Coordinated Multi-Point (CoMP) in LTE
Wireless Communications Seminar

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Contents

Overview of CoMP in LTE
  CoMP Basics
  3GPP’s View of CoMP

Multi-User MIMO Transmission
  Mathematical System Model
  Block-Diagonalization Precoding
  Antenna Combining

Application Scenario

Conclusions
Estimated growth of mobile traffic (1 Exabyte = $10^{18}$ bytes); Ericsson traffic exploration tool [Ericsson, 2013b]

- Expected **exponential growth** in mobile data
- Mobile data traffic increases 10 – 17 fold between 2012 and 2017
- How to face the expected **Capacity Crunch**?
CoMP Motivation (2)

- Common approaches to improve network capacity
  - *Increase* the amount of available *spectrum*
    e.g., 200 kHz in GSM ⇒ 100 MHz in LTE-A (carrier-aggregation)
  - *Improve the PHY*: AMC, MIMO, OFDM
  - *Densify the network*: small cells (micro/pico/femto)

- Significant bandwidth expansions cannot be expected in the near future
  - Possible long-term solution *Millimeter Waves*
    [Rappaport et al., 2013] (30 – 300 GHz ⇔ 1 – 10 mm)

- Potential PHY improvements with *massive MIMO* [Marzetta, 2010]

- Feasible short-term solution: *increasing the network density*
  - Heterogeneous networks [Andrews, 2013]
  - Implies enlarging the cell edge
  - Increased inter-cell interference
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CoMP Principles

- Solution to cell edge problematic: remove the cell edge!

- Definition of CoMP:
  - Coordinated transmission/reception of data among several transmission/reception points to reduce or even exploit interference
  - Transmission/reception points:
    base stations, relays, access points, remote radio heads, user equipments

- Coordination is not for free: backhaul infrastructure
  - High bandwidth, low latency (beyond X2)
  - Fiber, dedicated micro-wave links
  - Central coordination unit
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First 3GPP studies in Rel’10:

- **3GPP TR 36.814** - Further advancements for E-UTRA physical layer aspects
- **3GPP TR 36.912** - Feasibility study for further advancements for E-UTRA (LTE-A)
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Introduction of CoMP into the standard in Rel’11:

- 3GPP TR 36.819 - Coordinated multi-point operation for LTE physical layer aspects
3GPP Time-Line

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Introduction of CoMP into the standard in Rel’11:
- 3GPP TR 36.819 - Coordinated multi-point operation for LTE physical layer aspects

Consideration of non-ideal backhaul in Rel’12 — :
- 3GPP TR 36.874 - Coordinated multi-point operation for LTE with non-ideal backhaul
Classification of CoMP Concepts

- **Coordinated scheduling:**
  - Time/frequency sharing
  - Dynamic point selection
  - Inter-cell interference coordination
    - ICIC (Rel. 8), eICIC (Rel. 10), FeICIC (Rel. 11)
  - **Advantage:** low overhead (control info)

- **Coordinated beamforming:**
  - Spatial interference mitigation
  - Signal to leakage and noise ratio (SLNR)
    - [Sadek et al., 2007]
  - **Advantage:** good trade-off (CSI only)

- **Joint transmission:**
  - Exploitation of interference
  - Distributed antenna system (DAS)
  - **Advantage:** potentially highest performance
  - **Disadvantage:** overhead (CSI and data)
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CoMP Scenarios considered by the 3GPP

Scenario 1: Intra-site CoMP

Scenario 2: Inter-site CoMP

Scenario 3: HetNet CoMP 1 (different cell-IDs, small cells)

Scenario 4: HetNet CoMP 2 (same cell-IDs, RRHs and relays)

HetNet... heterogeneous network, RRH... remote radio head
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Channel State Information (CSI) Acquisition and Sharing

- Coordinated beamforming and joint transmission require **other-cell CSI**
- Extended **reference signals** to support other-cell CSI estimation
- 3GPP defines a **measurement set** for CSI reporting
- **Performance** and **overhead** increase with the size of the measurement set
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Multi-User MIMO Broadcast Channel

\[ \begin{align*}
\text{Base station} & \quad \text{Remote radio unit} \quad \text{User} \\
\text{Low-latency high-bandwidth connection} &
\end{align*} \]

\[ y_u = G_u H_u F_u x_u \]

