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Low Resolution Phase Shifters Suffice for Full-Duplex mmWave Communications

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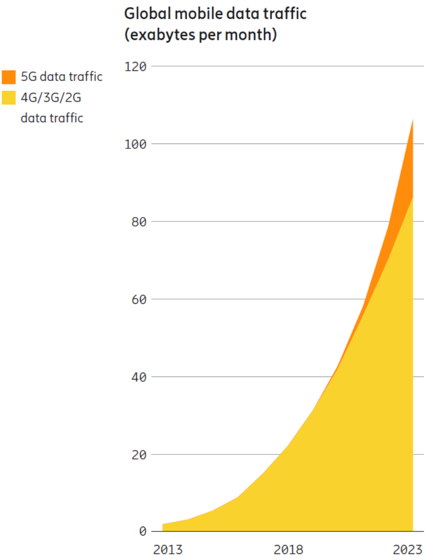
Need for higher rates in 5G

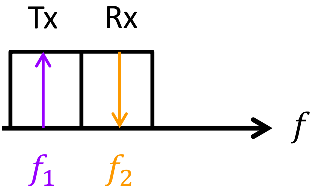


[Ericsson18]

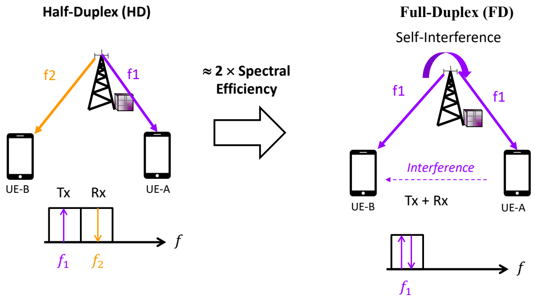
How to meet this demand?

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

Half-Duplex



Why full-duplex and mmWave?



- High pathloss → low UL-to-DL interference
- Narrow beams → 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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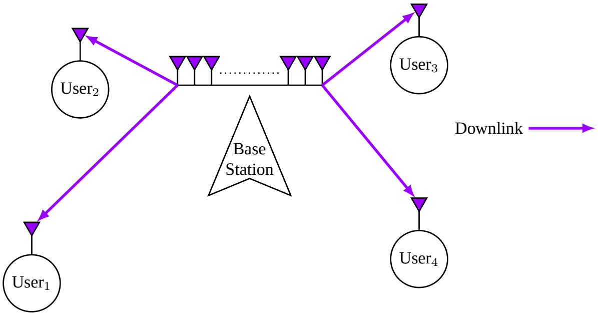
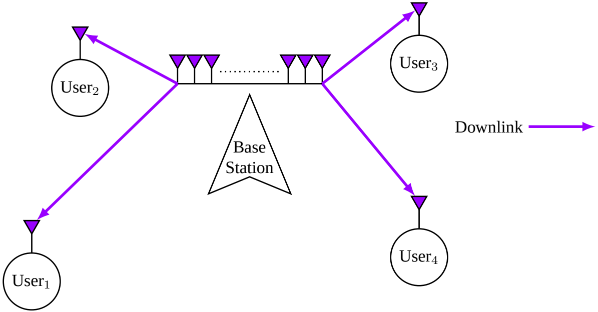
mmWave characteristics in cellular networks



Benefits

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

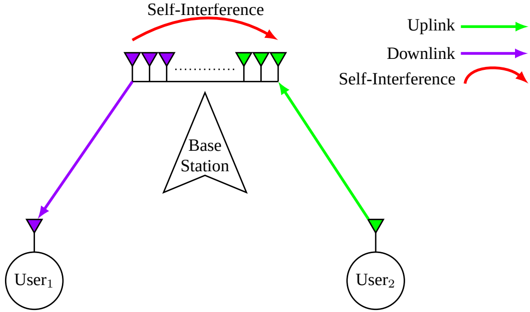
mmWave characteristics in cellular networks



Challenges

- High pathloss and attenuations
- Need sharp beams to counter the pathloss
- Fully digital precoding too costly

