Limited Feedback based Double-Sided Full-Dimension MIMO for Mobile Backhauling

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Motivation – Mobile Backhauling

- Increasing usage of mobile devices in public/private transportation
- Frequently unsatisfactory QoS at high mobility due to PHY/MAC inefficiency
- Promising solution: vehicle-mounted small cells for traffic aggregation
  ⇒ High-performance wireless backhaul required
  ⇒ Directive beamforming utilizing full-dimension (FD) MIMO arrays
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Double-directional channel of user $u$ between RX antenna $i$ and TX antenna $j$:

$$h_{i,j}^{(u)}(t, \tau, \phi_R, \theta_R, \phi_T, \theta_T) = \sum_{c=1}^{N_c} g_u^{(c)} \sum_{r=1}^{N_r} \alpha_u^{(c,r)} a_{i,u}^{(R)}(\phi_R, \theta_R) a_j^{(T)}(\phi_T, \theta_T) \delta(\tau - \tau_u^{(c)}) \delta(\phi_R - \phi_{A,u}^{(c,r)}) \delta(\theta_R - \theta_{A,u}^{(c,r)}) \delta(\phi_T - \phi_{D,u}^{(c,r)}) \delta(\theta_T - \theta_{D,u}^{(c,r)})$$

Time-variant channel impulse response by integrating over $(\phi_R, \theta_R), (\phi_T, \theta_T)$.
Effective subcarrier-wise base-band channel after OFDM processing

\[ y_u[n, k] = g_u[n, k]^H H_u[n, k] \sum_{j \in S} f_j[n, k] s_j[n, k] + g_u[n, k]^H n_u[n, k] \]

CSI at TX obtained via dedicated limited feedback from users

⇒ CSI pilots inserted every \( mT_s \) TTIs on pilot subcarriers \( \mathcal{P} \subseteq \{1, \ldots, K\} \)
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Transceiver Strategies

- Single layer transmission per user + multi-user multiplexing

- Users estimate channel matrices $H_u[n, k], \forall k \in P$ and $n = mT_s$

Geometric approach

- Non-frequency-selective/wide-band processing $\Rightarrow$ potentially in RF

- Max-angular-gain/max-angular SLNR beamforming at TX (updated every $mT_s$ TTIs)

- Max-angular-gain antenna combining at RX (updated every TTI)

Algebraic approach

- Frequency-selective $\Rightarrow$ base-band processing

- Zero-forcing beamforming at TX (updated every $mT_s$ TTIs, nearest-neighbor interpolation)

- MET or blind residual interference cancellation at RX (updated every TTI on each subcarrier)
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**Algebraic approach**
- Frequency-selective $\Rightarrow$ base-band processing
- Zero-forcing beamforming at TX (updated every $mT_s$ TTIs, nearest-neighbor interpolation)
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Max-angular-gain receive beamforming\(^1\)

\[
g_u[n] = \arg \max \sum_{k \in \mathcal{P}} \| g^H H_u[n, k] \|^2,
\]

subject to:

\[
g = a_u^{(R)} (\phi, \theta), \quad (\phi, \theta) \in \Phi_q \times \Theta_q
\]

Effective channel-vector

\[
h_u[n, k] = H_u[n, k]^H g_u[n]
\]

\(^1\) For concreteness we consider UPAs

\[
[a(\phi, \theta)]_{(\ell - 1)N_h + k} = \frac{1}{\sqrt{N_r}} \exp(j2\pi(\delta_v (\ell - 1) \cos \theta) + \delta_h (k - 1) \sin \phi \sin \theta),
\]

\[
\ell \in \{1, \ldots, N_v\}, \quad k \in \{1, \ldots, N_h\}
\]
Geometric Approach – CSI Feedback

Feedback of $N_e$ strongest angular directions and corresponding gains

- Consider the angular energy-distribution

\[
A_1(\phi, \theta) = \sum_{k \in \mathcal{P}} |a(\phi, \theta)^H h_u[n, k]|^2, (\phi, \theta) \in \Phi_q \times \Theta_q
\]

- First direction:

\[
(\phi^{(1)}_{T,u}, \theta^{(1)}_{T,u}) = \arg\max_{(\phi, \theta) \in \Phi_q \times \Theta_q} A_1(\phi, \theta),
\]

\[
g_{1,u} = \text{quant} \left( A_1(\phi^{(1)}_{T,u}, \theta^{(1)}_{T,u}) \right)
\]

