IA schemes are based on
  - CSIT feedback followed exchange across links
  - Pilot based CSI estimation + TX-RX iterations
  - Direct broadcast of the estimates [Ayach and Heath, 2012, TWC]
- Quantized feedback in Interference Alignement
  - Similar results as broadcast channels apply (feedback bits must grow with $K(MN-1)\log SNR$, to achieve maximum DoF) [Thukral and Boelcskei, 2009, ISIT]
  - Possible to improve over this feedback rate by exploiting rotational invariance [Rezaee and Guillaud, 2012, ITW]

Inter-transmitter Signaling Limitation

- Virtually all cooperation methods require shared channel state information at the transmitters (CSIT)
- Perfect sharing of CSIT is not scalable in large networks
- In some networks inter-TX links are capacity limited (e.g. wireless backhaul, corgnitive radios)
- Any exchange of CSIT is likely to induce latency and/or quantization $\rightarrow$ TX-dependent CSIT noise

Transmitter Cooperation with Clustering



Approaches:

- Network-centric clustering
- User-centric clustering [Papadogiannis et al., 2008, ICC]

Limitations:

- Cluster too big: feedback sharing overhead heavy [Lozano et al., 2013, TIT]
- Cluster too small: edge-effects (inter-cluster interference) predominant

Limited Signaling: Backhaul Quantization Model

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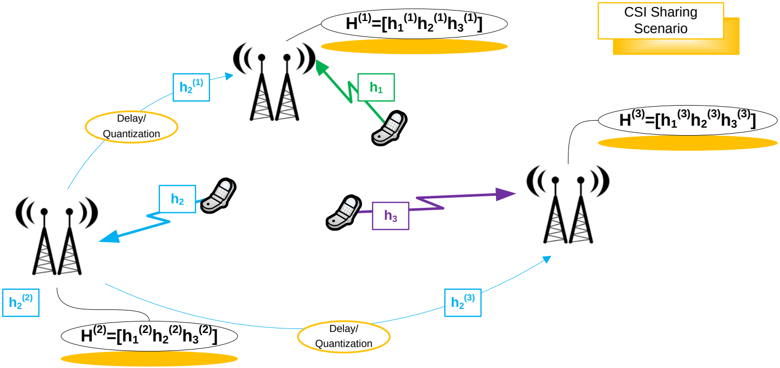
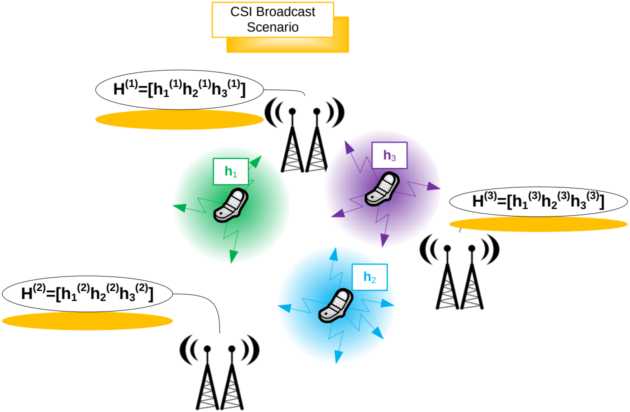
- Backhaul signaling introduces delays and possible quantization noise
- LTE compliant feedback: User feeds back to its home eNB only



Over-the-air Signaling: Feedback Broadcast

- CSIT can be shared directly over-the-air without backhaul links



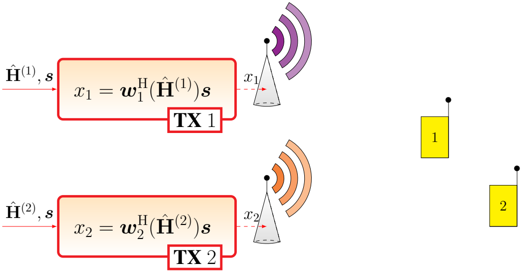
A Distributed Channel State Information Model

- Imperfect CSIT at TX j modeled as

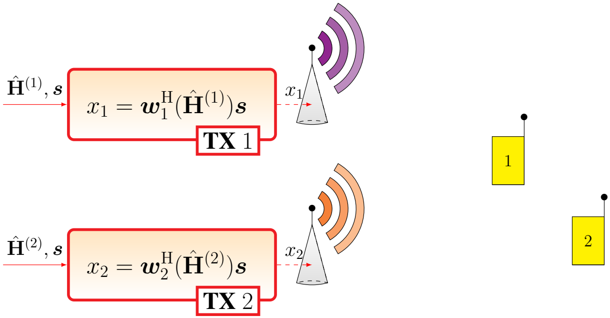
$$\{\hat{\mathbf{H}}^{(j)}\}_{i,k} = \sqrt{1 - 2^{-B_{i,k}^{(j)}}}\sigma_{i,k}\{\mathbf{H}\}_{i,k} + \sqrt{2^{-B_{i,k}^{(j)}}}\sigma_{i,k}\{\mathbf{\Delta}\}_{i,k}^{(j)}, \qquad \forall i, k$$

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

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



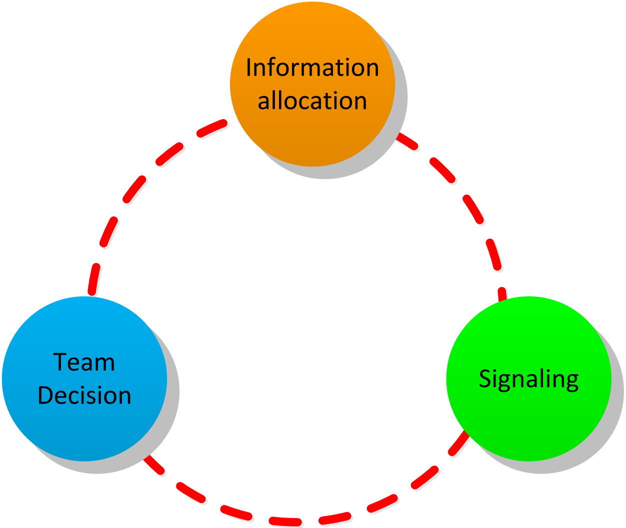
Joint Precoding with Distributed CSIT



Key questions:

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 $\boldsymbol{w}_1(\mathbf{H}^{(1)})$ and $\boldsymbol{w}_2(\mathbf{H}^{(2)})$ be designed?

