Fractional Base Station Cooperation
Cellular Network

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  - Dynamic clustering

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Cell-edge problem

- If user at the cell-edge location
  - Low SNR
  - Co-channel interference from adjacent BSs
  - High antenna correlation

Low user throughput

Co-channel interference

High antenna correlation

1st path

2nd path
Conventional solution for cell-edge problem

• **Conventional solution**
  
  – Frequency reuse
    • Each BSs uses different frequency channel from surrounding cells.
      ✗ It causes degrading of system throughput.
  
  – Interference cancellation using terminal adaptive array
    • cancels interference by terminals.
      ✗ It requires many antennas to perform multiplexing and cancellation at the same time.
Base station cooperation

- **Base Station Cooperation (BSC)**
  - BSC transmits multiple streams to cooperate with adjacent BSs.
  - There are no problems of nor inter-cell interference nor high antenna correlation.

- **BSC single-user (BSC-SU)**
  - For single user
    - BSC-SU wastes many resources to a user.

- **BSC multi-user (BSC-MU)**
  - For multiple users
    - BSC-MU uses resource more efficient than BSC-SU.
Base station cooperation block diagonalization multi-user MIMO

- Transmission model of \((K_{BS}, M) \times (K_{MS}, N)\) BSC-MU-MIMO

\[
\begin{align*}
&g_{11}(d_1) \quad 1^{\text{st}} \text{BS} & d_1 & 1^{\text{st}} \text{user} & g_12(D-d_1) \\
& & & \quad D \\
&g_{21}(D-d_2) \quad 2^{\text{nd}} \text{user} & d_2 & 2^{\text{nd}} \text{BS} & g_{22}(d_2)
\end{align*}
\]

\(d_i\) : distance between \(i\)th BS and \(i\)th user \quad \(g_{ij}\) : pathloss between \(j\)th BS and \(i\)th user

- Receive signal of \(i\)th user

\[
y_i = H_{i1}x_{i1} + H_{i2}x_{i2} + \cdots + H_{iK_{BS}}x_{iK_{BS}} + n_i = H_iQ_i\tilde{V}_is_i + n_i
\]

\(y_i\) : receive signal vector \quad \(H_{ij}\) : channel matrix \quad \(Q_i\) : precoding matrix of block diagonalization

\(x_{ij}\) : transmit signal vector \quad \(n_i\) : noise vector \quad \(\tilde{V}_i\) : precoding matrix of SVD-MIMO

\(s_i\) : transmit data signal vector
Base station cooperation block diagonalization multi-user MIMO

- **Precoding matrix** $Q$

$$\begin{bmatrix} H_1^T, \ldots, H_{i-1}^T, H_{i+1}^T, \ldots, H_{K_{MS}}^T \end{bmatrix}^T = H_i \quad \text{svd}(H_i) = U \Sigma \quad O \begin{bmatrix} V_{\downarrow i}^\dagger & Q_i \end{bmatrix}^H$$

- **Block diagonalization**

$$\begin{bmatrix} y_1 \\ \vdots \\ y_{K_{MS}} \end{bmatrix} = \begin{bmatrix} H_1 Q_1 \tilde{V}_1 & \ldots & H_1 Q_{K_{BS}} \tilde{V}_{K_{BS}} \\ \vdots & \ddots & \vdots \\ H_{K_{MS}} Q_1 \tilde{V}_1 & \ldots & H_{K_{MS}} Q_{K_{BS}} \tilde{V}_{K_{BS}} \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_{K_{BS}} \end{bmatrix} + \begin{bmatrix} n_1 \\ \vdots \\ n_{K_{MS}} \end{bmatrix}$$

$$= \begin{bmatrix} \tilde{H}_1 \tilde{V}_1 & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & \tilde{H}_{K_{MS}} \tilde{V}_{K_{BS}} \end{bmatrix} \begin{bmatrix} s_1 \\ \vdots \\ s_{K_{BS}} \end{bmatrix} + \begin{bmatrix} n_1 \\ \vdots \\ n_{K_{MS}} \end{bmatrix}$$

$$H_j Q_i = \begin{cases} \tilde{H}_i \\ 0 \end{cases} \quad (j = i)$$

$$\begin{cases} \quad 0 \end{cases} \quad (j \neq i)$$

Channel matrix is block diagonalized
Base station cooperation block diagonalization multi-user MIMO