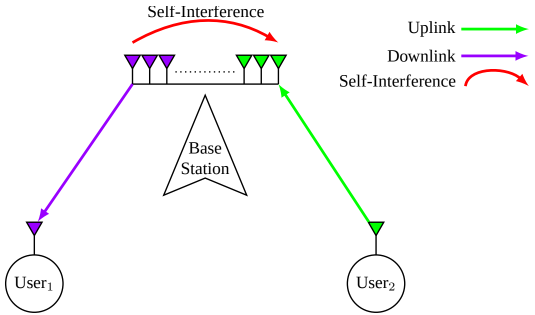
FD mmWave characteristics in cellular networks



Benefits

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

FD mmWave characteristics in cellular networks



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

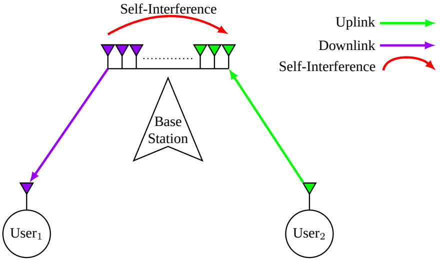
Need for joint architecture

- 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

Contributions



Sum Spectral Efficiency Maximization

- Hybrid precoding → equivalence sum spectral efficiency maximization & WMMSE minimization
- WMMSE minimization → nonconvex optimization with coupling constraints
- Spectral efficiency gains → Yes, even with 1-bit phase shifter

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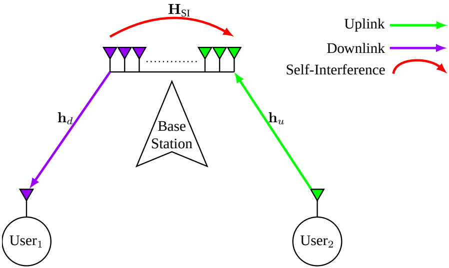
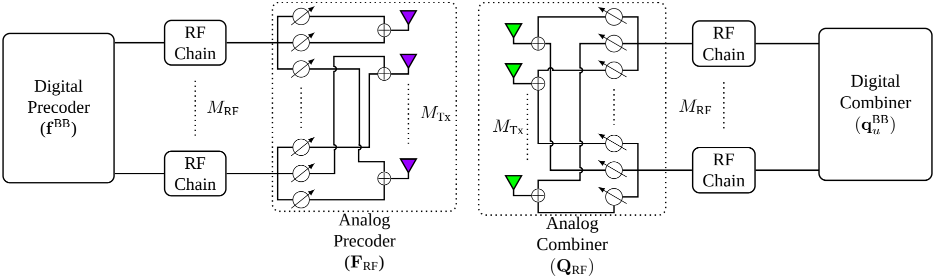
System model (1/3)



- Single-cell cellular system $\rightarrow$ only BS is FD-capable
- $M_{\mathsf{Tx}}/M_{\mathsf{Rx}}$ antennas $\&$ M_{RF} RF chains at BS
- Single-antenna UL/DL users
- Flat fading channel with L paths $\rightarrow$ $\mathbf{h}_u \in \mathcal{C}^{M_{\mathsf{Rx}} \times 1}$, $\mathbf{h}_d \in \mathcal{C}^{M_{\mathsf{Tx}} \times 1}$
- SI cancellation matrix $\rightarrow$ $\mathbf{H}_{\mathsf{SI}} \in \mathbb{C}^{M_{\mathsf{Rx}} \times M_{\mathsf{Tx}}}$

System model (2/3)



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

	UL	DL
Precoder	$w_u = w_u^{\text{RF}} w_u^{\text{BB}}$	$\mathbf{f}_d = \mathbf{F}_{\text{RF}} \mathbf{f}_d^{\text{BB}} \in \mathcal{C}^{M_{\text{Tx}} \times 1}$
Combiner	$\mathbf{q}_u = \mathbf{Q}_{\text{RF}} \mathbf{q}_u^{\text{BB}} \in \mathcal{C}^{M_{\text{Rx}} \times 1}$	$v_d = v_d^{\text{RF}} v_d^{\text{BB}}$