Three Coordination Problems



Outline

Wireless Coordination Problems

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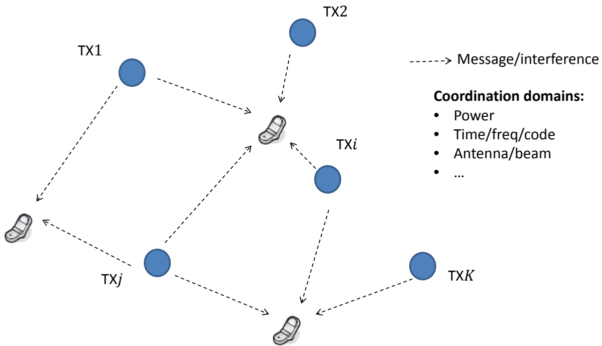
- K nodes in a network seek to cooperate towards the maximization of a common utility
- Each node i must make best decision based on:
  - local measurement or feedback
  - finite rate signaling with neighbor nodes

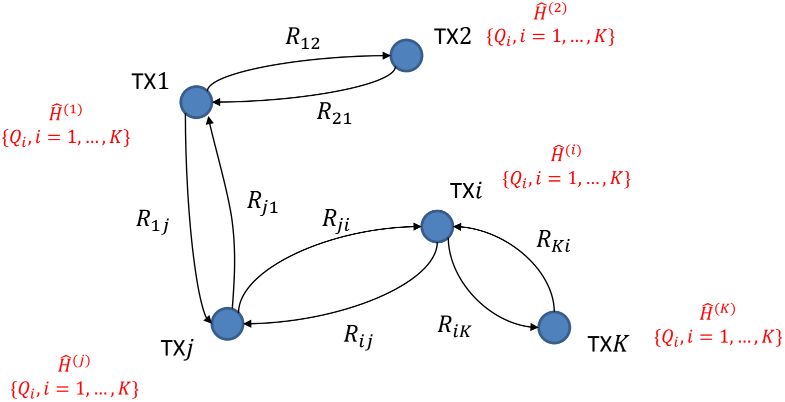


Coordination Problems

The coordination problem is decomposed into three related optimizations:

- Problem 1: Channel state information allocation
  - What should the local information $\hat{\mathbf{H}}^{(i)}$ be? (under a typical feedback constraint)
  - How uncorrelated can it be?
- Problem 2: Signaling
  - What to communicate over R_{ij} bits? $\rightarrow Z_{ij}$
  - Very challenging as it involves second problem
- Problem 3: (Team) decision making
  - $W_i(\hat{\mathbf{H}}^{(i)}, Q_1, Q_2, ..Q_K, Z_{1i}, Z_{2i}, ..Z_{Ki})$
  - Team decision optimization (challenging enough..)

One-shot Coordination Graph



A priori information:

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

Q_i: Error covariance

Coordination link rates:

From i to j: R_{ij}

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 $\hat{\mathbf{H}}^{(i)} \neq \hat{\mathbf{H}}^{(j)}$.

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

Some Distributed Information Structures

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- **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 $\hat{\mathbf{H}}^{(i_1)} \subset \hat{\mathbf{H}}^{(i_2)} \subset \hat{\mathbf{H}}^{(i_3)} \subset ...$
- **Master Slave**: Hierarchical where $\hat{\mathbf{H}}^{(i_1)} = []$, and $\hat{\mathbf{H}}^{(i_2)} = \mathbf{H}$ (can be extended to $K > 2$.)

Typical Distributed Information Structures

Consider the K transmitter (N antennas each) K user (single antenna) channel. Let $\boldsymbol{h}_{ij}^{\mathrm{H}}$ be the $1 \times N$ vector channel between the jth transmitter and the ith user.

- Local CSIT with TDD reciprocity

$$(\hat{\mathbf{H}}^{(j)})^{\mathrm{H}} = \begin{bmatrix} \mathbf{0} & \boldsymbol{h}_{1j}^{\mathrm{H}} & \mathbf{0} \\ \vdots & \vdots & \vdots \\ \mathbf{0} & \boldsymbol{h}_{Kj}^{\mathrm{H}} & \mathbf{0} \end{bmatrix}$$

- Local CSIT with LTE feedback mode

$$(\hat{\mathbf{H}}^{(j)})^{\mathrm{H}} = \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \boldsymbol{h}_{j1}^{\mathrm{H}} & \dots & \boldsymbol{h}_{jK}^{\mathrm{H}} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix}$$

- Fully local CSIT

$$(\hat{\mathbf{H}}^{(j)})^{\mathrm{H}} = \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \boldsymbol{h}_{jj}^{\mathrm{H}} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix}$$

Problem 2: Signaling for Coordination

What is most relevant to communicate of the signaling link?

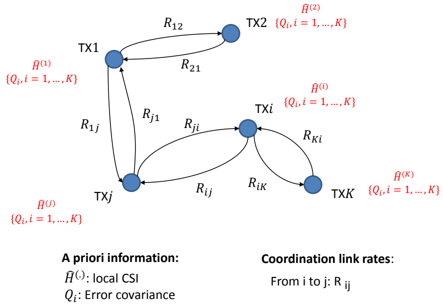
- Many interesting heuristics (precoding decisions, measurements, etc.)
- Optimal signaling an open problem
- Optimal signaling strategy coupled with optimum decision making W_i

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 $\mathbf{Q}_i$!
  3. Exploit coordination graph for CSI improvement:
     - Use R_{ij} bit signaling to create optimal estimates $\hat{\hat{\mathbf{H}}}^{(i)}$
- 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]

Some Open Problems

- Coordination over more than one shot
  - No constraint over number bits exchanged: Convergence? Speed?
  - Constraint on total number of bits exchanged
    - With more signaling slots, opportunity to learn from past actions
    - With fewer signaling slots, less latency effects
- Implicit coordination [Larrousse and Lasaulce, 2013, ISIT]
- Sequential coordination over the graph