- Frequency-flat input-output relationship of user \( u \) (OFDM)
- Channel matrix \( H_u \in \mathbb{C}^{N_t \times N_r} \), linear transceivers \( G_u \in \mathbb{C}^{N_r \times L} , F_u \in \mathbb{C}^{N_t \times L} \)
- \( L \) ... streams per user, \( N_r \) ... receive antennas, \( N_t \) ... transmit antennas
- \( S \) = \(|S| \) ... users served in parallel
- Interesting case: \( L \leq N_r \leq N_t \)
Multi-User MIMO Broadcast Channel

Frequency-flat input-output relationship of user \( u \) (OFDM)

\[
y_u = y_u^{\text{intended signal}} + y_u^{\text{interference}} + y_u^{\text{noise}}
\]

\[
y_u = \underbrace{G_u^H H_u^H F_u x_u}_{\text{intended signal}} + \underbrace{G_u^H H_u^H \sum_{s \in S, s \neq u} F_s x_s}_{\text{interference}} + \underbrace{G_u^H z_u}_{\text{noise}}
\]

\[
\text{channel matrix } \ H_u \in \mathbb{C}^{N_t \times N_r}, \quad \text{linear transceivers } \ G_u \in \mathbb{C}^{N_r \times L}, \quad F_u \in \mathbb{C}^{N_t \times L}
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Multi-User MIMO Motivation

- Practical situation: $N_r \ll N_t$ (especially in joint transmission CoMP)

- **Single-user MIMO:**
  - Number of parallel users: $S = 1$
  - Number of spatial streams: $L \leq \min(N_r, N_t)$ [Telatar, 1999]
  - Multiplexing gain of base station cannot be exploited

- Remedy: *multi-user MIMO*
  - Serve multiple users in parallel $S \geq 1$ each over $L \leq N_r$ streams
  - **Advantage:** total number of streams $S \cdot L \leq N_t$ [Goldsmith et al., 2003]
  - Total multiplexing gain not confined by user capabilities

- **Questions:**
  - How to select the users $S$?
  - How to design the transceivers $F_u, G_u$?
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Transceiver Design

- Assume the schedule $S$ to be given
- Nonlinear interference pre-cancellation *dirty paper coding* [Costa, 1983]
  - Suboptimal algorithmic attempts
    - *Vector-perturbation* precoding [Hochwald et al., 2005]
    - *Tomlinson-Harashima* based joint transceiver design [Mezghani et al., 2006]
  - Disadvantage: complexity
- Practically more relevant: *linear transceivers*
  - Linear interference pre-cancellation [Spencer et al., 2004]
    - *Zero-forcing* beamforming
    - *Block-diagonalization* precoding
  - *Iterative joint optimization*, e.g., based on MMSE criteria [Shi et al., 2008]
Transceiver Design

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Considered Transceiver Architecture

- Problem of iterative approaches: large signaling overhead
- We consider non-iterative linear transceiver designs:
  - *Selfish* selection of $G_u$
  - *Block-diagonalization* precoding at base station
  - Selection of $S$ based on achievable rate estimate
- Advantages of this approach:
  - *Reduced* computational *complexity* (closed-form solutions)
  - *Decreased* signaling *overhead* when $L < N_r$

\[
H_{u}^{\text{eff}} = H_u G_u \in \mathbb{C}^{N_t \times L} \text{ versus } H_u \in \mathbb{C}^{N_t \times N_r}
\]  

(2)
Multi-User MIMO Transmission

Block-Diagonalization (BD) Precoding

- Assume for now $G_u$ as given and $S = \{1, \ldots, S\}$

$$y_u = (H_u^{\text{eff}})^H F_u x_u + (H_{u}^{\text{eff}})^H \sum_{s=1}^{S} F_s x_s + G_u^H z_u$$

- Goal of BD precoding: *eliminate multi-user interference*

$$\left( H_s^{\text{eff}} \right)^H F_u = 0, \quad \forall s, u \in S \text{ and } s \neq u, \quad (3)$$

$$\text{rank} \left( (H_{u}^{\text{eff}})^H F_u \right) = L, \quad \forall u \in S \quad (4)$$

- This can be achieved by selecting the precoders as follows $\forall u \in S$
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$$\tilde{H}_u = \left[ H_1^{\text{eff}}, \ldots, H_{u-1}^{\text{eff}}, H_{u+1}^{\text{eff}}, \ldots, H_S^{\text{eff}} \right]^H \in \mathbb{C}^{(S-1)L \times N_t},$$

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Block-Diagonalization (BD) Precoding (2)

