Hybrid Precoding for Millimeter Wave MIMO Systems
- Algorithm Design and Hardware Implementation

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Collaborators

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Hybrid Precoding for mm-Wave MIMO Systems

Outline

- Background and Motivation
- Introduction to Hybrid Precoding
- Algorithm Design & Hardware Implementation
  - Single Phase Shifter (SPS) Implementation
  - Double Phase Shifter (DPS) Implementation
  - Fixed Phase Shifter (FPS) Implementation
- Conclusions
Hybrid Precoding for mm-Wave MIMO Systems

Background and Motivation

- **Spectrum crunch: A fundamental bottleneck**

- **mm-wave bands: Less congested, more bandwidth**

[U.S. Frequency Allocation Chart as of October 2011]
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Background and Motivation

Severe rain attenuation

Huge path loss

Sensitive to blockage

[G. R. MacCartney et al., 2013]
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Background and Motivation

- Large-scale antennas can be patched together
  - Large antenna gain to compensate the path loss

- Conventional Approach: **Analog beamforming**
  - State-of-art in mm-wave WiGig systems [E. Perahia et al., 2010]
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Introduction to Hybrid Precoding

- **New transceiver architecture**

  - Sub-6 GHz systems: fully digital precoder
  - mm-wave systems: hybrid precoder

- **Key differentiating component**
  - Mapping from RF chains to antennas

  - $N^t_{RF} < N_t$

- **Q1**: Can it approach the performance of the fully digital precoding?

- **Q2**: How many RF chains are needed?
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Introduction to Hybrid Precoding

- Analog RF precoder structure

  ➢ Signal flow determines the “mapping strategy”

Q3: How to connect RF chains and antennas?
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Introduction to Hybrid Precoding

- Analog RF precoder structure (cont’d)
  - Adopted hardware determines the “implementation”
  - For each connected signal flow

Q4: How many phase shifters are needed?
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Introduction to Hybrid Precoding

- General multiuser multicarrier systems

- One single digital precoder $F_{BBk,f}$ for each user on each subcarrier
- Analog precoder $F_{RF}$ is shared by all the users and subcarriers
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Introduction to Hybrid Precoding

Problem formulation

- Minimize the Euclidean distance between the hybrid precoders and the fully digital precoder [O. El Ayach et al., 2014]

\[
\text{minimize}_{F_{RF}, F_{BB}} \| F_{opt} - F_{RF} F_{BB} \|_F^2
\]

subject to

\[
\| F_{RF} F_{BB} \|_F^2 \leq P_{max}
\]

\( F_{RF} \in A_x \)

Power constraint

Difficulty

\( A_x \) varies according to different mappings and implementations

\[
F_{opt} = \begin{bmatrix} F_{opt_{1,1}}, \cdots, F_{opt_{k,f}}, \cdots, F_{opt_{K,F}} \end{bmatrix} \in N_t \times KN_s F
\]

\[
F_{BB} = \begin{bmatrix} F_{BB_{1,1}}, \cdots, F_{BB_{k,f}}, \cdots, F_{BB_{K,F}} \end{bmatrix} \in N_{RF}^t \times KN_s F
\]

Q4: How to efficiently design hybrid precoding algorithms?
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Introduction to Hybrid Precoding

❖ Existing works

➢ Most focused on the SPS implementation

■ Orthogonal Matching Pursuit (OMP) [O. El Ayach et al., 2014] [T. E. Bogale et al., 2014]
  ❖ A candidate set for $F_{RF}$
  ❖ Array response vectors or DFT matrix

■ Channel phase extraction [L. Liang et al., 2014]

■ Successive interference cancellation (SIC) [X. Gao et al., 2016]

➢ How to achieve the fully digital precoder [E. Zhang et al., 2014] [T. E. Bogale et al., 2016]

■ Large numbers of RF chains and PSs needed
Introduction to Hybrid Precoding

- Performance metrics
  - “Scoring triangle”

Baseline: SPS fully-connected with OMP
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Key Questions