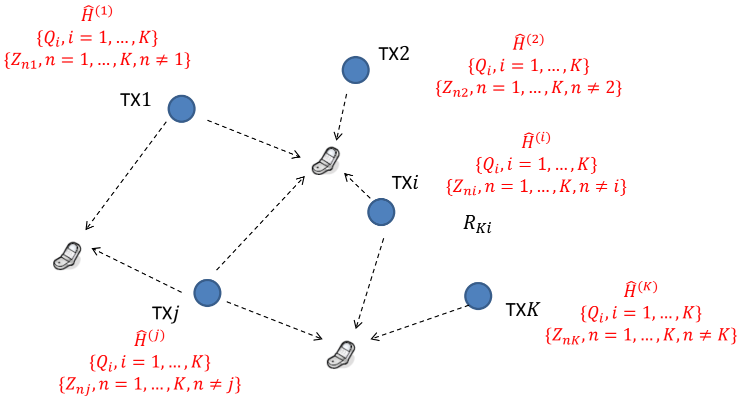


Problem 3: Team Decisional Coordination

Team Decision theoretic problems:

- 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
- Classical "robust" design does not work...
- Introduced first in economics and control [Ho, 1980, IEEE], recently in wireless [Zakhour and Gesbert, 2010, ITA]

Team Decision with Finite Signaling



Local information at TXi after signaling

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

Q_i: Error covariance, i=1..K

Z_{mi}: Coordination signal from TXm to TXi

Decision making: Example, precoder W i

Team Decision Theory: Buying a Baguette or not?

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In 1936, a french 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*

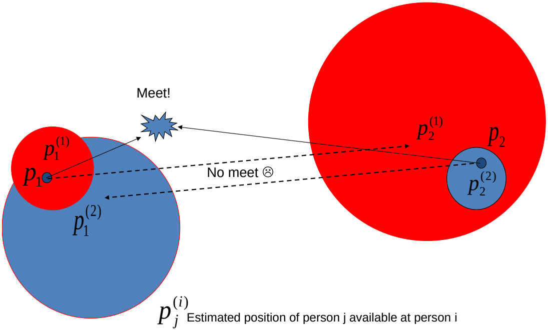
When should each person buy bread?

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

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

The Distributed Rendez-vous Problem

- Two visitors arrive independently in Firenze 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*



Team Decisional Transmitter Cooperation

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Let us consider the following K-transmitter framework:

1. Distributed information structure:
   Each transmitter i has knowledge of $\hat{\mathbf{H}}^{(i)}$, which exhibits *some* arbitrary correlation with $\mathbf{H}$
2. Zero rate coordination links (R_{ij})
3. Decision space for each transmitter i
   Example: $\mathbf{W}_i(\hat{\mathbf{H}}^{(i)})$ where $\mathbf{w}_i$ is a complex matrix. (e.g. $\mathbf{W}_i \in \mathbb{C}^{N \times K}$ for K-user network MIMO)
4. A network utility

$$u = \sum_{i=1}^{K} u_i(\mathbf{W}_1(\hat{\mathbf{H}}^{(1)}), .., \mathbf{W}_K(\hat{\mathbf{H}}^{(K)}), \mathbf{H})$$

Can Team Problems be Solved with Games?

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Key idea: Let autonomous transmitting devices interact to solve their interference conflicts

Players → transmitters

Actions → transmit decision (power, frequency, beam, ..)

Strategy → Utility maximization (max rate, min power, min delay,..)

Timing → simultaneous, sequential,..

Equilibrium → Nash, Stackelberg, Nash Bargaining,..

From Selfish Games to "Team Playing"

Why interference coordination can be different from a typical "game"':

- Team agents (network nodes) are not conflicting players (different from players in a cooperative game)
- Agents seek maximization of the same network utility
- It is the lack of shared information which hinders cooperation, not the selfish of their interests
- Agents are not required to improve over the performance of the Nash equilibrium
- 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).

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

Model-based Decision Making

The model-based approach:

- Replace $\mathbf{w}_i(\hat{\mathbf{H}}^{(i)})$ by $\mathbf{f}(\mathbf{a}_i, \hat{\mathbf{H}}^{(i)})$ where $\mathbf{f}(.,.)$ is a functional model and $\mathbf{a}_i$ a vector of deterministic parameters to be determined at transmitter i.
- Solve for (still hard ;-))

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

Solving the Problem

We now target the following problems:

- What information is really needed where?
- Distributed cooperative precoding: conventional and robust solutions

We use the following approaches:

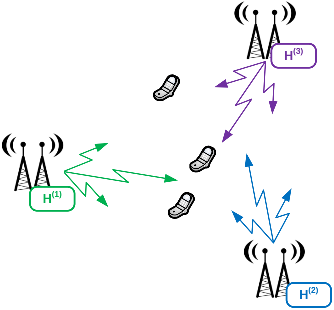
- The high SNR regime
- The large scale analysis

Outline

Information Allocation

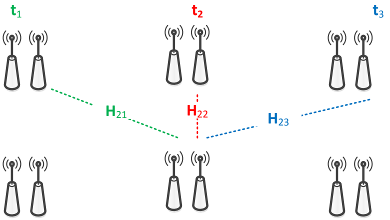
- Study here the CSI feedback allocation problem
- No signaling possible between TXs
- Intuitively: CSI allocation should be TX dependent

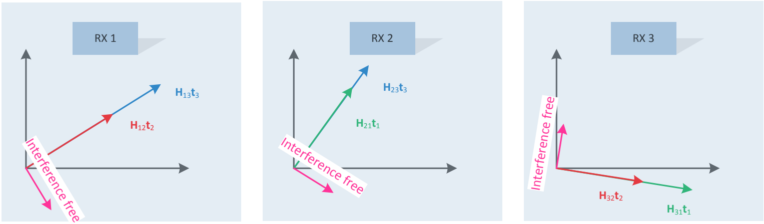
➥ Can we quantify this intuition?



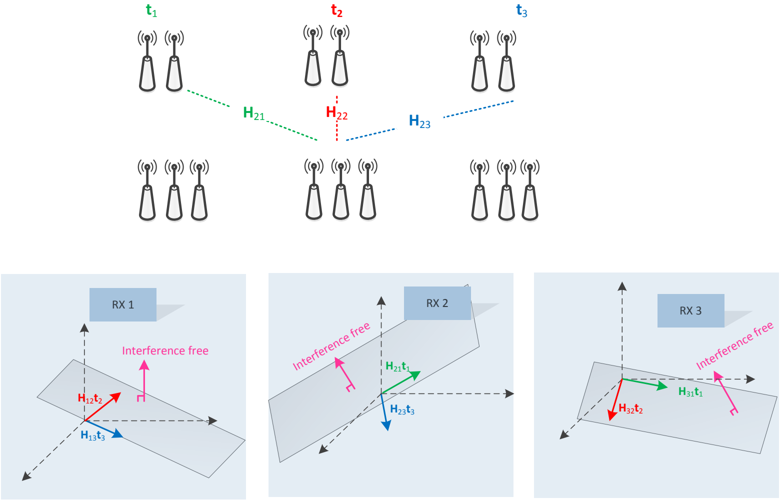
- Is it optimal for each TX to receive the same information?
- How does the required information accuracy depend on the network geometry?