- **Feasibility condition** for BD precoding

\[
\text{rank} \left( \mathbf{F}_u \right) = L \Rightarrow \text{rank} \left( \text{null} \left( \tilde{\mathbf{H}}_u \right) \right) = \max \left( 0, N_t - (S - 1)L \right) = L
\]
\[
\Rightarrow N_t - (S - 1)L = L \Rightarrow S = \frac{N_t}{L} \tag{7}
\]

- A solution can be determined from a singular-value decomposition of \( \tilde{\mathbf{H}}_u \)

- Special case: zero-forcing beamforming \( L = 1 \)

\[
y_u = (\mathbf{h}^\text{eff}_u)^H \mathbf{f}_u x_u + (\mathbf{h}^\text{eff}_u)^H \sum_s f_s x_s + g^H_u z_u \tag{8}
\]

- Closed form solution

\[
\mathbf{F} = [\mathbf{f}_1, \ldots, \mathbf{f}_S] = \mathbf{H}^H \left( \mathbf{H} \mathbf{H}^H \right)^{-1}, \tag{9}
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Illustration of Zero-Forcing Beamforming

Zero interference conditions:

\[ h_2^H f_1 = h_3^H f_1 = 0 \]

Intended signal power:

\[ P_1 = |h_1^H f_1|^2 \]

\[ \Rightarrow \text{Orthogonal user selection} \]

\[ R_{ZF} \propto N_t \log \left(1 + \frac{P}{N_t} \log U\right) \propto R_{DPC} \]

[Yoo and Goldsmith, 2006, Boccardi and Huang, 2007]
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Multi-User MIMO Transmission

Channel State Information (CSI) Feedback

- Remember, the BD precoders are obtained by the base station from

\[ F_u \in \text{null} (\tilde{H}_u), \quad \tilde{H}_u = \left[ H_{1}^{\text{eff}}, \ldots, H_{u-1}^{\text{eff}}, H_{u+1}^{\text{eff}}, \ldots, H_{S}^{\text{eff}} \right]^H \]

- What *channel state information* does the base station need, i.e., what *feedback information* do the users have to provide?

- Notice, \( H_{j}^{\text{eff}} \) can be replaced with any matrix spanning the same subspace

\[ H_{j}^{\text{eff}} \equiv \tilde{H}_j \in \mathbb{C}^{N_t \times L} \iff \text{span} \left( H_{j}^{\text{eff}} \right) = \text{span} \left( \tilde{H}_j \right), \quad (11) \]

\[ (H_{j}^{\text{eff}})^H F_u = 0 \iff \tilde{H}_j^H F_u = 0 \quad (12) \]

⇒ the users have to convey \( \text{span} \left( H_{j}^{\text{eff}} \right) \) to the base station

- This subspace is a point on the *Grassmann manifold* of \( L \) dimensional subspaces in the \( N_t \) dimensional complex Euclidean space.
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Channel State Information (CSI) Feedback (2)

- Feedback channel with limited capacity ⇒ \( \text{span}(H_{\text{eff}}^j) \) must be quantized
  ⇒ Grassmannian quantization [Love and Heath, Jr., 2005]
- The subspace is represented with an orthonormal basis \( \tilde{H}_j \in \mathbb{C}^{N_t \times L} \)

\[
\text{span}(H_{\text{eff}}^j) = \text{span}(\tilde{H}_j), \quad \tilde{H}_j^H\tilde{H}_j = I_L 
\]

- For quantization a codebook is employed \((b \text{ bits of feedback})^1\)

\[
Q = \left\{ Q_i \in \mathbb{C}^{N_t \times L} \mid Q_i^HQ_i = I_L, \ i \in \{1, \ldots, 2^b\} \right\} 
\]

- The quantized subspace is obtained from

\[
\hat{H}_j = \arg\min_{Q_i \in Q} d_c^2(H_{\text{eff}}^j, Q_i) = \arg\min_{Q_i \in Q} L - \text{tr} \left( \hat{H}_j^HQ_iQ_i^H\hat{H}_j \right) 
\]

- \( d_c^2(\cdot, \cdot) \) subspace chordal distance

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1 [Ravindran and Jindal, 2008, Schwarz et al., 2013a, Schwarz et al., 2013b]

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- The subspace is represented with an orthonormal basis $\tilde{H}_j \in \mathbb{C}^{N_t \times L}$

\[
\text{span} \left( H_{\text{eff}}^j \right) = \text{span} \left( \tilde{H}_j \right), \quad \tilde{H}_j^H \tilde{H}_j = I_L \quad (13)
\]

