Multiuser MIMO in Distributed Antenna Systems with Limited Feedback

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- **What is a DAS?**
  - **Multiple antenna arrays** distributed in the cell (Remote Radio Units - RRUs)
  - RRUs connected to the base station (BS) over dedicated low latency/high bandwidth links
  - Together all antennas form a virtual MIMO system

- **Why DASs?**
  - Improve **coverage**, mitigate shadowing and penetration losses [Saleh et al., 1987]
  - Reduce the **outage probability** and increase the **capacity** [Kerpez and Ariyavisitakul, 1994, Choi and Andrews, 2007]
  - Better exploitation of spatial multi-user **diversity** [Heath, Jr. et al., 2011]
Distributed Antenna Systems (DASs) - Overview

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DAS System Model

We focus on the downlink of the broadcast system

Single-stream transmission per user is assumed

The received signal of user $u$ can be written as:

$$y_u = h_u^H f_u x_u + h_u^H \sum_{k=1, k \neq u}^U f_k x_k + o_u + n_u$$

$h_u \in \mathbb{C}^{N_t}$ MISO channel vector

$f_u \in \mathbb{C}^{N_t}$ beamformer of user $u$

$x_u$ transmit symbol of user $u$

$o_u$ out-of-cell interference; considered in simulations [Heath, Jr. et al., 2011]

$n_u$ receiver noise
Impact of Distributed Antennas

- The spatial separation of the RRUs causes pathloss differences
- Model for the channel vector:

\[ h_u = C_u^{1/2} \bar{h}_u \]  \hspace{1cm} (2)

\[ C_u = \begin{bmatrix}
\gamma_u^{(1)} & 0 & \cdots & 0 \\
0 & \gamma_u^{(2)} & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & \gamma_u^{(N_t)}
\end{bmatrix} \]  \hspace{1cm} (3)

- \( \bar{h}_u \sim \mathcal{CN} (0, I) \) models the small-scale Rayleigh fading
- \( C_u \) models the large-scale effects (pathloss, shadowing)
- Future extension: correlation between different antennas
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Zero Forcing Multiuser Beamforming

- DASs are likely to support **many TX antennas**
- SU-MIMO won’t be able to support the full multiplexing capabilities
  - Available space in handhelds
  - Antenna correlation
- **Remedy**: spatially multiplex users — MU-MIMO
- We consider **Zero Forcing Beamforming**:
  - Single stream per user
  - Complete cancellation of in-cell inter-user interference
  - Different cells do not cooperate

\[
F = H^H \left( HH^H \right)^{-1} \text{diag} (p)^{1/2}
\]

\[
H = [h_1, \ldots, h_U]^H
\]
Zero Forcing Multiuser Beamforming

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Channel State Information (CSI)

- ZF-beamforming requires CSI at the transmitter (CSI-T)
- In practice limited feedback is used to obtain CSI-T
- **Goal:** minimize overhead for a given accuracy
- For ZF-beamforming channel subspaces must be quantized
- Grassmannian-quantization on $G(N_t, 1)$ [Love et al., 2003]
- The accuracy directly impacts the residual interference [Jindal, 2006]

\[ h_u = \|h_u\| \tilde{h}_u \] (6)
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Channel Direction Quantization

- **Independent quantization**: ignore correlation over time
  - Advantage: low complexity, codebook pre-computed
  - Disadvantage: poor accuracy
- Optimal quantization codebooks $Q_G$ for uniform quantization on the Grassmann-manifold exist [Love, D.]\(^1\)
- **BUT**: these codebooks are not optimal for a DAS
- **Reason**: the channel direction is not uniformly distributed on $G(N_t, 1)$
- Assuming knowledge of $C_u$ at the users and the BS we employ a statistically matched codebook [Love and Heath, Jr., 2004]

$$q_i^{(c)} = \frac{C_u^{1/2} q_i^{(g)}}{\|C_u^{1/2} q_i^{(g)}\|}, \forall q_i^{(g)} \in Q_G.$$  \hspace{1cm} (7)

---

\(^1\) In simulations we average over random isotropic codebooks.
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Channel Direction Quantization (2)

- **Differential/predictive quantization:** exploit correlation over time
  - Advantage: good accuracy in low-mobility scenarios
  - Disadvantage: high computational complexity
  - Quantization codebook is adapted to the channel evolution

- We extend our **predictive Grassmann-manifold quantizer** [Schwarz and Rupp, 2012]:
  - Predict the current channel direction $\tilde{h}_u[k]$
  - Generate a local Grassmannian codebook around $h_u^{(p)}[k]$
  - The span of the local codebook is adapted to the prediction accuracy
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Grassmann manifold
Predictive Channel Direction Quantization

- Extension of [Schwarz and Rupp, 2012] to correlated channels
- Model for the evolution of the channel

\[ h_u[k] = C_u^{1/2} \tilde{h}_u[k] \] (8)

\[ \tilde{h}_u[k] = G(\tilde{h}_u[k-1], \tilde{h}_u[k-2], \ldots) + \tilde{i}_u[k] \] (9)

\[ \tilde{i}_u[k] \sim N(0, \sigma_i^2 I) \] (10)