Key Intuition with IA





Key Intuition with IA



Exploiting Distributed Precoding

Can we reduce the CSIT requirements in general antenna configurations without additional antennas?

Model for Incomplete CSIT

- $\mathbf{H}_{ik}$ 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 matrix such that

$$\hat{\mathbf{H}}^{(j)} = \mathbf{F}^{(j)} \odot \mathbf{H}$$

- $\mathrm{Size}(\mathcal{F})$ the size of a CSIT allocation $\mathcal{F} = \{\mathbf{F}^{(j)} | j = 1, \ldots, K\}$

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

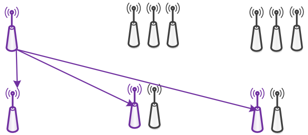
Example

- $(1,1)(2,3)(2,3)$ IC:
  - Conventional CSIT allocation

$$\mathbf{F}^{(1)} = \mathbf{F}^{(2)} = \mathbf{F}^{(3)} = \mathbf{1}_{5\times 7}$$

  - IA possible with

$$\mathbf{F}^{(1)} = \mathbf{0}_{5\times 7}, \mathbf{F}^{(2)} = \mathbf{1}_{5\times 7}, \mathbf{F}^{(3)} = \mathbf{1}_{5\times 7}$$



Minimal CSIT Allocation

- $\mathcal{F}_{\text{comp}}$ complete CSIT allocation:

$$\mathrm{Size}\left(\mathcal{F}_{\text{comp}}\right) = K\left(\mathrm{Size}\left(\mathbf{1}_{N_{\text{tot}} \times M_{\text{tot}}}\right)\right)$$

- Study only feasible settings: IA feasible with $\mathcal{F}_{\text{comp}}$
- Study only single-streams transmissions

Optimization Problem

Find the most incomplete CSIT allocation where IA remains feasible

Tightly-Feasible and Super-Feasible Settings

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Definition

Tightly-feasible IC $\Leftrightarrow$ feasible IC and removing any antenna makes IA unfeasible$\Leftrightarrow$ feasible and $\sum_{i=1}^{K} N_i + M_i = K(K+1)$

Definition

Super-feasible IC $\Leftrightarrow$ feasible IC and it is possible to remove at least one antenna without making IA unfeasible

Definition

A sub-IC is the (generalized) IC formed by any subset $\mathcal{S}_{\text{RX}}$ of RXs and any subset $\mathcal{S}_{\text{TX}}$ of TXs

Feasibility Condition

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Theorem (reformulation of [Razaviyayn et al., 2012, TSP])

IA is feasible if and only if,

$$\mathcal{N}_{\text{var}}(\mathcal{S}_{\text{RX}},\mathcal{S}_{\text{TX}}) \geq \mathcal{N}_{\text{eq}}(\mathcal{S}_{\text{RX}},\mathcal{S}_{\text{TX}}), \quad \forall \mathcal{S}_{\text{TX}},\mathcal{S}_{\text{RX}} \subseteq \{1,\ldots,K\}$$

where

$$\mathcal{N}_{\text{var}}(\mathcal{S}_{\text{RX}},\mathcal{S}_{\text{TX}}) \triangleq \sum_{i\in\mathcal{S}_{\text{RX}}} N_i - 1 + \sum_{i\in\mathcal{S}_{\text{TX}}} M_i - 1$$

$$\mathcal{N}_{\text{eq}}(\mathcal{S}_{\text{RX}},\mathcal{S}_{\text{TX}}) \triangleq \sum_{k\in\mathcal{S}_{\text{TX}}} \sum_{j\in\mathcal{S}_{\text{RX}},j\neq k} 1$$

Tightly Feasible Setting

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Theorem

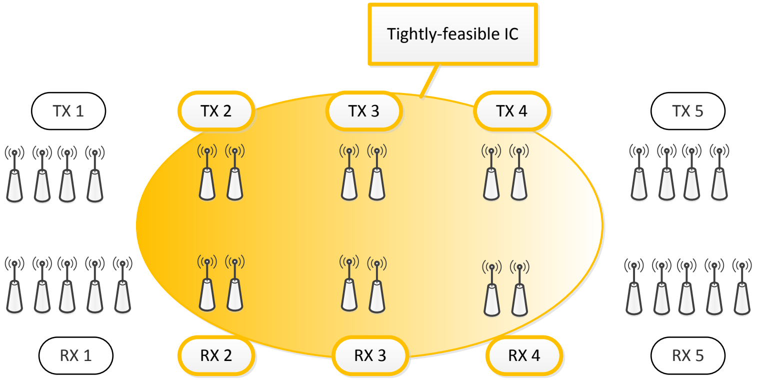
In a tightly-feasible $[\prod_{k=1}^{K}(N_k, M_k)]$ IC, if there exists a tightly-feasible sub-IC formed by the set of TXs $\mathcal{S}_{\text{TX}}$ and the set of RXs $\mathcal{S}_{\text{RX}}$, i.e.,

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

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

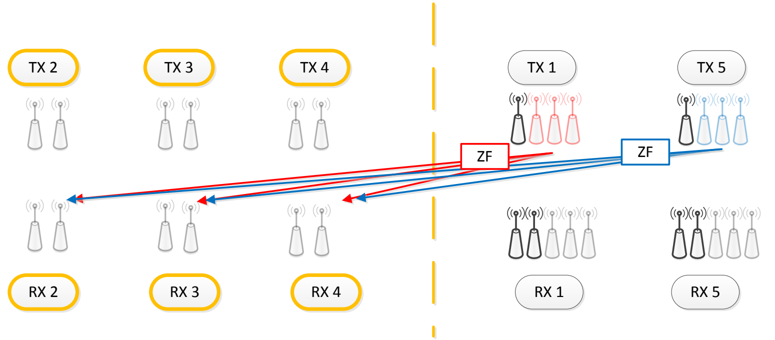
$$\begin{aligned}
\mathbf{F}^{(j)} &= \mathbf{F}_{\mathcal{S}_{\text{RX}},\mathcal{S}_{\text{TX}}}, && \forall j \in \mathcal{S}_{\text{TX}} \\
\mathbf{F}^{(j)} &= \mathbf{F}_{\mathcal{K},\mathcal{K}} = \mathbf{1}_{N_{\text{tot}} \times M_{\text{tot}}}, && \forall j \notin \mathcal{S}_{\text{TX}}.
\end{aligned}$$