- Subtract energy-contribution corresponding to this direction

\[
A_2(\phi, \theta) = \max \left( A_1(\phi, \theta) - g_{1,u} P(\phi, \theta), 0 \right),
\]

\[
P(\phi, \theta) = |a(\phi, \theta)^H a(\phi^{(1)}_{T,u}, \theta^{(1)}_{T,u})|^2
\]

- Iterate to find further directions
- Incoherent energy-based channel decomposition
Geometric Approach – CSI Feedback

Feedback of $N_e$ strongest angular directions and corresponding gains

- Consider the angular energy-distribution

$$A_1(\phi, \theta) = \sum_{k \in P} |a(\phi, \theta) H_u[n, k]|^2, (\phi, \theta) \in \Phi_q \times \Theta_q$$

- First direction:

$$\left( \phi_{T,u}^{(1)}, \theta_{T,u}^{(1)} \right) = \arg\max_{(\phi, \theta) \in \Phi_q \times \Theta_q} A_1(\phi, \theta),$$

$$g_{1,u} = \text{quant} \left( A_1(\phi_{T,u}^{(1)}, \theta_{T,u}^{(1)}) \right)$$

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$$A_2(\phi, \theta) = \max \left( A_1(\phi, \theta) - g_{1,u} P(\phi, \theta), 0 \right),$$

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- Iterate to find further directions
- Incoherent energy-based channel decomposition
Geometric Approach – TX Processing

- Max-angular-gain transmit beamforming

\[ f_j[n] = a(\phi_{T,j}^{(1)}, \theta_{T,j}^{(1)}) \]

- Max-angular-SLNR transmit beamforming (incoherent addition of leakage energy)

\[ f_j[n] = \frac{\tilde{f}_j^{(L)}[n]}{\|\tilde{f}_j^{(L)}[n]\|}, \quad \tilde{f}_j[n] = \left(\sigma_n^2 I_{N_t} + L\right)^{-1} a(\phi_{T,j}^{(1)}, \theta_{T,j}^{(1)}) \]

\[ L = \sum_{\ell \in S, \ell \neq j} \sum_{i=1}^{N_o} g_{i,\ell} a(\phi_{T,\ell}^{(i)}, \theta_{T,\ell}^{(i)}) a(\phi_{T,\ell}^{(i)}, \theta_{T,\ell}^{(i)})^H \]

- Greedy multi-user scheduling based on incoherent SINR estimate
Geometric Approach – TX Processing

- Max-angular-gain transmit beamforming

\[ f_j[n] = a(\phi_{T,j}^{(1)}, \theta_{T,j}^{(1)}) \]

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  (incoherent addition of leakage energy)

\[
\begin{align*}
  f_j[n] &= \frac{\tilde{f}_j^{(L)}[n]}{\|\tilde{f}_j^{(L)}[n]\|}, \\
  \tilde{f}_j[n] &= \left(\sigma_n^2 I_{N_t} + L\right)^{-1} a(\phi_{T,j}^{(1)}, \theta_{T,j}^{(1)}), \\
  L &= \sum_{\ell \in S, \ell \neq j} \sum_{i=1}^{N_e} g_{i,\ell} a(\phi_{T,\ell}^{(i)}, \theta_{T,\ell}^{(i)}) a(\phi_{T,\ell}^{(i)}, \theta_{T,\ell}^{(i)})^H
\end{align*}
\]

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Geometric Approach – TX Processing

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- Greedy multi-user scheduling based on incoherent SINR estimate
Maximum eigenmode transmission (MET)

\[ g_u[n, k] = u_u^{(1)}[n, k], \]

\[ h_u[n, k] = \sigma_u^{(1)}[n, k]v_u^{(1)}[n, k], \]

\[ H_u[n, k] = U_u[n, k]\Sigma_u[n, k]V_u[n, k]^H \]

Maximum expected achievable rate combining (MERC) \(^2\)

\[ \Rightarrow \text{Blind residual interference cancellation based on quantized CSI} \]

\(^2\)S. Schwarz and M. Rupp, *Maximum expected achievable rate combining for limited feedback block-diagonalization*, ICASSP 2015
Algebraic Approach – RX Beamforming