- UL and DL received signals

$$\mathbf{y}_U = \underbrace{\mathbf{h}_u w_u s_u}_{\text{Tx signal}} + \underbrace{\mathbf{H}_{\mathsf{SI}} \mathbf{f}_d s_d}_{\text{Self-Interference}} + \underbrace{\mathbf{n}_U}_{\text{Noise}}, \quad y_d = \underbrace{\mathbf{h}_d^{\mathrm{H}} \mathbf{f}_d s_d}_{\text{Tx signal}} + \underbrace{n_d}_{\text{Noise}}.$$

- The spectral efficiencies of UL/DL are

$$R^u = \log_2 \left(1 + \frac{\left| w_u \mathbf{q}_u^{\mathsf{H}} \mathbf{h}_u \right|^2}{\mathbf{q}_u^{\mathsf{H}} \mathbf{\Psi}_u \mathbf{q}_u} \right), \quad R^d = \log_2 \left(1 + \frac{\left| v_d^{\mathsf{H}} \mathbf{h}_d^{\mathsf{H}} \mathbf{f}_d \right|^2}{\left| v_d \right|^2 \psi_d} \right).$$

where $\mathbf{\Psi}_u$ and ψ_d are

$$\mathbf{\Psi}_u = \mathbf{H}_{\mathsf{SI}} \mathbf{f}_d \mathbf{f}_d^{\mathsf{H}} \mathbf{H}_{\mathsf{SI}}^{\mathsf{H}} + \sigma^2 \mathbf{I}_{M_{\mathsf{Tx}}}, \quad \psi_d = \sigma^2.$$

Spectral efficiency maximization problem

- UL/DL hybrid precoding for spectral efficiency maximization

$$
\begin{aligned}
\underset{\substack{\{\mathbf{F}_{\mathsf{RF}},\mathbf{f}_d^{\mathsf{BB}}\},\{w_u^{\mathsf{RF}},w_u^{\mathsf{BB}}\}\\ \{v_d^{\mathsf{RF}},v_d^{\mathsf{BB}}\},\{\mathbf{Q}_{\mathsf{RF}},\mathbf{q}_u^{\mathsf{BB}}\}}}{\text{maximize}} \quad & R_u + R_d && \text{(Objective)}\\
\text{subject to} \quad & \operatorname{tr}\left(\mathbf{f}_d \mathbf{f}_d^{\mathsf{H}}\right) \leq P_{\mathsf{max}}^d, && \text{(Maximum Tx. power DL)}\\
& |w_u|^2 \leq P_{\mathsf{max}}^u, && \text{(Maximum Tx. power UL)}\\
& |[\mathbf{F}_{\mathsf{RF}}]_{r,s}| = 1\, \forall (r,s), && \text{(Unit DL Prec.)}\\
& \left| w_u^{\mathsf{RF}} \right| = 1, && \text{(Unit UL Prec.)}\\
& |[\mathbf{Q}_{\mathsf{RF}}]_{r,s}| = 1\, \forall (r,s), && \text{(Unit UL Comb.)}\\
& \left| v_d^{\mathsf{RF}} \right| = 1, && \text{(Unit DL Comb.)}\\
& \mathbf{F}_{\mathsf{RF}}, w_u^{\mathsf{RF}}, \mathbf{Q}_{\mathsf{RF}}, v_d^{\mathsf{RF}} \in \mathcal{A}. && \text{(Quant. association)}
\end{aligned}
$$

- Nonconvex problem with coupling and constant modulus constraints

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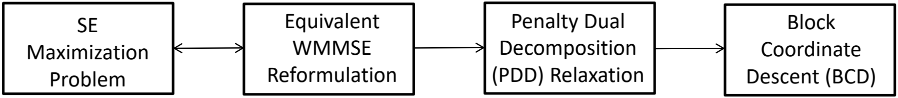
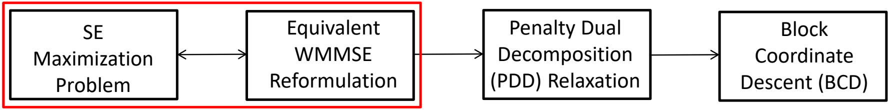
Solution approach