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



Remark: Tightly-feasible approach exploits heterogeneity of antenna configuration

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



- CSIT allocation for tightly-feasible and super-feasible settings in [de Kerret and Gesbert, 2014b, TWC]

Remark: Tightly-feasible approach exploits heterogeneity of antenna configuration

Super-feasible Settings

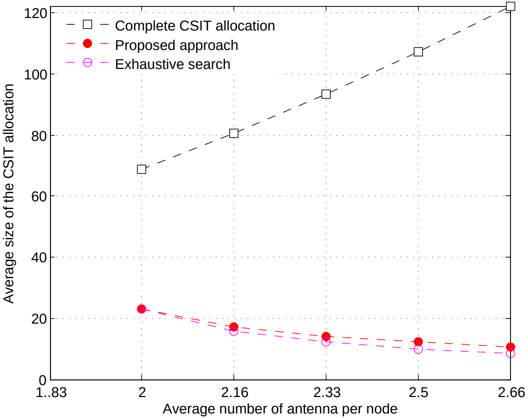


Figure: Average feedback size for $K = 3$ users with the antennas allocated uniformly at random to the TXs and the RXs

Key Aspects

- Perfect IA possible without full CSIT sharing
- Adapted CSI allocation provides strong gains with no DoF reduction
- In fact, we also designed a new IA algorithm: Joint CSI allocation/precoding design

CSIT Reduction in Centralized IA

- Large literature on IA feasibility assume perfect centralized CSIT [Razaviyayn et al., 2012, TSP],[Gonzalez et al., 2014, TIT]
- Previous intuition developed in [Rao et al., 2013, TSP]
  - Investigate trade-off Antenna/CSI/DoF
  - Propose new precoding schemes and new IA feasibility conditions
- Exploit Grassmanian invariance to reduce feedback from the RXs [Rezaee and Guillaud, 2012, ITW]

Exploiting Distributed Precoding

- CSI exchange is reduced by using iterative exchange between TXs in [Cho et al., 2012, TSP]
  - Only for particular stream/antenna configurations
  - Requires iterations between the TXs/RXs

Outline

TX Cooperation in Large Networks

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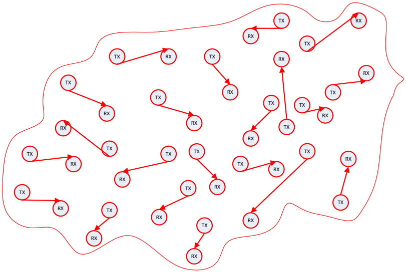
- Joint precoding: user's data symbols are shared
- Consider large networks: TX cooperation even more challenging
  - Channel estimation
  - CSI exchange
  - Amount of CSI increases quickly
- Recent results suggest that even with perfect transmitter cooperation, performances are fundamentally limited as the network size increases [Lozano et al., 2013, TIT]

Is it possible to manage interference via TX cooperation in asymptotically large networks?

Goal

- Find a CSIT allocation verifying
  - TX coordination: Global interference management
  - Scalability: Two users asymptotically far away should not exchange any CSI



Received Signal

- Received signal

$$\begin{bmatrix} \boldsymbol{y}_1 \\ \vdots \\ \boldsymbol{y}_K \end{bmatrix} = \mathbf{H}^{\mathrm{H}} \boldsymbol{x} + \boldsymbol{\eta} = \begin{bmatrix} \boldsymbol{h}_1^{\mathrm{H}} \\ \vdots \\ \boldsymbol{h}_K^{\mathrm{H}} \end{bmatrix} \begin{bmatrix} \boldsymbol{t}_1 & \dots & \boldsymbol{t}_K \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_K \end{bmatrix} + \begin{bmatrix} \eta_1 \\ \vdots \\ \eta_K \end{bmatrix}$$

with

- $\|\boldsymbol{t}_i\|^2 = P, \forall i$
- s_i i.i.d. $\mathcal{N}_{\mathbb{C}}(0, 1)$
- η_i i.i.d. $\mathcal{N}_{\mathbb{C}}(0, 1)$

Generalized DoF and Interference Level Matrix

- Define the generalized DoF

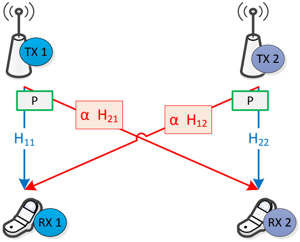
$$\mathrm{DoF}_i(\mathbf{\Gamma}) \triangleq \lim_{P\to\infty} \frac{R_i}{\log_2(P)} \quad \text{, subject to } \sigma_{i,j}^2 = P^{-\{\mathbf{\Gamma}\}_{i,j}}, \quad \forall i, j$$

- Define $\mathbf{\Gamma} \in [0, \infty]^{K\times K}$ the interference level matrix
- $\mathbf{\Gamma}$ represents the network geometry:
  - Transmission at SNR P_0 with channel variances $\sigma_{i,j,0}^2$
  - Define $\mathbf{\Gamma}$ as

$$\Gamma_{i,j} \triangleq -\frac{\log(\sigma_{i,j,0}^2)}{\log(P_0)}, \qquad \forall i, j$$

Example (Generalized DoF)

- 2-user IC, single-antenna nodes, $\alpha^2 = 10^{-12}$, $H_{i,j} \sim \mathcal{N}_{\mathbb{C}}(0,1)$



- DoF analysis: $\text{DoF}_i = 0.5$ [Etkin et al., 2008, TIT]
- Generalized DoF analysis: For $P = 20dB$,

$$\mathbf{\Gamma} = \begin{bmatrix} 0 & 6 \\ 6 & 0 \end{bmatrix}$$

and $\text{DoF}_i(\mathbf{\Gamma}) = 1$

Distributed CSIT

- Imperfect CSIT at TX j modeled as

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

  where $\{\mathbf{\Delta}\}_{i,k}^{(j)} \sim \mathcal{CN}(0,1)$
- CSIT allocation $\mathbf{B}^{(j)}$ at TX j defined as $\{\mathbf{B}^{(j)}\}_{i,k} = B_{i,k}^{(j)}, \qquad \forall i, k$
- CSIT allocation characterized by $\{\mathbf{B}^{(j)}\}_{j=1}^{K}$

