On the Value of Coherent and Coordinated Multi-point Transmission

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Motivation

- Conventional cellular systems are interference limited
  - In-cell users are processed independently by each base station (BS)
  - Other users are treated as inter-cell interference
  - Interference mitigated by sharing and reusing available resources

- Coordinated multi-point transmission (CoMP) with multi-user precoding
  - Increased spatial degrees of freedom in a multi-user MIMO channel
  - A system with $N$ distributed antennas can ideally accommodate up to $N$ streams
  - Inter-stream interference can be controlled or eliminated by a proper beamformer design.
  - Coherent multi-cell MIMO: user data transmitted over a large virtual MIMO channel
Coordinated Multi-point Transmission

- Distributed antenna system based on, e.g. Radio over Fibre (RoF)
  - Capability of joint control of the signals at multiple cells
Coordinated Multi-point Transmission

- Complete *channel state information* (CSI) of all jointly processed links (ideally) needed
- **Centralised RRM** mechanisms to perform scheduling and precoding

**Coherent multi-cell transmission**
- Each data stream may be transmitted from multiple nodes
- **Tight synchronisation** across the transmitting nodes (common phase reference)
- A high-speed backbone network, e.g. Radio over Fibre

**Non-coherent multi-cell processing**
- Dynamic multi-cell scheduling and inter-cell interference avoidance
- Coordinated precoder design and beam allocation
- Each data stream is transmitted from a single BS node
- No carrier phase coherence requirement
- Looser requirement on the coordination and the backhaul
Linear transceiver design

- A generalised method for joint design of linear transceivers with
  - Coordinated multi-cell processing
  - Per-BS or per-antenna power constraints
  - Subject to various optimisation criteria

- The proposed method [1] can accommodate any scenario between
  - Coherent multi-cell beamforming across virtual MIMO channel
  - Single-cell beamforming with inter-cell interference coordination and beam allocation

- The presented methods require a complete CSI between all pairs of users and BSs
  - The solution represent an upper bound for the less ideal solutions with an incomplete CSI.
System Model

Coordinated multi-cell MIMO system:

- \( N_B \) BSs, \( N_T \) TX antennas per BS and \( N_{R_k} \) RX antennas per user \( k \)
- A user \( k \) is served by \( M_k \) BSs from the joint processing set \( B_k \), \n\[ B_k \subseteq B = \{1, \ldots, N_B\} \]
\[
\mathbf{y}_k = \sum_{b \in B} a_{b,k} \mathbf{H}_{b,k} \mathbf{x}'_b + \mathbf{n}_k \tag{1}
\]
\[
= \sum_{b \in B_k} a_{b,k} \mathbf{H}_{b,k} \mathbf{x}_{b,k} + \sum_{b \in B_k} a_{b,k} \mathbf{H}_{b,k} \sum_{i \neq k} \mathbf{x}_{b,i}
+ \sum_{b \in B \setminus B_k} a_{b,k} \mathbf{H}_{b,k} \mathbf{x}'_b + \mathbf{n}_k
\]
- \( a_{b,k} \mathbf{H}_{b,k} \in \mathbb{C}^{N_{R_k} \times N_T} \) channel from BS \( b \) to user \( k \)
- \( \mathbf{x}'_b \in \mathbb{C}^{N_T} \) total TX signal from BS \( b \), and
- \( \mathbf{x}_{b,k} = \mathbf{M}_{b,k} \mathbf{d}_k \in \mathbb{C}^{N_T} \) transmitted data vector from BS \( b \) to user \( k \), where
  - \( \mathbf{M}_{b,k} \in \mathbb{C}^{N_T \times m_k} \) pre-coding matrix,
  - \( \mathbf{d}_k = [d_{1,k}, \ldots, d_{m_k,k}]^T \) vector of normalised data symbols,
  - \( m_k \leq \min(N_T M_k, N_{R_k}) \) number of active data streams.
Linear Transceiver Design

- Per data stream processing: $N_B$ BS transmitters send $S$ independent streams, $S \leq \min(N_B N_T, \sum_{k \in U} N_{R_k})$.