- 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)

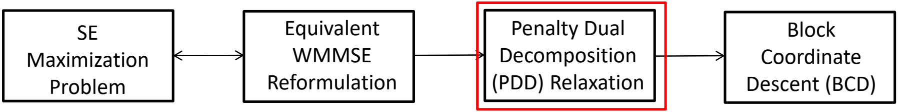
$$E_u = \underbrace{\left|1 - \mathbf{q}_u^{\mathsf{H}} \mathbf{h}_u w_u\right|^2}_{\text{Tx Signal}} + \underbrace{\mathbf{q}_u^{\mathsf{H}} \mathbf{\Psi}_u \mathbf{q}_u}_{\text{Interf. + Noise}}, \quad E_d = \left|1 - v_d^{\mathsf{H}} \mathbf{h}_d^{\mathsf{H}} \mathbf{f}_d\right|^2 + |v_d|^2 \psi_d,$$

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

$$\underset{\substack{\{\rho_u, \rho_d\}, \{\mathbf{F}_{\mathsf{RF}}, \mathbf{f}_d^{\mathsf{BB}}\}, \\ \{w_u^{\mathsf{RF}}, w_u^{\mathsf{BB}}\}, \{v_d^{\mathsf{RF}}, v_d^{\mathsf{BB}}\} \\ \{\mathbf{Q}_{\mathsf{RF}}, \mathbf{q}_u^{\mathsf{BB}}\}}}{\text{minimize}} \quad (\rho_u E_u - \log(\rho_u)) + (\rho_d E_d - \log(\rho_d))$$

subject to previous constraints.

Penalty Dual Decomposition



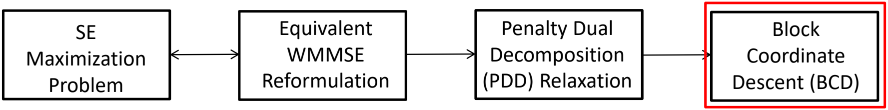
- Solve nonconvex and nonsmooth optimization problems [Shi2017]
  - Differentiable and nonsmooth term in the objective function
  - Coupling and nonconvex constraints
- Lagrangian duality $\rightarrow$ coupling constraints by penalty terms in objective function
- Introduce two auxiliary variables $\rightarrow$ $z_u = w_u$ and $\mathbf{z}_d = \mathbf{f}_d$
- Dual loop iterative solution approach

PDD Problem Reformulation

- Relaxed problem using PDD

$$
\begin{aligned}
\underset{\substack{\{z_u,\mathbf{z}_d\},\{\rho_u,\rho_d\}\\ \{\mathbf{F}_{\mathsf{RF}},\mathbf{f}_d^{\mathsf{BB}}\},\{w_u^{\mathsf{RF}},w_u^{\mathsf{BB}}\}\\ \{v_d^{\mathsf{RF}},v_d^{\mathsf{BB}}\},\{\mathbf{Q}_{\mathsf{RF}},\mathbf{q}_u^{\mathsf{BB}}\}}}{\text{minimize}} \quad & (\rho_u E_u - \log(\rho_u)) + (\rho_d E_d - \log(\rho_d)) + \\
& \underbrace{\frac{1}{2\delta}\left|z_u - w_u^{\mathsf{RF}} w_u^{\mathsf{BB}} + \delta\lambda_u\right|^2}_{\text{UL Penalty}} + \\
& \underbrace{\frac{1}{2\delta}\left\|\mathbf{z}_d - \mathbf{F}_{\mathsf{RF}}\mathbf{f}_d^{\mathsf{BB}} + \delta\boldsymbol{\lambda}_d\right\|_2}_{\text{DL Penalty}} \\
\text{subject to} \quad & \mathrm{tr}\left(\mathbf{z}_d\mathbf{z}_d^{\mathsf{H}}\right) \le P_{\mathsf{max}}^d, \quad \text{(DL Power Constraint)} \\
& z_u z_u^{\mathsf{H}} \le P_{\mathsf{max}}^u, \quad \text{(UL Power Constraint)} \\
& \text{previous constraints.}
\end{aligned}
$$

