Multi-Cell Beamforming with Decentralized Coordination in Wireless Networks

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Outline

- Our contributions during IMANET/IMANET+
- Latest research problem and system model
- Decentralized multi-cell MIMO beamforming algorithm
- Simulation results
- Conclusions
Publications during IMANET/IMANET+

■ Journal articles:

■ Conference articles:
Proposed decentralized beamforming algorithms

- Cellular multi-cell multiuser MISO [1,3,6]
- Cognitive multi-cell multiuser MISO [1,7]
- Cellular multi-cell multiuser MISO (imperfect CSI) [2]
- Cellular multi-cell multiuser MIMO [4,5]
Research problem and system assumptions

Assumptions:
- Multi-cell multiuser MIMO
- Fixed user association
- Local CSI available
- Coordination via backhaul
- Linear TX-RX processing
- Single data stream per user

Problem: Sum power minimization
- User specific minimum SINR targets
Prior work and our contribution

Prior work:
- Centralized algorithm [1]
- Decentralized algorithm [2]
  - Suitable only for static channels
  - Requires backhaul and over-the-air signaling

Our latest contribution:
- Decentralized algorithm [3]
  - Suitable also for time-correlated channels
  - Requires only backhaul signaling

Signal model

- Received signal vector for user $k$

$$y_k = H_{b_k,k}m_k d_k + \sum_{i=1, i\neq k}^{K} H_{b_i,k}m_i d_i + n_k$$  \hspace{1cm} (1)

- $H_{b_k,k} \in \mathbb{C}^{R \times T}$: channel matrix
- $m_k \in \mathbb{C}^{T \times 1}$: transmit beamforming vector (TX)
- $d_k \in \mathbb{C}$: data symbol
- $n_k \sim \mathcal{CN}(0, N_0 I)$: Gaussian noise vector
Problem formulation

\[
\begin{align*}
\text{min.} & \quad \sum_{k \in \mathcal{U}} \| \mathbf{m}_k \|^2_2 \\
\text{s. t.} & \quad \frac{\| \mathbf{w}_k^H \mathbf{H}_{b_k,k} \mathbf{m}_k \|^2}{N_0 + \sum_{i=1,i \neq k}^K \| \mathbf{w}_k^H \mathbf{H}_{b_i,k} \mathbf{m}_i \|^2} \geq \gamma_k, \forall k \in \mathcal{U} \\
& \quad \| \mathbf{w}_k \|^2_2 = 1, \forall k \in \mathcal{U}
\end{align*}
\]

- \( \mathbf{w}_k \in \mathbb{C}^{T \times 1} \): receive beamforming vector (RX)
- \( \gamma_k \): SINR target (fixed)
- \( \mathcal{U} \): set of all users

Problem (2) jointly non-convex w.r.t. \( \{ \mathbf{m}_k \}_{k \in \mathcal{U}} \) and \( \{ \mathbf{w}_k \}_{k \in \mathcal{U}} \)
Steps toward decentralized implementation (1/2)

Auxiliary variables

▶ Inter-cell interference (ICI) power from BS $b$ to user $k$:

$$
\chi_{b,k} = \sum_{i \in U_b} |w_k^H H_{b,k} m_i|^2 = w_k^H \left( \sum_{i \in U_b} H_{b,k} m_i m_i^H H_{b,k}^H \right) w_k,
$$

\(\forall b \in B, \forall k \notin U_b\)

▶ $B$: set of all BSs

▶ $U_b$: set of users served by the BS $b$
Steps toward decentralized implementation (2/2)

- Worst case RX assumption at BS $b$ for other cells’ users (i.e., $\forall k \notin \mathcal{U}_b$)
  - Such $w_k$ assumed that interference power is maximized
  - Resulting interference power is given by

$$
\lambda_{\text{max}} \left( \sum_{i \in \mathcal{U}_b} H_{b,k} m_i m_i^H H_{b,k}^H \right) \tag{4}
$$

- Sub-optimal assumption, but facilitates decentralized implementation
Reformulated problem

\[
\begin{align*}
\min_{\{m_k, w_k\}_{k \in \mathcal{U}}, \chi} & \quad \sum_{k \in \mathcal{U}} \|m_k\|^2_2 \\
\text{s. t.} & \quad N_0 + \sum_{b' \in \mathcal{B}\setminus b_k} \chi_{b', k} + \sum_{i \in \mathcal{U}_b \setminus k} |w_k^H H_{b_k, k} m_i|^2 \geq \gamma_k, \forall k \in \mathcal{U} \\
& \quad \lambda_{\max} \left( \sum_{i \in \mathcal{U}_b} H_{b, k} m_i m_i^H H_{b, k}^H \right) \leq \chi_{b, k}, \forall b \in \mathcal{B}, \forall k \notin \mathcal{U}_b
\end{align*}
\]

- \(\chi\): consists of all \(\chi_{b, k}, \forall b \in \mathcal{B}, \forall k \notin \mathcal{U}_b\)

- Decentralized implementation via alternating optimization
  - TX-RX optimization step: BS-level \(\Rightarrow\) Local CSI
  - ICI optimization step: Network-level \(\Rightarrow\) Backhaul signaling
TX optimization

