Low Resolution Phase Shifters Suffice for Full-Duplex mmWave Communications

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Need for higher rates in 5G

Global mobile data traffic (exabytes per month)

5G data traffic
4G/3G/2G data traffic

How to meet this demand?
- ↑ antennas at the base station → massive MIMO
- ↑ spectrum → mmWave
- ↑ cells → densification
- ↑ spectral efficient? → evolve half-duplex (HD)

Half-Duplex

Tx
Rx

$f_1$
$f_2$
Why full-duplex and mmWave?

- High pathloss $\rightarrow$ low UL-to-DL interference
- Narrow beams $\rightarrow$ reduced Self-Interference (SI)

Recent advances on SI
- Practical SI cancellation in SISO, MIMO, and mmWave
  [Duarte12-TWC, Bharadia13-SIGCOMM, Everett16-TWC, Krishnaswamy16]
  - Full-duplex is possible
Outline

1. Overview of FD & mmWave Communications
2. System Model & Problem Formulation
3. Solution Approach using Penalty Dual Decomposition
4. Numerical Results and Discussions
5. Concluding remarks
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mmWave characteristics in cellular networks

Benefits
- Huge bandwidth available
- Limited by noise and not interference (usually)
Challenges

- **High** pathloss and attenuations
- Need sharp beams to counter the pathloss
- Fully digital precoding too costly
FD mmWave characteristics in cellular networks

Benefits

- High pathloss → low UL-to-DL interference
- Narrow beams → reduced SI
Challenges

- Hybrid beamforming → complex due to UL/DL coupling
- Low resolution phase shifter → no additional analog device in full-duplex
Research gap in FD mmWave networks

Need for joint architecture

- Joint full-duplex & mmWave
  - Short range communication
  - Limited UL-to-DL interference
  - Potential reduction in SI with precoding

Lack of efficient cross-layer procedures

- What is the optimal hybrid beamforming algorithm under practical considerations?
  - Digital SI cancellation → precoding to help mitigate SI
  - Hybrid precoding architecture → Base station and users
  - Practical analog precoding → quantized phase shifter
  - Performance analysis → sum spectral efficiency
Sum Spectral Efficiency Maximization

- Hybrid precoding $\rightarrow$ equivalence sum spectral efficiency maximization & WMMSE minimization
- WMMSE minimization $\rightarrow$ nonconvex optimization with coupling constraints
- Spectral efficiency gains $\rightarrow$ Yes, even with 1-bit phase shifter
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Single-cell cellular system $\rightarrow$ only BS is FD-capable

- $M_{Tx}/M_{Rx}$ antennas & $M_{RF}$ RF chains at BS
- Single-antenna UL/DL users
- Flat fading channel with $L$ paths $\rightarrow \mathbf{h}_u \in \mathbb{C}^{M_{Rx} \times 1}$, $\mathbf{h}_d \in \mathbb{C}^{M_{Tx} \times 1}$

- SI cancellation matrix $\rightarrow \mathbf{H}_{SI} \in \mathbb{C}^{M_{Rx} \times M_{Tx}}$
System model (2/3)

- Hybrid precoding/combining at BS and UE
- $N_b$ bits to quantize elements of analog precoder/combiner
  \[ \mathcal{A} = \{\exp\left(\frac{2\pi i k_b}{2^{N_b}}\right) | k_b = 0, 1, \ldots, 2^{N_b} - 1\} \]

<table>
<thead>
<tr>
<th></th>
<th>UL</th>
<th>DL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precoder</td>
<td>$w_u = w_u^{RF} w_u^{BB}$</td>
<td>$f_d = F_{RF} f_d^{BB} \in \mathbb{C}^{M_{Tx} \times 1}$</td>
</tr>
<tr>
<td>Combiner</td>
<td>$q_u = Q_{RF} q_u^{BB} \in \mathbb{C}^{M_{Rx} \times 1}$</td>
<td>$v_d = v_d^{RF} v_d^{BB}$</td>
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Mairton Barros (jmbdsj@kth.se) | ICC’19 (W17-FDCOMM) | System Model & Problem Formulation 8/20
UL and DL received signals

\[ y_U = h_u w_u s_u + H_{SI} f_d s_d + n_U, \quad y_d = h_d^H f_d s_d + n_d. \]

The spectral efficiencies of UL/DL are

\[ R^u = \log_2 \left( 1 + \frac{|w_u q_u^H h_u|^2}{q_u^H \Psi_u q_u} \right), \quad R^d = \log_2 \left( 1 + \frac{|v_d^H h_d^H f_d|^2}{|v_d|^2 \psi_d} \right). \]

where \( \Psi_u \) and \( \psi_d \) are

\[ \Psi_u = H_{SI} f_d f_d^H H_{SI}^H + \sigma^2 I_{M_{Tx}}, \quad \psi_d = \sigma^2. \]
Spectral efficiency maximization problem

- UL/DL hybrid precoding for spectral efficiency maximization

\[
\begin{align*}
\text{maximize} & \quad R_u + R_d \\
\text{subject to} & \quad \text{tr} \left( f_d f_d^H \right) \leq P_{\text{max}}^d, \quad (\text{Maximum Tx. power DL}) \\
& \quad |w_u|^2 \leq P_{\text{max}}^u, \quad (\text{Maximum Tx. power UL}) \\
& \quad |[F_{RF}]_{r,s}| = 1 \forall (r, s), \quad (\text{Unit DL Prec.}) \\
& \quad |Q_{RF}| = 1, \quad (\text{Unit UL Prec.}) \\
& \quad |v_d|^2 \leq 1, \quad (\text{Unit DL Comb.}) \\
& \quad |q_u|^2 = 1, \quad (\text{Unit UL Comb.}) \\
& \quad F_{RF}, w_u, Q_{RF}, v_d \in \mathcal{A}. \quad (\text{Quant. association})
\end{align*}
\]