Solution Steps using BCD



- Separate the variables in blocks $\rightarrow$ use BCD to randomly update the blocks
- The block variables are
  1. WMMSE weights: $\{\rho_u, \rho_d\}$
  2. Baseband combiners: $\{\mathbf{q}_u^{\text{BB}}, v_d^{\text{BB}}\}$
  3. Baseband precoders: $\{w_u^{\text{BB}}, \mathbf{f}_d^{\text{BB}}\}$
  4. Auxiliary variables: $\{z_u, \mathbf{z}_d\}$
  5. Analog combiners: $\{v_d^{\text{RF}}, \mathbf{Q}_{\text{RF}}\}$
  6. Analog precoders: $\{w_u^{\text{RF}}, \mathbf{F}_{\text{RF}}\}$
- Update Lagrangian multipliers $\lambda_u, \boldsymbol{\lambda}_d$ if constraint violations lower than threshold
- Update penalty term δ if condition above does not hold

Summary

- Convergence criteria $\rightarrow$ small constraint violations
- Infinite phase shifter resolution at analog precoder/combiner $\rightarrow$ convergence to stationary solution
- Quantized phase shifter at analog precoder/combiner $\rightarrow$ 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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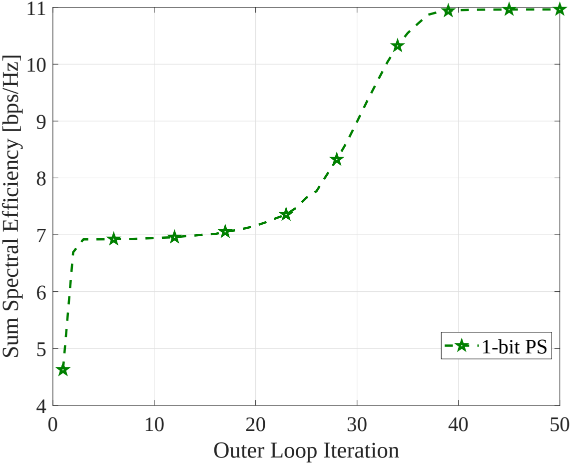
Simulation Paramters

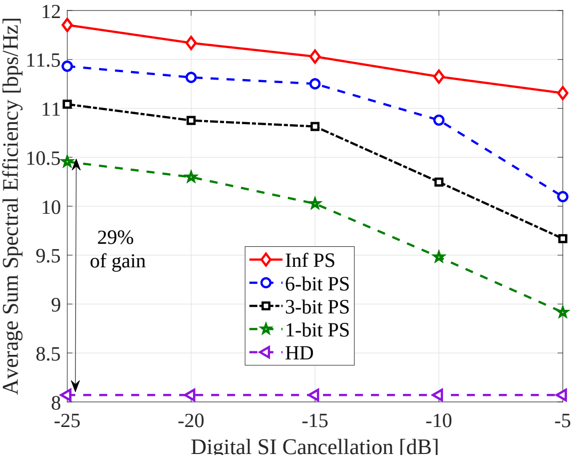
- $M_{\mathsf{Tx}} = 64$ and $M_{\mathsf{RF}} = 4$
- Digital SI cancellation only
  - Analog SI cancellation too costly
  - Split antennas between Tx and Rx
  - Use precoding to mitigate remaining SI
  - Residual SI power after cancellation
    $\rightarrow\ -20\log_{10}\sigma_{\mathsf{SI}} = [-25\ -20\ \cdots\ -5]$dB
- $28\,\mathrm{GHz}$ 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

Average Spectral Efficiency × Digital SI Cancellation



- 1-bit phase shifter
  - 29% gain compared to HD
  - Outperforms HD even with low digital SI cancellation

Outline

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

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