- We decompose the channel matrix into fading matrix and pathloss matrix

\[ \mathbf{H}_i = \begin{bmatrix} \mathbf{H}_{i1} & \mathbf{H}_{i2} \end{bmatrix} = \begin{bmatrix} \mathbf{H}_{i1}^{\text{id}} & \mathbf{H}_{i2}^{\text{id}} \end{bmatrix} \begin{bmatrix} \mathbf{G}_{i1} & \mathbf{O} \\ \mathbf{O} & \mathbf{G}_{i2} \end{bmatrix} = \mathbf{H}_{i1}^{\text{id}} \mathbf{G}_i \]

\[ \mathbf{H}_{ij}^{\text{id}} : \text{fading matrix} \]

\[ \mathbf{G}_{ij} = \sqrt{g_{ij}} \mathbf{I} \]

- Block diagonalization precoding matrix of BSC

\[ \mathbf{Q}_i = \mathbf{H}_{j\neq i}^{\perp} = \frac{1}{\left\| \mathbf{G}_{j \neq i}^{-1} \right\|_F} \mathbf{G}_{j \neq i}^{-1} \left( \mathbf{H}_{j \neq i}^{\text{id}} \right)^\perp \quad \mathbf{H}_{j\neq i}^{\text{id}} \left( \mathbf{H}_{j\neq i}^{\text{id}} \right)^\perp = \mathbf{O} \quad \mathbf{H}_i \mathbf{Q}_{j\neq i} = \mathbf{O} \]

- Receive signal of \( i \)th user

\[ \mathbf{y}_i = \mathbf{H}_i \mathbf{Q}_i \tilde{\mathbf{V}}_i \mathbf{s}_i + \mathbf{n}_i = \tilde{\mathbf{H}}_i \tilde{\mathbf{V}}_i \mathbf{s}_i + \mathbf{n}_i \]

\[ \tilde{\mathbf{H}}_i = \mathbf{H}_i \mathbf{Q}_i = \frac{1}{\left\| \mathbf{G}_{j \neq i}^{-1} \right\|_F} \mathbf{H}_{i}^{\text{id}} \mathbf{G}_i \mathbf{G}_{j \neq i}^{-1} \left( \mathbf{H}_{j \neq i}^{\text{id}} \right)^\perp = \sqrt{\frac{g_{11}g_{22} + g_{12}g_{21}}{g_{j\neq i1} + g_{j\neq i2}}} \tilde{\mathbf{H}}_i^{\text{id}} \]

\[ \tilde{\mathbf{H}}_i^{\text{id}} : \text{The equivalent fading matrix of } i \text{th user} \]
Base station cooperation block diagonalization multi-user MIMO

- **Transmit power from \( j \)th BS**
  \[ P_j = E\left[ x_j^H x_j \right] \leq \Omega P \]

- **Power normalization factor**
  - \( \Omega \) regulates the transmit power
  \[
  \Omega = \begin{cases} 
  \frac{1}{g_{12} + \frac{g_{21} + g_{22}}{g_{11} + g_{12}}} & d_1 \geq d_2 \\
  \frac{g_{11} + g_{12}}{g_{11}} + \frac{g_{21} + g_{22}}{g_{21}} & d_1 \leq d_2 
  \end{cases}
  \]

- **Average receive SNR of \( i \)th user**
  \[
  \gamma_i = \frac{E\left[ |\tilde{H}_i \tilde{V}_i s_i|^2 \right]}{M\sigma^2} = \frac{g_{11}g_{22} + g_{12}g_{21} + \Omega P}{g_{j\neq i1} + g_{j\neq i2} + \sigma^2}
  \]

- **Capacity of \( i \)th user**
  \[
  C_i = \sum_{k=1}^{2} \log_2 \left( 1 + \lambda_k \gamma_i \right)
  \]
  \( \lambda_k \) : \( k \)th eigenvalue of equivalent channel
Power normalization factor $\Omega$

- $d_1 = d_2$
  - $\Omega_{\text{max}} = 1$
- $d_1 \gg d_2$, $d_1 \ll d_2$
  - $\Omega_{\text{min}} = 2/3$

**Co-scheduling**

The BSs select users with the same SINR
Capacity of (2,2)x(2,2) BSC-MU-MIMO

Average capacity of 1\textsuperscript{st} user at different distance

- 2x2 SC-MIMO Ideal
- 2x2 SC-MIMO
- (2,2)x(2,2) BSC-MU co-schedule
- (2,2)x(2,2) BSC-MU user2 at cell-edge