- For quantization a codebook is employed ($b$ bits of feedback)$^1$

\[
Q = \left\{ Q_i \in \mathbb{C}^{N_t \times L} \mid Q_i^H Q_i = I_L, i \in \{1, \ldots, 2^b\} \right\} \quad (14)
\]

- The quantized subspace is obtained from

\[
\hat{H}_j = \arg\min_{Q_i \in Q} d_c^2 \left( H_{\text{eff}}^j, Q_i \right) = \arg\min_{Q_i \in Q} L - \text{tr} \left( \tilde{H}_j^H Q_i Q_i^H \tilde{H}_j \right) \quad (15)
\]

- $d_c^2 (\cdot, \cdot)$ subspace chordal distance

---

$^1$ [Ravindran and Jindal, 2008, Schwarz et al., 2013a, Schwarz et al., 2013b]

Stefan Schwarz
Multi-User MIMO versus Single-User MIMO

- LTE compliant system with $N_t = 8$, $N_r = 2$ and $U = 4$ users
- Low user mobility: 5 km/h @ 2 GHz center frequency
- Multi-user MIMO: $S = 4$ user spatially multiplexed with $L = 2$ streams each
- Single-user MIMO: $S = 1$ user selected with $L = 2$ streams

RCSQ... random channel subspace quantization [Ravindran and Jindal, 2008]
ACSQ... adaptive channel subspace quantization [Schwarz et al., 2013b]
Maximum eigenmode transmission (MET)

\[
H_u = U_u \Sigma_u V_u^H \Rightarrow G_u^{(\text{MET})} = V_u(:,1:L),
\]

\[
H_u^{\text{eff}} = U_u(:,1:L) \text{ diag } (\sigma_1,u,\ldots,\sigma_L,u)
\]

Select \( L \) maximum eigenmodes out of \( N_r \)

Theorem (MET)

\( S \) users are served with \( L \) spatial streams each over i.i.d. Rayleigh fading channels, using \( b \) bits to quantize and feedback the channel state information.

\[
R_{\text{MET}} - R_{\text{MET-Quant}} \leq \sum_{\ell=1}^{L} \log_2 \left( 1 + \rho c_{\text{MET}}^{(\ell)} D_{\text{MET}} \right),
\]

\[
D_{\text{MET}} \propto 2^{-\frac{b}{L(N_t-L)}}, \quad \rho = \frac{P}{\sigma_0^2 S L}, \quad \rho_{\text{dB}} = 10 \log_{10} (\rho)
\]

MET feedback bit-scaling for constant rate offset:

\[
\frac{\partial b}{\partial \rho_{\text{dB}}} \propto L (N_t - L)
\]

[Schwarz and Rupp, 2013b]
Maximum eigenmode transmission (MET)

\[ H_u = U_u \Sigma_u V_u^H \Rightarrow G_u^{(MET)} = V_u(:, 1 : L), \]  
\[ H_u^{\text{eff}} = U_u(:, 1 : L) \text{ diag } (\sigma_{1,u}, \ldots, \sigma_{L,u}) \]  

Select \( L \) maximum eigenmodes out of \( N_r \)

Theorem (MET)

\( S \) users are served with \( L \) spatial streams each over i.i.d. Rayleigh fading channels, using \( b \) bits to quantize and feedback the channel state information.

\[ R_{\text{MET}} - R_{\text{MET-Quant}} \leq \sum_{\ell=1}^{L} \log_2 \left( 1 + \rho \frac{c_{\text{MET}}^{(\ell)} D_{\text{MET}}}{\sigma^2} \right), \]  
\[ D_{\text{MET}} \propto 2^{- \frac{b}{L(N_t - L)}}, \quad \rho = \frac{P}{\sigma^2 S L}, \quad \rho_{\text{dB}} = 10 \log_{10} (\rho) \]  

**MET feedback bit-scaling** for constant rate offset:  
\[ \frac{\partial b}{\partial \rho_{\text{dB}}} \propto L (N_t - L) \]  

---

[Schwarz and Rupp, 2013b]
Subspace quantization based combining (SQBC)

\[
\left\{ G_u^{(SQBC)}, \hat{H}_u^{(SQBC)} \right\} = \arg\min_{G, Q_j \in Q_u} d_c^2 (H_u^{\text{eff}}, Q_j) = \arg\min_{G, Q_j \in Q_u} d_c^2 (H_u G, Q_j)
\]  

\[ (21) \]