Distributed Zero Forcing

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

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

- TX j transmits only $x_j = \boldsymbol{e}_j^{\mathrm{H}} \mathbf{T}^{(j)} \boldsymbol{s}$ such that

$$\mathbf{T}^{\mathrm{DCSI}} \triangleq \begin{bmatrix} \boldsymbol{e}_1^{\mathrm{H}} \mathbf{T}^{(1)} \\ \boldsymbol{e}_2^{\mathrm{H}} \mathbf{T}^{(2)} \\ \vdots \\ \boldsymbol{e}_K^{\mathrm{H}} \mathbf{T}^{(K)} \end{bmatrix}$$

Size of the CSIT Allocation

- Size of the CSIT allocation $\mathbf{B}^{(j)}$ at TX j

$$\mathrm{Size}(\mathbf{B}^{(j)}) \triangleq \lim_{P \to \infty} \frac{\sum_{i,k} B_{i,k}^{(j)}}{\log_2(P)}.$$

- Size of the CSIT allocation $\{\mathbf{B}^{(j)}\}_{j=1}^{K}$

$$\mathrm{Size}(\{\mathbf{B}^{(j)}\}_{j=1}^{K}) \triangleq \sum_{j=1}^{K} \mathrm{Size}(\mathbf{B}^{(j)})$$

Optimization Problem

- DoF-achieving CSIT allocation $\mathbb{B}_{\text{DoF}}(\mathbf{\Gamma})$ as

$$\mathbb{B}_{\text{DoF}}(\mathbf{\Gamma}) \triangleq \{\{\mathbf{B}^{(j)}\}_{j=1}^{K} | \forall i, \text{DoF}_i(\{\mathbf{B}^{(j)}\}_{j=1}^{K}, \mathbf{\Gamma}) = 1\}$$

with $\mathbf{\Gamma} \in [0, \infty]^{K \times K}$ the interference level matrix

Optimization problem

$$\text{minimize } \text{Size}\left(\{\mathbf{B}^{(j)}\}_{j=1}^{K}\right), \text{ subject to } \{\mathbf{B}^{(j)}\}_{j=1}^{K} \in \mathbb{B}_{\text{DoF}}(\mathbf{\Gamma}).$$

Conventional CSIT Allocation

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Proposition

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

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

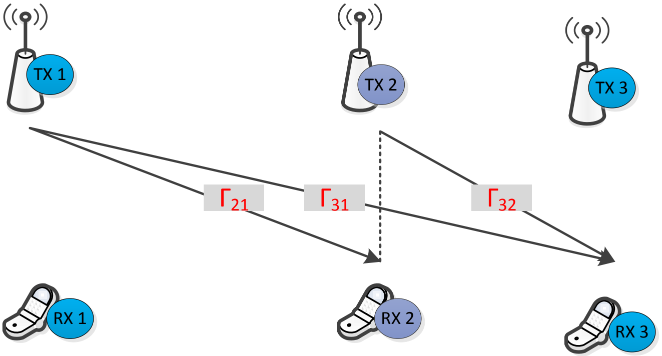
is DoF achieving, i.e., $\{\mathbf{B}^{\text{conv},(j)}\}_{j=1}^{K} \in \mathbb{B}_{\text{DoF}}$.

Remark

$$\text{Size}(\mathbf{B}^{\text{conv},(j)}) \geq O(K), \qquad \forall j$$

Shortest Path: Example $\Gamma_{1\to3}$

Example



$$\Gamma_{1\to3} = \min\left(\Gamma_{2,1} + \Gamma_{3,2}, \Gamma_{3,1}\right).$$

Shortest Path

- Definitions
  - $(j, a_2 \ldots, a_{n-1}, k)$: Path from TX j to RX k
  - $\mathrm{L}(a_1, \ldots, a_n)$: Length of the path $(a_1, \ldots, a_n)$:

$$\mathrm{L}(a_1, \ldots, a_n) \triangleq \sum_{i=1}^{n-1} \Gamma_{a_{i+1}, a_i}$$

  - $\Gamma_{j \to k}$: Shortest path from TX j to RX k:

$$\Gamma_{j \to k} \triangleq \min_{(a_2 \ldots, a_{n-1})} \mathrm{L}(j, a_2 \ldots, a_{n-1}, k)$$

Distance Based CSIT Allocation

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

We define the Distance-based CSIT allocation $\{\mathbf{B}^{\text{dist},(j)}\}_{j=1}^{K}$

$$\{\mathbf{B}^{\text{dist},(j)}\}_{k,i} \triangleq \lceil [1-\Gamma_{k,i}-\gamma_{k,i}^{(j)}]^{+} \log_2(P) \rceil, \qquad \forall k,i,j$$

with

$$\gamma_{k,i}^{(j)} \triangleq \min\left(\Gamma_{k\to j}, \min_{\ell}\left(\Gamma_{\ell\to i}+\Gamma_{j,\ell}\right)\right)$$

Then $\mathbf{B}^{\text{dist}} \in \mathbb{B}_{\text{DoF}}$

Interpretation (1)

- $P^{-\Gamma_{k,i}}$ is the variance of the quantized element
- $\gamma_{k,i}^{(j)}$ is the CSIT reduction relative to $H_{k,i}$ at TX j
- $\gamma_{k,i}^{(j)} = \Gamma_{k\to j}$ gives

$$\mathrm{E}[\|\mathbf{e}_j^{\mathrm{H}}(\mathbf{H}^{(j)})^{-1}\mathbf{e}_i - \mathbf{e}_j^{\mathrm{H}}\mathbf{H}^{-1}\mathbf{e}_i\|^2] \doteq P^{-1}, \qquad \forall i$$

- $\gamma_{k,i}^{(j)} = \min_\ell \left(\Gamma_{\ell\to i} + \Gamma_{j,\ell}\right)$ gives

$$\mathrm{E}\left[\left|\|(\mathbf{H}^{(j)})^{-1}\mathbf{e}_i\|^2 - \|\mathbf{H}^{-1}\mathbf{e}_i\|^2\right|\right] \doteq P^{-1}, \qquad \forall i$$