- Maximum eigenmode transmission (MET)

\[ g_u[n, k] = u_u^{(1)}[n, k], \]
\[ h_u[n, k] = \sigma_u^{(1)}[n, k]v_u^{(1)}[n, k], \]
\[ H_u[n, k] = U_u[n, k]\Sigma_u[n, k]V_u[n, k]^H \]

- Maximum expected achievable rate combining (MERC)\(^2\)

⇒ Blind residual interference cancellation based on quantized CSI

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\(^2\)S. Schwarz and M. Rupp, *Maximum expected achievable rate combining for limited feedback block-diagonalization*, ICASSP 2015
Decompose the channel into a sum of plane-waves using an over-complete basis of quantized directions $\Phi_q \times \Theta_q$

$$\left\{ g_i, u[k], \phi_{T, u}^{(i)}[k], \theta_{T, u}^{(i)}[k] \right\} = \arg\min_{g_i, (\phi_i, \theta_i)} \left\| h_u[n, k] - \sum_{i=1}^{N_e} g_i a_P(\phi_i, \theta_i) \right\|_2^2,$$

subject to:

$$g_i \in \mathbb{C}, \ (\phi_i, \theta_i) \in \Phi_q \times \Theta_q$$

Iterative solution using orthogonal matching pursuit (OMP) – perfect reconstruction with at most $N_t$ coefficients

Coherent channel decomposition

Frequency-selective feedback on CSI pilot positions
Algebraic Approach – TX Processing

- Frequency-selective **greedy** multi-user **scheduling** \(^3\)
  \(\Rightarrow\) Constant schedule in-between CSI feedback positions in time and frequency

- **Zero-forcing (ZF) beamforming** based on quantized CSI
  \(\Rightarrow\) increasing CSI mismatch over time is neglected

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Simulation Setup

- One base station serving ten UEs at 2.1 GHz
- UEs traveling at approx. 50 km/h (100 Hz Doppler)
- UPA of dimension 10 × 10 at TX
- UPA of dimension \{1 \times 1, 2 \times 2, 4 \times 4\} at RX
- Microscopic fading only at SNR = 20 dB
- CSI feedback every \(mT_s = 10\) TTI (delayless)
- Non-line of sight propagation (3GPP 3D model)
- Normalized TTI: \(\tau_s f_d, \tau_s \in [0, mT_s - 1]\)
- Feedback of \(N_e = 4\) angular directions
Angular CSI Feedback

Fig. 1: Angular CSI feedback of the geometric method (left) and the algebraic method (right).

- Geometric method: $N_e$ peaks of signal-energy distribution
- Algebraic method: phase-coherent decomposition into $N_e$ multipath-components
Fig. 2: Max gain transmit beamforming (left) and max SLNR transmit beamforming (right).

- Max gain: largest signal gain but potentially strong interference
- Max SLNR: decreased interference for the cost of reduced intended signal

⇒ Smart multi-user scheduling important in both cases
Achievable Rate Comparison $1 \times 1$

- Large achievable rate of BD (algebraic method) with accurate CSI
- More robust behavior of geometric beamforming $\Leftrightarrow$ angles change slowly
Achievable Rate Comparison $2 \times 2$

- Similar behavior with multiple RX and interference-ignorant receivers
- Significant performance gain through RX-side interference-suppression

Graph showing achievable rate comparison with different scenarios:
- BD perfect CSI
- BD-MET $F_s=1$
- BD-MET $F_s=12$
- Single user perfect CSI
- Max SLNR $F_s=72$
- Max Gain $F_s=72$
Achievable Rate Comparison $2 \times 2$

- Similar behavior with multiple RX and interference-ignorant receivers
- Significant performance gain through RX-side interference-suppression
Achievable Rate Comparison 4 × 4

- Sufficient spatial degrees of freedom to virtually suppress all residual interference (even blindly)
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Summary and Outlook

- Geometric beamforming performs more robustly
- Algebraic approach has much higher spatial multiplexing potential/capabilities
- Hardware-complexity advantages of geometric approach
- Without RX-side interference-suppression geometric beamforming with imperfect CSI outperforms algebraic approach
- RX-side interference-suppression can safe the day (even blindly)
- Selection of appropriate method depending on CSI accuracy
- Combination of geometric TX beamforming (robustness) and algebraic RX beamforming (interference-suppression)
- Hybrid combination of both methods
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