- **Co-scheduling**
  BSC-MU is almost the same capacity as 2x2 SC-MIMO ideal

- **User2 at cell-edge**
  Capacity is decreased about 3bps where distance is from 100m to 300m

Co-scheduling is the optimal user selection
Cooperative region

• Analysis considering overhead is necessary
  – Overhead: the cost of resource for transmission (ex. Reference signal, guard band, cyclic prefix)

Comparison of spectral efficiency

• Spectral efficiency
  \[ R^{SC} = \chi_{SU}C^{SC} \]
  \[ R^{MC} = \chi_{MU}C^{MC} \]
  \[ \chi \]: bandwidth inefficiencies considering overhead

• Cell-inner
  – Non-cooperative region
    • Single-cell MIMO is efficient at cell-inner

• Cell-edge
  – Cooperative region
    • BSC MIMO is efficient at cell-edge
Fractional Base Station Cooperation

- **Single-cell MIMO** (conventional cellular system)
  - Cell-inner: efficient
  - Cell-edge: not efficient

- **Base station cooperation MIMO**
  - Cell-inner: not efficient
  - Cell-edge: efficient

Fractional Base Station Cooperation (FBSC)

- Cell-inner: uses single-cell MIMO
- Cell-edge: uses BSC MIMO

FBSC is performed to achieve gains both at the cell-inner and cell-edge.
Cooperation clustering

• Clustering
  – Static clustering
    • Cooperation set is fixed
      ✗ By-product cell-edge is created.
  – Dynamic clustering
    • makes cooperation set adaptively.
      ✓ Cooperation is efficient at all cell-edges.
Dynamic clustering

: master cell
: slave cell
Fractional base station cooperation cellular network

- Fractional base station cooperation
- Dynamic clustering

Diagram:
- Distributed controller
- Backhaul
- Cooperative region
- Non-cooperative region
- Network layer
- Physical layer
Simulation scenario

• **Comparison transmission**
  
  – Single-cell SISO
  
  – Single-cell MIMO
    • 2x2 SVD-MIMO
  
  – Multi-cell static clustering
    • BSC is performed at all locations
    • Static clustering
  
  – Fractional Base Station Cooperation Cellular Network (FBSC-CN)
## Simulation scenario

### Simulation parameter

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of cell</td>
<td>19 cells</td>
</tr>
<tr>
<td>Number of user</td>
<td>10 users / cell</td>
</tr>
<tr>
<td>Number of cooperation set</td>
<td>3 cells</td>
</tr>
<tr>
<td>Number of antenna (BS, user)</td>
<td>1, 1 (SISO) or 2, 2 (MIMO)</td>
</tr>
<tr>
<td>Channel model</td>
<td>i.i.d. Rayleigh</td>
</tr>
<tr>
<td>Pathloss model</td>
<td>$34.5 + 35 \log_{10}(d[m])$ [dB] \ (3GPP TR 25.996 : Urban Macro)</td>
</tr>
<tr>
<td>Transmit power</td>
<td>40[dBm]</td>
</tr>
<tr>
<td>Noise level</td>
<td>-100[dBm]</td>
</tr>
<tr>
<td>Site to site distance</td>
<td>1000 m</td>
</tr>
<tr>
<td>Scheduler</td>
<td>Round-robin &amp; co-scheduling</td>
</tr>
<tr>
<td>Single-user MIMO scheme</td>
<td>SVD-MIMO</td>
</tr>
<tr>
<td>Multi-user MIMO scheme</td>
<td>Generalized BD [*]</td>
</tr>
</tbody>
</table>

Simulation result

User capacity at the distance locations

Fractional BSC
- User capacity at the cell-inner is as high as Single-cell MIMO
- User capacity at the cell-edge is almost the same with BS cooperation
Simulation result

- FBSC is higher capacity than other scheme at all probability

CDF of instantaneous capacity at cell-edge user

- Single-cell SISO
- Single-cell MIMO
- Multi-cell static clustering
- FBSC-CN
The average cell spectral efficiency of FBSC is slightly improved than single-cell MIMO.

The cell-edge user spectral efficiency of FBSC is 2.4 times as high as that of single-cell MIMO.
Conclusion

• **BSC solves the cell-edge problem.**

• **Fractional BSC is proposed.**
  – FBSC performs to achieve gains both at the cell-inner and cell-edge.

• **FBSC cellular network is proposed.**
  – In FBSC-CN, cooperation sets are constructed dynamically.

• **Numerical simulation shows that FBSC performs efficiently both at cell-inner and cell-edge.**
Thank you for your attention.