Exploiting Transmit Correlation for Beamforming and Scheduling in Multiuser MIMO Networks

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Outline

- Introduction: *Challenges and the crucial role of CSIT*
- Existing solutions & drawbacks
- Why use long-term (statistical) CSIT?

**PART I** Transmit Correlation-aided Scheduling and Beamforming
- Exploiting statistical CSIT in User Selection

**PART II** Transmit Correlation-aided Scheduling with Opportunistic Beamforming
- Combining short-term and long-term CSIT for
  - user selection (based on a coarse channel estimate)
  - joint scheduling/beamforming

Conclusions
The role of Channel Knowledge at the Transmitter (CSIT)

Consider a multiuser MISO downlink with $M$ antennas at the BTS and $K$ users in the cell.

With **full Channel State Information (CSIT)** at the transmitter, the capacity scales as

$$C_{sum} \sim M \log \log K$$

**Dirty Paper Coding** is the capacity-achieving strategy
MISO Broadcast Capacity with no CSIT

Sum Capacity is limited by the single-user capacity
(superposition coding is equivalent to time-sharing)

$$C_{\text{sum}} \sim \log M + O(1)$$

(fixed transmit power per antenna)

Sum Capacity is \textit{independent} of the number of users
→ NO multi-user diversity

→ With no feedback: NO GAIN

However in practice, perfect CSIT is difficult to obtain
→ What to do with a little feedback ?
Challenges in Multiuser MIMO Networks

- The need for (spatial) Channel Information is a limiting factor in Multiuser MIMO systems

- Such information must be fed back at the Tx, but the amount of feedback should be kept minimal

- What kind of partial CSIT is necessary and sufficient?!!
  - to identify ‘good’ users to be scheduled
  - to design efficient beamforming techniques (amplify the rx signal and reduce the multiuser interference)
  
  → To achieve sum rate performance close to full CSIT

- How to exploit the useful information contained in the transmit correlation matrix for the purpose of MIMO-SDMA scheduling?
Statistical Knowledge at the Transmitter

- **Advantage**
  - it can be obtained with no or little feedback

- The channel statistics change slowly compared with the instantaneous channel realizations (little feedback overhead)

- Long-term statistical information can be obtained
  - Low-rate feedback
  - Uplink measurements at the transmitter (need for frequency translations)
Existing solutions

- Eigenbeamforming
  - ignores the spatial information given by current realization

- Opportunistic Beamforming
  - ignores information provided by the long-term channel statistics

- SNR-supported eigenbeamforming (in TDMA context)

No methods have been proposed in SDMA systems
PART I

Transmit Correlation-aided Scheduling and Beamforming [ICASSP 2006]
System Model

We consider the dowlink of multiuser MISO system with $K$ users

The received signal is

$$y_k = h_k x(t) + n_k, \quad k = 1, \ldots, K$$

Transmit correlation of $k$-th user is assumed to be perfectly known at both ends of the link

$$R_k = E\{h_k^H h_k\} = U_k \Sigma_k U_k^H$$
Optimal Linear Filtering (MMSE)

For a set of selected users $S$, the beamforming vector matrix that minimizes the MSE is given by

$$W_{MMSE}(S) = \arg \min_{\|W\|^2 \leq P} \mathbb{E} \{ \|s(S) - y(S)\|^2 \}$$

The optimal filter matrix is given by

$$W_{MMSE}(S) = (H(S)^H H(S) + \mu I)^{-1} H(S)^H$$

The optimal scheduling set is given by

$$S^* = \arg \max_{\forall S \in \mathcal{N}} 2 \Re \text{Tr} \left\{ (F(S) + \mu I)^{-1} F(S) \right\} - \text{Tr} \left\{ \left( (F(S) + \mu I)^{-1} F(S) \right)^2 \right\}$$

where

$$F(S) = H(S)^H H(S)$$
Greedy User Selection

We define

\[ \hat{\mathbf{F}}(S) = \sum_{\forall k \in S} \mathbf{R}_k = E\{\mathbf{H}(S)^H \mathbf{H}(S)\} \]

If we replace \( \mathbf{F}(S) \) by its statistical estimate \( \mathbf{R}(S) \)

A low complexity scheduling set is given by

\[ S_{ce} = \arg \max_{\forall S \in \mathcal{N}} 2 \Re \text{Tr} \left\{ \left( \hat{\mathbf{F}}(S) + \mu \mathbf{I} \right)^{-1} \hat{\mathbf{F}}(S) \right\} - \text{Tr} \left\{ \left( \left( \hat{\mathbf{F}}(S) + \mu \mathbf{I} \right)^{-1} \hat{\mathbf{F}}(S) \right)^2 \right\} \]
Channel Estimate-based User Selection