Remark (Reminder)

$$\gamma_{k,i}^{(j)} \triangleq \min\left(\Gamma_{k\to j}, \min_\ell \left(\Gamma_{\ell\to i} + \Gamma_{j,\ell}\right)\right)$$

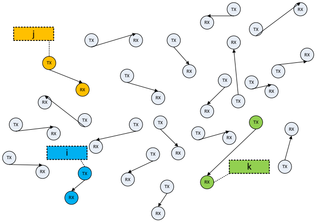
Interpretation (2)

- Symmetric: If $\Gamma_{k,i} = \Gamma_{i,k}, \forall i, k,$

$$\gamma_{k,i}^{(j)} = \min\left(\Gamma_{k \to j}, \Gamma_{i \to j}\right)$$

- Distance: If $\Gamma_{k,j} \leq \Gamma_{k,i} + \Gamma_{i,j}, \forall i, j, k,$

$$\Gamma_{k \to j} = \Gamma_{j,k}$$



Remark (Reminder)

$$\{\mathbf{B}^{\text{dist},(j)}\}_{k,i} \triangleq \lceil [1 - \Gamma_{k,i} - \gamma_{k,i}^{(j)}]^+ \log_2(P) \rceil, \qquad \forall k, i, j$$

Scaling Properties

- Denote by $\mathcal{K}_j$ the set containing the user's data symbols which have to be shared to TX j
- Assume symmetric interference level matrices
- Finite number of significant interferers

$$\lim_{K\to\infty} |\{i|\mathbf{\Gamma}_{i\to j} < 1\}| < \infty, \qquad \forall j$$

Corollary

$$\lim_{K\to\infty} \mathrm{Size}(\mathbf{B}^{\mathrm{dist},(j)}) < \infty, \qquad \forall j$$

Corollary

$$\lim_{K\to\infty} |\mathcal{K}_j| < \infty, \qquad \forall j$$

In Wireless Networks

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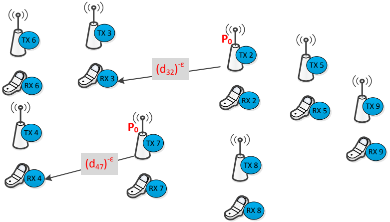

- Interference level matrix

$$\Gamma_{i,j} = -\frac{\log(d_{i,j}^{-\varepsilon})}{\log(P_0)}, \qquad \forall i,j$$

- It holds

$$\Gamma_{i,j} > 1, \qquad \text{if } d_{ij} > d_0$$

with

$$d_0 \triangleq P_0^{\frac{1}{\varepsilon}}$$

Global Coordination with Local Cooperation

- Corollaries apply:
  - ⇒ Each TX requires CSIT from only a neighborhood
  - ⇒ Each TX requires data symbols from only a neighborhood
- Distance-based CSIT allocation has the desired properties!

Hard boundary of clusters are replaced by a smooth decrease of the cooperation strength

Key Messages

- Provide each TX with the CSI needed
  - ➡ Uniform/conventional CSI allocation is very inefficient
  - ➡ Adapt to network geometry
- Overcome fundamental limitations of clustering
  - ➡ Achieve global coordination with local cooperation

Outline

Outline

Impact of Distributed CSIT

- First, fix precoding to ZF: avoid team decision problem
- Focus on performance evaluation
  - Results for centralized CSIT do not apply any longer
  - How can we relate CSI qualities to performance?
  - Little investigated: simulations results provided in [Fritzsche and Fettweis, 2011, VTC]

Are the guidelines for system designs impacted by distributed CSIT?

Distributed CSIT

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- Imperfect CSIT at TX j modeled as

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

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

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

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

Distributed Zero Forcing

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

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

- TX j transmits only $x_j = \boldsymbol{e}_j^{\mathrm{H}} \mathbf{T}^{(j)} \boldsymbol{s}$ such that

$$\mathbf{T}^{\mathrm{DCSI}} \triangleq \begin{bmatrix} \boldsymbol{e}_1^{\mathrm{H}} \mathbf{T}^{(1)} \\ \boldsymbol{e}_2^{\mathrm{H}} \mathbf{T}^{(2)} \\ \vdots \\ \boldsymbol{e}_K^{\mathrm{H}} \mathbf{T}^{(K)} \end{bmatrix}$$

DoF in the Centralized MIMO BC

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- MIMO BC with M antennas at the TX and M single-antenna RXs
- Channel estimate of channel to user i denoted by $\hat{\boldsymbol{h}}_i$ quantized using B_i bits
- CSI scaling coefficients $A_i \triangleq \lim_{P\to\infty} \frac{B_i}{(M-1)\log_2(P)}$ with $A_i \in [0,1]$
- DoF achieved by user i equal to [Jindal, 2006, TIT]

$$\text{DoF}_i = A_i$$

With distributed CSI, how does it extend?

Degrees of Freedom with Conventional ZF

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Theorem

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

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

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

An example of transmission using Conventional ZF

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- Feedback scaling coefficients:
  - At TX 1 $A_1^{(1)} = 1, A_2^{(1)} = 0$
  - At TX 2 $A_1^{(2)} = 1, A_2^{(2)} = 1$ *–essentially perfect–*
- ZF precoder $\mathbf{T}^\star$ with central perfect CSI:

$$\mathbf{T}^\star = \begin{bmatrix} 10.3181 - 10.4874i & -3.6281 - 7.0377i \\ 23.3905 + 7.3537i & 8.9583 + 6.2782i \end{bmatrix}$$

- At TX 1, computes

$$\mathbf{T}^{(1)} = \frac{(\mathbf{H}^{(2)})^{-1}\sqrt{P}}{\|(\mathbf{H}^{(2)})^{-1}\|_{\mathrm{F}}} = \begin{bmatrix} -3.6624 + 15.0075i & -0.5470 - 4.0157i \\ -24.8765 + 6.5603i & 6.4073 + 6.4812i \end{bmatrix}$$

- At TX 2, computes $\mathbf{T}^{(2)} \approx \mathbf{T}^\star$
- Precoding matrix used to transmit:

$$\mathbf{T} = \begin{bmatrix} -3.6624 + 15.0075i & -0.5470 - 4.0157i \\ 23.2421 + 6.7577i & 8.9867 + 6.2038i \end{bmatrix}$$

Impact of Distributed CSIT

- DoF
  - Strong impact over the DoF
  - Heterogeneous CSIT quality is disastrous

Need for new precoding paradigms when faced with distributed CSIT

Remark

Similar insights hold for Interference Alignment

Outline

Robust Precoding

- Distributed ZF very sensitive to CSI having unequal qualities
- Are there more robust precoding schemes?
- Consider here the Team Decision problem

Conventional Robust Zero Forcing

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- Robust counterpart from literature [Shenouda and Davidson, 2006, ICASSP]

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

with $\boldsymbol{R}_{\boldsymbol{\Delta}}^{(j)}$ 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.