- For each data stream $s$, scheduler associates a user $k_s$, with the channel matrices $H_{b,k_s}$, $b \in B_s$.
  - In some special cases $B_s \subseteq B_{k_s}$. For example, a user may receive data from several BSs, while $|B_s| = 1 \ \forall \ s$. 

\[ \gamma_s = \left| \sum_{b \in B_s} a_{b,k_s} w_{s} H_{s} H_{b,k_s} m_{b,s} e^{j\phi_b} \right|^2 + N_0 \left| w_s \right|^2 + S \sum_{i=1, i \neq s} \left| \sum_{b \in B_i} a_{b,k_s} w_{s} H_{s} H_{b,k_s} m_{b,i} e^{j\phi_b} \right|^2 (2) \] 

$\phi_b$ represents the possible carrier phase uncertainty of BS $b$. 

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- Let \( m_{b,s} \in \mathbb{C}^{N_T} \) and \( w_s \in \mathbb{C}^{N_{R_{k_s}}} \) be arbitrary TX and RX beamformers for the stream \( s \)

- SINR per stream:
  \[
  \gamma_s = \frac{\left| \sum_{b \in B_s} a_{b,k_s} w_s^H H_{b,k_s} m_{b,s} e^{j\phi_b} \right|^2}{N_0 \| w_s \|_2^2 + \sum_{i=1, i \neq s}^S \left| \sum_{b \in B_i} a_{b,k_s} w_s^H H_{b,k_s} m_{b,i} e^{j\phi_b} \right|^2}
  \]

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Transceiver Optimisation with CoMP

General method for linear transceiver optimisation with CoMP:

1. Coherent multi-cell beamforming \((B_s = B_k = B \forall s, k)\) with per BS and/or per-antenna power constraints \([2, 3]\)
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  2. Coordinated single-cell beamforming ($|B_s| = 1 \ \forall \ s$): all transceivers are jointly optimised while considering the other-cell transmissions as inter-cell interference [4]

Optimization criteria, e.g.,

1. Weighted sum rate maximisation [3]:
   \[ S \sum_{s=1}^{S} \beta_s r_s = S \sum_{s=1}^{S} \beta_s \log_2(1 + \gamma_s) \]

2. Max min weighted SINR per data stream [6]:
   \[ \max \ \min_{s=1,\ldots,S} \beta_s^{-1} s \gamma_s \]

3. Maximisation of weighted common user rate [6]:
   \[ r_o = \min_{k \in A} \beta_k^{-1} \sum_{s \in P_k} \log_2(1 + \gamma_s), \]  
P_k is a subset of data streams that correspond to user k
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  3. Any combination of above two, where $|\mathcal{B}_k|$ and $|\mathcal{B}_s|$ may be different for each user $k$ and/or stream $s$.

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2. **Max min weighted SINR per data stream** [6]:
   $$\max \min_s = 1, \ldots, S \beta_{s-1} \gamma_s$$

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  3. **Maximisation of weighted common user rate** \([6]\):
     \[
     r_o = \min_{k \in \mathcal{A}} \frac{1}{k} \sum_{s \in \mathcal{P}_k} \log_2(1 + \gamma_s),
     \]
     \(\mathcal{P}_k\) is a subset of data streams that correspond to user \(k\).
BS Coordination with Linear Processing

- Linear MIMO transceiver optimisation problems cannot be solved directly, in general – **iterative procedures** are required
  - No cooperation between users
  - Transmitter and receivers optimised separately in an iterative manner
  - Some controlled inter-user interference allowed
BS Coordination with Linear Processing

Iteration $t$

Transmit beamformers fixed

Receive beamformers optimised

Guaranteed bit rate users

Best effort users

Controller
BS Coordination with Linear Processing

Iteration $t+1$

Transmit beamformers optimised

Receive beamformers fixed

Guaranteed bit rate users

Best effort users

Controller
BS Coordination with Linear Processing

The general system optimisation objective is to maximise a function $f(\gamma_1, \ldots, \gamma_K)$ that depends on the individual SINR values

$$\max \ f(\gamma_1, \ldots, \gamma_S) \quad \text{s. t.}$$

$$N_0 \left\| w_s \right\|_2^2 + \sum_{i=1, i\neq s}^S \left| \sum_{b \in B_i} a_{b,k_s} w_s^H H_{b,k_s} m_{b,i} \right|_2^2 \geq \gamma_s,$$

$$s = 1, \ldots, S$$

$$\sum_{s \in S_b} \left\| m_{b,s} \right\|_2^2 \leq P_b, \quad b = 1, \ldots, N_B$$