- The small-scale fading determines the temporal evolution
- We predict the deterministic evolution of the channel

\[ \tilde{h}_u[k] = \tilde{h}_u^{(p)}[k] + \tilde{p}_u[k] + \tilde{i}_u[k] \] (11)

\[ \tilde{p}_u[k] \sim N(0, \sigma_p^2 I) \] (12)

- The channel can then be written as

\[ h_u[k] = h_u^{(p)}[k] + e_u[k] \] (13)

\[ e_u[k] = C_u^{1/2} (\tilde{p}_u[k] + \tilde{i}_u[k]) \sim N(0, \sigma_e^2 C_u) \] (14)
Predictive Channel Direction Quantization

- Extension of [Schwarz and Rupp, 2012] to correlated channels

- Model for the evolution of the channel

\[ h_u[k] = C_u^{1/2} \tilde{h}_u[k] \]  
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- The small-scale fading determines the temporal evolution

- We predict the deterministic evolution of the channel

\[ \tilde{h}_u[k] = \bar{h}_u^{(p)}[k] + \bar{p}_u[k] + \bar{i}_u[k] \]  
\[ \bar{p}_u[k] \sim N(0, \sigma_p^2 I) \]  

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Predictive Channel Direction Quantization (2)

- What does that mean for the subspace error?
- The error on the manifold can be described with a tangent vector

\[
\mathbf{e}_{u}^{(t)}[k] = \left( \mathbf{I} - \tilde{\mathbf{h}}_{u}^{(p)}[k]\tilde{\mathbf{h}}_{u}^{(p)}[k]^{H} \right) \mathbf{h}_{u}[k] \left( \tilde{\mathbf{h}}_{u}^{(p)}[k]^{H} \mathbf{h}_{u}[k] \right)^{-1}
\]

- The local codebook is generated to match the tangent error distribution

\[
\mathbf{e}_{u}^{(t)}[k] \approx \mathbf{P}_{u} \frac{\mathbf{e}_{u}[k]}{c_{R}}, \quad \frac{\mathbf{e}_{u}[k]}{c_{R}} \sim \mathcal{N} \left( 0, \frac{\mathbf{C}_{u}\sigma_{\tilde{e}}^{2}}{c_{R}^{2}} \right)
\]

- Observe: the error only depends on the predicted subspace
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Simulation Settings

- LTE-A compliant simulator [Mehlführer et al., 2011]
- System bandwidth 1.4 MHz
- 8 transmit antennas per cell
- 8 single antenna users per cell
- Different DAS configurations
  - 8 central, 0 RRUs (8 − 0/0)
  - 2 central, 6 RRUs with 1 antenna (2 − 1/6)
- RRUs on a ring of radius $\frac{2}{3}$ times the cell radius
Throughput Comparison

- Users randomly distributed in the cell area
- Low mobility scenario: 10 Hz maximum Doppler frequency
- Comparison of perfect and quantized CSIT (independent and differential)
Conclusion

- DASs have a large potential for **improving the cell capacity**, especially in combination with MU-MIMO
- Disadvantage: **increased network cost** (multiple antenna sites, additional backbone links)

**Quantized CSIT — even larger gains:**

- The channel direction is mostly determined by the strong RRU
- Concentrate the feedback bits on these RRU ($C_u$)
- Impact of residual interference is less severe
- Interference is more distributed over the cell area
Conclusion

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**Thanks for your attention!**
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Impact of Quantized Channel State Information (CSI)

- The expected value of the **SINR with imperfect CSI** at the transmitter (CSIT) can be lower bounded \([Trivellato et al., 2007]\)

\[
\mathbb{E}(\beta_{u,i}) \geq \frac{\frac{P}{N_i} \|h_{u,i}\|^2 \cos^2(\phi_{u,i})}{\frac{P}{N_i} \|h_{u,i}\|^2 \sin^2(\phi_{u,i}) + \tilde{\sigma}_n^2}
\]

\[d_c^2(q_{u,i}, \tilde{h}_{u,i}) = \sin^2(\phi_{u,i}) = 1 - |\tilde{h}_{u,i}^H q_{u,i}|^2\]

- The accuracy of \(q_{u,i}\) is critical
- The chordal distance \(d_c(q_{u,i}, \tilde{h}_{u,i})\) is used as quantization metric
Throughput versus Distance to Central Antennas

- Users randomly distributed on rings of fixed radius
- Perfect channel state information

![Graph showing throughput versus distance to central antennas with points marked at distances of 0, 50, 100, 150, 200, 250, 300, 350, 400, 450, and 500 meters. The graph includes lines for 8 users at 0/0, 4 users at 1/4, 2 users at 1/6, and 2 users at 2/3.]
Throughput Comparison

- Users randomly (uniformly) distributed in the cell area
- Moderate mobility scenario: 50 Hz maximum Doppler frequency
- Comparison of perfect and quantized CSIT (independent and differential)