- Solution for \( G_u^{(SQBC)} \) available in closed form
- \textbf{Minimize} the subspace \textbf{quantization error}

\textbf{Theorem (SQBC)}

\( S \) users are served with \( L \) spatial streams each over i.i.d. Rayleigh fading channels, using \( b \) bits to quantize and feedback the channel state information.

\[
R_{BD}^{(L)} - R_{SQBC}^{(L,N_r)} \leq L \log_2 \left( 1 + \rho c_{SQBC} D_{SQBC} \right) + d_{SQBC}^{(L,N_r)}, \quad D_{SQBC} \propto 2^{-\frac{b}{L(N_t-N_r)}}
\]

\[ (22) \]

\textbf{SQBC feedback bit-scaling:}

\[
\frac{\partial b}{\partial \rho_{dB}} \propto L (N_t - N_r), \quad \left( \text{MET: } L (N_t - L) \right)
\]

\[ (23) \]

[Schwarz and Rupp, 2013a, Schwarz and Rupp, 2013b]
Subspace quantization based combining (SQBC)

\[
\left\{ \mathbf{G}^{(\text{SQBC})}_u, \mathbf{H}^{(\text{SQBC})}_u \right\} = \arg\min_{\mathbf{G}, \mathbf{Q}_j \in \mathcal{Q}_u} d_c^2 \left( \mathbf{H}^{\text{eff}}_u, \mathbf{Q}_j \right) = \arg\min_{\mathbf{G}, \mathbf{Q}_j \in \mathcal{Q}_u} d_c^2 \left( \mathbf{H}_u \mathbf{G}, \mathbf{Q}_j \right) \tag{21}
\]

- Solution for \( \mathbf{G}_u^{(\text{SQBC})} \) available in closed form
- **Minimize** the subspace quantization error

Theorem (SQBC)

\( S \) users are served with \( L \) spatial streams each over i.i.d. Rayleigh fading channels, using \( b \) bits to quantize and feedback the channel state information.

\[
R^{(L)}_{\text{BD}} - R^{(L, N_r)}_{\text{SQBC}} \leq L \log_2 \left( 1 + \rho c_{\text{SQBC}} D_{\text{SQBC}} \right) + d^{(L, N_r)}_{\text{SQBC}}, \quad D_{\text{SQBC}} \propto 2^{-\frac{b}{L(N_t - N_r)}} \tag{22}
\]

**SQBC feedback bit-scaling:**

\[
\frac{\partial b}{\partial \rho_{\text{dB}}} \propto L (N_t - N_r), \quad \left( \text{MET: } L (N_t - L) \right) \tag{23}
\]

[Schwarz and Rupp, 2013a, Schwarz and Rupp, 2013b]
MET versus SQBC

- $N_t = 6$ transmit antennas, $N_r \in \{2, \ldots, 5\}$ receive antennas, $L = 2$ data streams
- Throughput loss of SQBC with perfect CSI at the base station
MET versus SQBC

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Multi-User MIMO Transmission

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- Feedback overhead for 1 bit/s/Hz rate loss with random vector quantization
- Significant reduction of feedback overhead with SQBC for moderate SNR loss
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SQBC versus MET (2)

- $N_t = 6$ transmit antennas, $N_r \in \{2, 4, 5\}$ receive antennas, $L = 2$ streams
- Comparison of performance with perfect and quantized CSIT
- Feedback overhead scaled for constant rate loss with $N_r = 5$: $b \in [0, 17]$ bits.

**Graph:**
- 95% confidence interval
- $SNR$ [dB]
- Achievable sum rate [bits/s/Hz]
- $N_r = 5$

**Legend:**
- SQBC perfect CSIT
- SQBC quant. CSIT

CSIT... channel state information at the transmitter

Stefan Schwarz
SQBC versus MET (2)

- $N_t = 6$ transmit antennas, $N_r \in \{2, 4, 5\}$ receive antennas, $L = 2$ streams
- Comparison of performance with perfect and quantized CSIT
- Feedback overhead scaled for constant rate loss with $N_r = 5$: $b \in [0, 17]$ bits.