**Objective** in this presentation: max. of min weighted SINR $f(\gamma_1, \ldots, \gamma_S) = \min_{s=1,\ldots,S} \beta_s^{-1} \gamma_s$

- Quasiconvex in $m_{b,s}$ [5, 6], and it can be solved optimally for fixed $w_s$ [1]
Coordinated single-cell beamforming

- Each stream is transmitted from a single BS, $|\mathcal{B}_s| = 1 \ \forall \ s$
- A user $k_s$ is typically allocated to $\arg \max_{b \in \mathcal{B}} a_{b,k_s}$
- Near the cell edge, the optimal beam allocation strategy depends on the channel $H_{b,k}$.
- Large gains from fast beam allocation (cell selection) available
  - A difficult combinatorial problem $\rightarrow$ exhaustive search
  - Sub-optimal allocation algorithms

Allocation objectives
- Generate the least inter-stream interference
- Provide large beamforming gains
Heuristic Beam Allocation Algorithms

1. **Greedy selection**: Beams with the largest component orthogonal to the previously selected set of beams are chosen.
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3. **Eigenbeam selection using maxmin SINR criterion**: 
   
   - A simplified exhaustive search over all possible combinations of user-to-cell and stream/beam-to-user allocations
   - Beamformers matched to the channel, i.e., $m_{b,s} = v_{b,k_s} \sqrt{P_T / \lvert S_b \rvert}$
   - For each allocation, the receivers $w_s$ and the corresponding SINR values $\gamma_s$ are recalculated
   - The selection of the allocation is based on the maximum rate criterion, i.e., $\arg \max_{b,k,l} \min_{s=1}^{S} \gamma_s$. 
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Simulation Cases

1. Coherent multi-cell MIMO transmission \((B_s = \mathcal{B} \ \forall \ s)\) with per BS power constraints

2. Coordinated single-cell transmission \((|B_s| = 1 \ \forall \ s)\)
   - Exhaustive search over all possible combinations of beam allocations. The SINR balancing algorithm is recomputed for each allocation.
   - Fixed allocation, i.e., user \(k_s\) is always allocated to a cell \(b\) with the smallest path loss, \(\arg \max_{b \in \mathcal{B}} a_{b,k_s}\).
   - Heuristic allocation methods

3. Non-coordinated single-cell transmission \((|B_s| = 1 \ \forall \ s)\), where the other-cell interference is assumed to be white Gaussian distributed

4. Single-cell transmission with time-division multiple access (TDMA), i.e., without inter-cell interference
Simulation Scenario

A flat fading multiuser MIMO system

- \( K = 2 - 4 \) users served simultaneously by 2 BSs
- \( \{ N_T, N_{R_k} \} = \{2-4, 1\} \)
- Equal maximum power limit \( P_T \) for each BS, i.e. \( P_b = P_T \ \forall \ b \)
- \( \text{SNR}_k = P_T \max_{b \in B} a_{b,k}^2 / N_0 \)

\[
\begin{align*}
a_{1,1} &= a_{1,2} \\
a_{1,3} &= a_{2,3} = a_{2,4}
\end{align*}
\]
Numerical Results - Full Spatial Load

(a) 0 dB single link SNR

(b) 20 dB single link SNR

Figure: Ergodic sum of user rates of \( \{K, N_B, N_T, N_{R_k}\} = \{4, 2, 2, 1\} \) system with per BS power constraint.
Figure: Ergodic sum rate of \( \{ K, N_B, N_T, N_{R_k} \} = \{2, 2, 2, 1\} \) system at 20 dB single link SNR.

Figure: Ergodic sum rate of \( \{ K, N_B, N_T, N_{R_k} \} = \{4, 2, 4, 1\} \) system at 20 dB single link SNR.
Conclusions

- A generalised method for joint design of linear transceivers with
  - Coordinated multi-cell processing
  - Per-BS or per-antenna power constraints
  - Optimisation objective: weighted SINR blancing

- The proposed method can accommodate any scenario between
  - Coherent multi-cell beamforming across virtual MIMO channel
  - Single-cell beamforming with inter-cell interference coordination and beam allocation
  - Upper bound for the less ideal solutions with an incomplete CSI.

- The coherent multi-cell beamforming greatly outperforms the non-coherent cases,
  - Especially at the cell edge and with a full spatial load.

- However, the coordinated single-cell transmission with interference avoidance and dynamic beam allocation performs considerably well with a partial spatial loading.
References