Semidefinite program (SDP) via semidefinite relaxation (SDR)

\[
\min_{\{Q_k\}_{k \in U_b}} \sum_{k \in U_b} \text{tr} (Q_k)
\]

\[
\text{s. t.} \quad \frac{1}{\gamma_k} \text{tr} \left( W_k H_{b,k} Q_k H_{b,k}^H \right) - \sum_{i \in U_b \setminus k} \text{tr} \left( W_k H_{b,k} Q_i H_{b,k}^H \right) \geq N_0 + \sum_{b' \in B \setminus b_k} \chi_{b',k}, \forall k \in U_b
\]

\[
\chi_{b,k} I - \sum_{i \in U_b} H_{b,k} Q_i H_{b,k}^H \succeq 0, \forall k \not\in U_b
\]

\[
Q_k \succeq 0, \forall k \in U_b
\]

(6)

- SDR: \( m_k m_k^H \) replaced with \( Q_k \), rank \((Q_k) \geq 1\)
- \( W_k = w_k w_k^H \)
- Fixed RX/ICI => Only local CSI required
**RX optimization**

- **Virtual linear MMSE receiver**

\[
\begin{align*}
\mathbf{w}_k &= \frac{\bar{\mathbf{w}}_k}{\|\bar{\mathbf{w}}_k\|_2}, \\
\bar{\mathbf{w}}_k &= \left( \sum_{i \in \mathcal{U}_{b_k \setminus k}} \mathbf{H}_{b_i,k} \mathbf{m}_i \mathbf{m}_i^H \mathbf{H}_{b_i,k}^H + \left( N_0 + \sum_{b' \in \mathcal{B} \setminus b_k} \chi_{b',k} \right) I_R \right)^{-1} \mathbf{H}_{b_k,k} \mathbf{m}_k
\end{align*}
\]

- Optimal receiver with respect to maximizing the SINR
- Fixed TX/ICI $\implies$ Only local CSI required
ICI optimization (1/3)

- Primal decomposition $\Rightarrow$ Decentralized implementation
  - Network-level master problem: Projected subgradient method
    - Updates ICI terms
    - Requires information exchange between BSs via backhaul links
  - BS-level subproblems: one SDP for each BS (RX fixed)
    - Provides subgradients for master problem
    - Signaling free
ICI optimization (2/3)

Network-level master problem

- Updates ICI terms via projected subgradient method

\[ \chi_{b,k}(t + 1) = P \left\{ \chi_{b,k}(t) - \sigma(t) \left( \lambda_{k}^{(b_k)}(t) - \text{tr} \left( \Delta_{k}^{(b)}(t) \right) \right) \right\} \quad (8) \]

- \( P \): projection to \( \mathbb{R}_{++} \), \( \sigma(t) \): step size
- \( \lambda_{k}^{(b_k)} \) - \( \text{tr} \left( \Delta_{k}^{(b)} \right) \): subgradient at a point \( \chi_{b,k} \)
- \( \lambda_{k}^{(b_k)} \): Lagrange multiplier w.r.t. SINR constraint in \( b_k \)th subproblem
- \( \Delta_{k}^{(b)} \): Lagrange multiplier w.r.t. ICI constraint in \( b \)th subproblem
ICI optimization (3/3)

- **Subproblem at BS \( b \): SDP**

\[
\begin{align*}
\text{min.} & \quad \sum_{k \in \mathcal{U}_b} \text{tr} (Q_k) \\
\text{s. t.} & \quad \frac{1}{\gamma_k} \text{tr} \left( W_k H_{b,k} Q_k H_{b,k}^H \right) - \sum_{i \in \mathcal{U}_{b_k} \setminus k} \text{tr} \left( W_k H_{b,k} Q_i H_{b,k}^H \right) \\
& \quad \geq N_0 + \sum_{b' \in \mathcal{B} \setminus b_k} \chi_{b',k}, \quad \forall \ k \in \mathcal{U}_b \\
& \quad \chi_{b,k} I - \sum_{i \in \mathcal{U}_b} H_{b,k} Q_i H_{b,k}^H \succeq 0, \quad \forall k \notin \mathcal{U}_b \\
& \quad Q_k \succeq 0, \quad \forall k \in \mathcal{U}_b
\end{align*}
\]

(9)

- Solve (9) for the Lagrange multipliers and exchange them with the coupled BSs via backhaul links
Decentralized MIMO algorithm

- Performed independently at BS $b$ for all $b \in \mathcal{B}$ in parallel

**Repeat**

- **Repeat**
  - Compute $\{m_k\}_{k \in \mathcal{U}_b}$ via SDP (6)
  - Compute $\{w_k\}_{k \in \mathcal{U}_b}$ via MMSE (7)

**Until** stopping criterion satisfied

- **Repeat**
  - Solve (6) for the Lagr. multipliers and signal them to the coupled BSs
  - Update $\chi^{(b)}$ via projected subgradient method (8)

**Until** stopping criterion satisfied

**Until** overall stopping criterion satisfied
Properties of the algorithm

- SINR targets satisfied at each iteration
  - Suitable for time-correlated fading channels
- Decreased performance as compared to centralized case
- Users real SINRs higher than minimum targets
- Converges in static channel conditions
Simulation parameters

- 2 BSs and 4 users
- 6TX/2RX antennas
- Path gain to noise ratio: $a/N_0 = 1$
- All the users at the cell-edge
Time-correlated fading scenario

- 0 dB SINR targets
- 2.7 km/h user speed
- 2 ms backhaul signaling period
Conclusions

- Decentralized MIMO beamforming algorithm
  - SINRs satisfied at each iteration $\Rightarrow$ suitable for time-correlated channels
  - Performance loss compared to the centralized case

- Ongoing work
  - MIMO beamforming with multiple streams per user
References