![Graph showing achievable sum rate vs. SNR for SQBC with perfect and quantized CSIT, for $N_r = 4$ and $N_r = 5$.](image-url)

CSIT... channel state information at the transmitter

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SQBC versus MET (2)

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![Graph showing achievable sum rate versus SNR for different values of $N_r$.]
SQBC versus MET (2)

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![Graph showing achievable sum rate vs SNR for different $N_r$ values and CSIT types.](image-url)
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Overview of CoMP in LTE
  CoMP Basics
  3GPP’s View of CoMP

Multi-User MIMO Transmission
  Mathematical System Model
  Block-Diagonalization Precoding
  Antenna Combining

Application Scenario

Conclusions
Evaluated cellular networking architectures

**Macro only network:**
- 120° sectorized antennas, $N_t = 8$ transmit antennas per sector
- Hexagonal grid (2 tiers of interferers)

**Macro-micro overlay network:**
- $N_t = 4$ macro antennas per sector + two micros with $N_t = 2$ antennas each
- Independent operation of macros and micros

**Macro network with remote radio units (RRUs):**
- Two RRUs per sector with $N_t = 2$ omnidirectional antennas each
- Joint transmission CoMP between macros and RRUs

Same total transmit *power* and *same number of antennas* in all networks

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*Same* total transmit **power** and **same number of antennas** in all networks

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Macro Network versus Macro-Micro Overlay Network

- **Low mobility scenario (5 km/h), 8 bit of feedback for CSI quantization**
- **Similar performance with accurate CSIT**
- **Significant gain with** micros and **memoryless quantization** (macro diversity)
- **Reasons for the observed behavior:**
  - No isolation between macro and micro layers (e.g., wall loss)
  - Same total transmit power and total number of transmit antennas
Macro-only Network versus Macro with RRUs

- **Performance improvement with remote radio units:**
  - Perfect CSIT and predictive quantization: ~ 30 – 40%
  - Memoryless quantization: ~ 100%
  - Reduced degradation with memoryless quantization (macro-diversity exploited)
Performance Comparison - Impact of Feedback Overhead

Macro/Micro

- Improvement with micro base stations @ low quantization accuracy
  - Macro network falls back to single-user MIMO
  - Spatial reuse with micros — multiplexing of several users within the same area
**Performance Comparison - Impact of Feedback Overhead**

- **Macro/Micro**
  - 95% confidence interval
  - 8x2 PedC 1.4MHz 8bit 8UE
  - 8x2 PedC 1.4MHz 8bit 8UE

- **Macro/RRUs**
  - 95% confidence interval
  - 8x2 PedC 1.4MHz 8bit 8UE

- **Improvement with micro base stations @ low quantization accuracy**
  - Macro network falls back to single-user MIMO
  - Spatial reuse with micros — multiplexing of several users within the same area

- **Performance with remote radio units always better**
  - Additional macro-diversity
  - Gain of joint transmission CoMP

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Conclusions
Summary and Conclusions

- Facing the expected capacity crunch: *network densification*
- This implies increased *inter-cell interference*
- Solution: *coordination* of transmissions (CoMP)
  - Scheduling, beamforming, joint transmission
  - *Multi-user MIMO* transmission (joint transmission)
    - Dirty paper coding (nonlinear, highly complex)
    - More practical: linear transceivers
  - *Block-Diagonalization* precoding with selfish antenna combining
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Coordinated Multi-Point (CoMP) in LTE
Wireless Communications Seminar

Stefan Schwarz

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March 27, 2014
References

Seven ways that HetNets are a cellular paradigm shift.
*IEEE Communications Magazine*, 51(3):136–144.

A near-optimum technique using linear precoding for the MIMO broadcast channel.
In *IEEE Int. Conf. on Acoustics, Speech and Signal Processing*, volume 3.

white paper.

Writing on dirty paper (corresp.).

Ericsson (2013a).
Ericsson mobility report.
white paper.

Ericsson (2013b).
Traffic exploration tool.
http://www.ericsson.com/TET.
[Online; accessed 03-July-2013].

Capacity limits of MIMO channels.
*IEEE Journal on Selected Areas in Communications*, 21(5):684–702.
References II

A vector-perturbation technique for near-capacity multiantenna multiuser communication-part II: perturbation.

Limited feedback unitary precoding for spatial multiplexing systems.

Noncooperative cellular wireless with unlimited numbers of base station antennas.

Iterative THP transceiver optimization for multi-user MIMO systems based on weighted sum-MSE minimization.
In IEEE 7th Workshop on Signal Processing Advances in Wireless Communications, pages 1–5.

Millimeter wave mobile communications for 5G cellular: It will work!
IEEE Access, 1:335–349.

Limited feedback-based block diagonalization for the MIMO broadcast channel.
References III