The channel is modelled as Rayleigh flat fading so that

$$h_k \sim CN(0, R_k)$$

We estimate the channel as the vector that maximizes the probability density function (pdf) of $h_k$ under the scalar constraint $\gamma_k = \left\| h_k \right\|^2$

This results to the following Optimization Problem:

$$\max_{h_k} h_k^* R_k^* h_k^T$$

subject to $\gamma_k = \left\| h_k \right\|^2$
Channel estimate-based User Selection

The optimization problem is related to the standard Eigenvalue Problem

\[ \hat{h}_k = \rho u_k^H \]

where \( u_k \) is the largest generalized eigenvector of \( R_k \) and \( \rho \) such that the channel norm constraint is satisfied.

- Based on this coarse channel estimate, we select the users that maximize the sum capacity under optimal linear beamforming (MMSE).
- Once the optimal scheduling set is defined, full CSIT is obtained for the selected users.
Simulated Performance

Sum rate as a function of angular spread for $M = 2$ and $K = 50$ users

Full CSIT is obtained for the selected users
Simulated Performance

Sum rate as a function of the number of users for $M = 2$ and angular spread $0.1\pi$
Simulated Performance

Sum rate as a function of antenna spacing for various user selection schemes with $M = 2$ and $K = 50$ users.
PART II

Channel estimation with partial CSIT for Scheduling and Beamforming in Multiuser MIMO Systems

[EUSIPCO 2006]
Combining short-term and long-term CSIT in an Opportunistic Beamforming context

- The statistical channel knowledge offers good performance on average, but does not exploit multiuser diversity

**Key Idea**

- combine the transmit correlation matrix information with instantaneous scalar feedback based on random opportunistic beamforming

- A coarse channel estimate can be derived and used for
  - user selection (based on a coarse channel estimate)
  - joint scheduling/beamforming
System Model

At time slot $t$, $M$ random beams are generated. The transmitted signal is

$$x(t) = \sum_{m=1}^{M} q_{m}(t)s_{m}(t)$$

$q_{m}$ are orthonormal vectors (beams), columns of $M \times M$ unitary matrix $Q$

$s_{m}(t)$ is the $m$-th transmitted symbol at time slot $t$

The received signal is given by

$$y_{k} = h_{k}^{T}x(t) + n_{k}, \quad k = 1, \ldots, K$$

Transmit correlation of $k$-th user is assumed to be perfectly known at both ends of the link

$$R_{k} = E\{h_{k}h_{k}^{H}\} = U_{k} \Sigma_{k} U_{k}^{H}$$
System Setting and Feedback (1)

BTS sends $M$ random orthogonal beams
System Setting and Feedback (2)

Each user feeds back instantaneous scalar feedback in the form of

$$\gamma_k = \left| h_k^T q_{\max,k} \right|^2$$

and the index of its preferred beam
Maximum Likelihood Channel Estimation (1)

The channel is modelled as Rayleigh flat fading so that

$$h_k \sim CN(0, R_k)$$

We estimate the channel as the vector that maximizes the probability density function (pdf) of $h_k$ under the scalar constraint $\gamma_k = |h_k^T q_{\text{max},k}|^2$

This results to the following Optimization Problem:

$$\max_{h_k} h_k^H R_k h_k$$

s.t. $\gamma_k = |h_k^T q_{\text{max},k}|^2$
Maximum Likelihood Channel Estimation (2)

The optimization problem is related to the Generalized Eigenvalue Problem (GEV)

The optimal solution is given by \( \hat{h}_k = \rho u_k \) where \( u_k \) is the largest generalized eigenvector of \( (R_k, q_{\text{max},k}^* q_{\text{max},k}^T) \) and \( \rho \) is such that the constraint \( \gamma_k = |h_k^T q_{\text{max},k}|^2 \) is satisfied.
Simulated Performance

Sum rate as a function of angular spread for $M = 2$ and $K = 50$ users
Full CSIT is obtained for the selected users
Simulated Performance

Sum rate as a function of the number of users for $M = 2$ and angular spread $0.1\pi$
Simulated Performance

Sum rate as a function of angular spread for \( M = 2 \) and \( K = 50 \) users
The MMSE filters are derived based on the channel estimate
Conclusions

• We show how statistical channel knowledge can be efficiently combined with instantaneous scalar feedback for the purpose of scheduling

• We derive new scheduling metrics for the downlink of multiuser MIMO networks

• Efficient channel estimation method based on maximum likelihood criterion is derived

• The proposed methods offer performance close to the full CSIT scheme when the multipath angular spread per user at the Tx is small enough