- Nonconvex problem with coupling and constant modulus constraints
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Solution approach

- Equivalent weighted minimum MSE (WMMSE) problem reformulation
  - Linear instead of logarithmic relations
  - Coupling & unit modulus constraints still present

- Penalty Dual Decomposition (PDD) relaxation
  - Nonsmooth and nonconvex constraints not a problem
  - Auxiliary variables instead of coupling constraints
  - Block coordinate descent + Lagrangian updates $\rightarrow$ dual loop iterative solution
  - Convergence to stationary solution for infinite phase shifter resolution
WMMSE Minimization Equivalence

- UL and DL mean squared error (MSE)

\[ E_u = \left| 1 - \mathbf{q}_u^\mathsf{H} \mathbf{h}_u \mathbf{w}_u \right|^2 + \mathbf{q}_u^\mathsf{H} \mathbf{\Psi}_u \mathbf{q}_u, \quad E_d = \left| 1 - \mathbf{v}_d^\mathsf{H} \mathbf{h}_d \mathbf{f}_d \right|^2 + |\mathbf{v}_d|^2 \psi_d, \]

- Sum SE maximization \(\leftrightarrow\) WMMSE minimization [Shi11-TSP]

\[
\minimize_{\{\rho_u, \rho_d\}, \{\mathbf{F}_{RF}, \mathbf{f}_{BB}^d\}, \{\mathbf{w}_{RF}^u, \mathbf{w}_{BB}^u\}, \{\mathbf{v}_{RF}^d, \mathbf{v}_{BB}^d\}, \{\mathbf{Q}_{RF}, \mathbf{q}_{BB}^u\}} (\rho_u E_u - \log(\rho_u)) + (\rho_d E_d - \log(\rho_d))
\]

subject to previous constraints.
Solve nonconvex and nonsmooth optimization problems [Shi2017]
- Differentiable and nonsmooth term in the objective function
- Coupling and nonconvex constraints
- Lagrangian duality $\rightarrow$ coupling constraints by penalty terms in objective function
- Introduce two auxiliary variables $\rightarrow z_u = w_u$ and $z_d = f_d$
- Dual loop iterative solution approach
PDD Problem Reformulation

- Relaxed problem using PDD

\[
\begin{aligned}
\text{minimize} & \quad \{ \rho_u E_u - \log(\rho_u) \} + \{ \rho_d E_d - \log(\rho_d) \} + \\
& \quad \frac{1}{2\delta} \left| z_u - w_u^{RF} w_u^{BB} + \delta \lambda_u \right|^2 + \\
& \quad \frac{1}{2\delta} \left\| z_d - F_{RF} f_d^{BB} + \delta \lambda_d \right\|_2 \\
\text{subject to} & \quad \text{tr} \left( z_d z_d^H \right) \leq P_d^{\text{max}}, \quad (\text{DL Power Constraint}) \\
& \quad z_u z_u^H \leq P_u^{\text{max}}, \quad (\text{UL Power Constraint}) \\
& \quad \text{previous constraints.}
\end{aligned}
\]
Solution Steps using BCD

- Separate the variables in blocks → use BCD to randomly update the blocks
- The block variables are
  1. WMMSE weights: \( \{\rho_u, \rho_d\} \)
  2. Baseband combiners: \( \{q_{BB}^u, v_{BB}^d\} \)
  3. Baseband precoders: \( \{w_{BB}^u, f_{BB}^d\} \)
  4. Auxiliary variables: \( \{z_u, z_d\} \)
  5. Analog combiners: \( \{v_{RF}^d, Q_{RF}\} \)
  6. Analog precoders: \( \{w_{RF}^u, F_{RF}\} \)
- Update Lagrangian multipliers \( \lambda_u, \lambda_d \) if constraint violations lower than threshold
- Update penalty term \( \delta \) if condition above does not hold
Summary

- Convergence criteria → small constraint violations
- Infinite phase shifter resolution at analog precoder/combiner → convergence to stationary solution
- Quantized phase shifter at analog precoder/combiner → suboptimal sequence of updates
- Number of iterations depend on
  - Required constraint violation
  - Updates in the penalty terms and Lagrangian multipliers
  - Number of antennas (matrix operations)
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Simulation Parameters

- $M_{Tx} = 64$ and $M_{RF} = 4$
- Digital SI cancellation only
  - Analog SI cancellation too costly
  - Split antennas between Tx and Rx
  - Use precoding to mitigate remaining SI
  - Residual SI power after cancellation
    \[\rightarrow -20 \log_{10} \sigma_{SI} = [-25 \quad -20 \quad \cdots \quad -5] \text{dB}\]
- 28 GHz and pathloss models according to [Akdeniz2014]
- Number of quantization bits $\rightarrow [6 \ 3 \ 1]$
- Benchmark solutions
  - Half-Duplex
  - Inf-resolution phase shifter
Convergence of Proposed Solution

- Smooth and fast convergence using just 1-bit phase shifter
- 1-bit phase shifter
- 29% gain compared to HD
- Outperforms HD even with low digital SI cancellation
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Some takeaways & Future works

Takeaway message

- Sum spectral efficiency maximization in FD mmWave networks
  - Non-trivial optimization problem
  - Use PDD to obtain optimal/close-to-optimal solution
- Full-duplex mmWave is possible
  - Outperforms HD for practical digital SI cancellation
  - Gains in spectral efficiency for even 1-bit phase shifter

Next steps

- Why do 1 or few bits work so well?
- Different # of antennas and RF chains → impact of quantization in phase shifters?
- Low-resolution ADCs
Some references (1/2)


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