Beacon Zero Forcing ($K = 2$)

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- Beamformer $\boldsymbol{t}_i^{\mathrm{bZF}} = [t_{1i}^{\mathrm{bZF}(1)}, t_{2i}^{\mathrm{bZF}(2)}]^{\mathsf{T}}$, where $\forall j \in \{1, 2\}$,

$$\begin{bmatrix} t_{1i}^{\mathrm{bZF}(j)} \\ t_{2i}^{\mathrm{bZF}(j)} \end{bmatrix} \triangleq \sqrt{\frac{P}{2}} \frac{\Pi^{\perp}_{\tilde{\boldsymbol{h}}_{\bar{i}}^{(j)}}(\boldsymbol{c}_i)}{\|\Pi^{\perp}_{\tilde{\boldsymbol{h}}_{\bar{i}}^{(j)}}(\boldsymbol{c}_i)\|}$$

with $\boldsymbol{c}_i$ a given vector revealed beforehand to the TXs: the beacon.

Theorem ([de Kerret and Gesbert, 2012])

The number of DoFs achieved with Beacon ZF at user i is

$$\mathrm{DoF}^{\mathrm{bZF}} = \min_{j \in \{1,2\}} A_1^{(j)} + \min_{j \in \{1,2\}} A_2^{(j)}$$

Active-Passive Zero Forcing ($K = 2$)

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

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

Theorem

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

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

Discussion Active-Passive ZF

- Assume wlog that $A_{\bar{i}}^{(2)} \geq A_{\bar{i}}^{(1)}$ (best estimate of $\tilde{\boldsymbol{h}}_{\bar{i}}$ at TX 2) then

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

- Achieves coordination based on the statistical common information: Choose common precoding strategy

Example

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Consider the distributed CSI with the coefficients

$$\boldsymbol{A} = \begin{bmatrix} A_1^{(1)} & A_2^{(1)} \\ A_1^{(2)} & A_2^{(2)} \end{bmatrix} = \begin{bmatrix} 1 & 0.5 \\ 0 & 0.8 \end{bmatrix}$$

- Conventional ZF: DoF fixed by the worst CSI:

$$\mathrm{DoF}^{\mathrm{cZF}} = 0 \text{ (Twice the minimum over the matrix)}$$

- Beacon ZF: DoF fixed by the worst CSI for each channel $\tilde{\boldsymbol{h}}_i$:

$$\mathrm{DoF}^{\mathrm{bZF}} = 0.5 \text{ (Sum of the minimum over the columns)}$$

- A-P ZF: DoF fixed by the best CSI for each channel $\tilde{\boldsymbol{h}}_i$

$$\mathrm{DoF}^{\mathrm{APZF}} = 1.8 \text{ (Sum of the maximum over the columns)}$$

Simulations

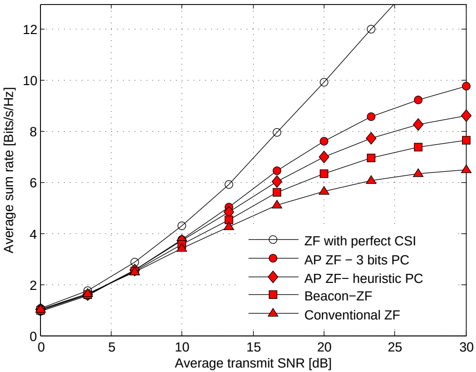

Figure: Sum rate in terms of the SNR with RVQ using $[B_1^{(1)}, B_1^{(2)}] = [6, 3]$ and $[B_2^{(1)}, B_2^{(2)}] = [3, 6]$.

Simulations

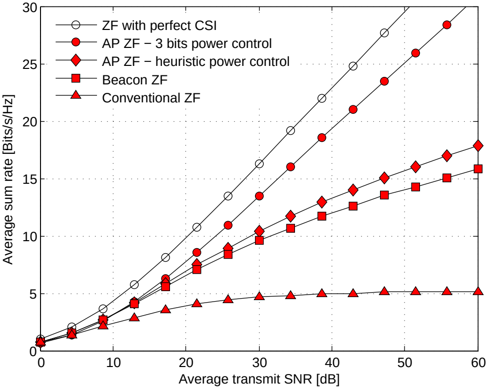

Figure: Sum rate in terms of the SNR with a statistical modeling of the error from RVQ using $[A_1^{(1)}, A_1^{(2)}] = [1, 0.5]$ and $[A_2^{(1)}, A_2^{(2)}] = [0, 0.7]$.

With K TX/RX Pairs

- Robust schemes proposed are efficient with $K = 2$
- No strong improvement for larger K

➥ Need for a new approach

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 $\boldsymbol{h}_i^{(j_1)}$ more accurate than $\boldsymbol{h}_i^{(j_2)}$, then TX j_1 has also knowledge of $\boldsymbol{h}_i^{(j_2)}$

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

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

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

- 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

Key Messages

- Fundamental impact of distributed CSIT
- Team Decision Problem: consistency between TXs is critical
  - Coordination based on statistical information
  - Use common precoding stragegy

  ➡ Functional optimization problem
- Large cost of distributedness: Strong coordination gains are possible

Outline

Keys Aspects of the Coordination Problem

- Wireless networks can strongly benefit from coordination mechanisms
- Distributed approaches are likely to be more robust and scalable
- Coordination of distant TXs
  - Uniform/conventional CSI allocation are very wasteful
  - Conventional precoding schemes are inefficient
- Promizing solutions exploiting
  - TX dependent CSI
  - Team precoding schemes

Open Problems

- Many
  - Making those approaches more practical (intermediate SNRs, small systems)
  - Signaling problem mostly open
  - Extension to other settings of wireless networks? (e.g., multi-hops)
  - Many other applications in general


thanks

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