- **Q1**: Can hybrid precoder provide performance close to the fully digital one?
- **Q2**: How many RF chains are needed?
- **Q3**: How to connect the RF chains and antennas?
- **Q4**: How many phase shifters are needed?
- **Q5**: How to efficiently design hybrid precoding algorithms?
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Key Design Aspects

- **Hardware complexity (# hardware components)**
- **Computational efficiency of precoding algorithms**
- **Achievable spectrum efficiency**
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Algorithm Design & Hardware Implementation I: SPS

❖ Single phase shifter (SPS) implementation

![Diagram of RF Chain with phase shifters and summing nodes]

\[ N = \begin{cases} 
N_t & \text{fully-connected} \\
N_t/N_{RF}^t & \text{partially-connected} 
\end{cases} \]

❖ Fully digital achieving condition:

\[ N_{RF}^t = 2KN_s, \quad N_{RF}^r = 2N_s \]

Q: Can we further reduce the number of RF chains?

Hybrid Precoding for mm-Wave MIMO Systems
Algorithm Design & Hardware Implementation I: SPS

- Fully-connected mapping

$$\minimize_{F_{RF}, F_{BB}} \| F_{opt} - F_{RF} F_{BB} \|^2_F$$

- Digital precoder: $F_{BB} = F_{RF}^\dagger F_{opt}$

- Difficulty: Analog precoder design with the unit modulus constraints

$$\minimize_{F_{RF}, F_{BB}} \| F_{opt} - F_{RF} F_{BB} \|^2_F$$
subject to $| (F_{RF})_{i,j} | = 1, \forall i, j.$

- The vector $x = \text{vec}(F_{RF})$ forms a complex circle manifold

$$\mathcal{M}^m = \{ x \in \mathbb{C}^m : |x_1| = |x_2| = \cdots = |x_m| = 1 \}, \quad m = N_t N_{RF}^t.$$
3 key elements in manifold optimization

Tangent space:
\[ T_\mathcal{M}^m = \{ y \in \mathbb{C}^m : \Re \{ y \circ x^* \} = 0_m \} \]

Riemannian gradient
\[ \nabla f(x) = \text{Proj}_x \nabla f(x) = \nabla f(x) - \Re \{ \text{diag} \{ \nabla f(x) \circ x^* \} \} x \]
\[ \nabla f(x) = -2(F_{BB}^* \otimes I_{N_t}) \left[ \text{vec} (F_{opt}) - (F_{BB}^T \otimes I_{N_t}) x \right] \]

Retraction:
\[ \text{Retr}_x : T_\mathcal{M}^m \to \mathcal{M}^m : \]
\[ \alpha d \mapsto \text{Retr}_x(\alpha d) = \text{vec} \left[ \frac{(x + \alpha d)_i}{|(x + \alpha d)_i|} \right] \]

Conjugate gradient algorithm

Local optimum guaranteed
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Algorithm Design & Hardware Implementation I: SPS

- Partially-connected mapping
  - Block diagonal structure of $F_{RF}$

$$F_{RF} = \begin{bmatrix} p_1 & 0 & \cdots & 0 \\ 0 & p_2 & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & p_{N_{RF}^t} \end{bmatrix}$$

$$p_i = \begin{bmatrix} \exp\left(j\theta_{(i-1)\frac{N_t}{N_{RF}}+1}\right), \cdots, \exp\left(j\theta_{i\frac{N_t}{N_{RF}}}\right) \end{bmatrix}^T$$

Phase shifters connected to the $i$-th RF chain

- Problem decoupled for each RF chain

- Closed-form solution for $F_{RF}$

$$\arg\left\{ (F_{RF})_{i,l} \right\} = \arg\left\{ (F_{opt})_{i,:} (F_{BB})_{l,:}^H \right\}, \quad 1 \leq i \leq N_t, l = \left\lfloor \frac{i N_{RF}^t}{N_t} \right\rfloor$$
Partially-connected mapping (cont’d)

Optimization of $F_{BB}$

\[
\begin{align*}
\text{minimize}_{F_{BB}} & \quad \|F_{opt} - F_{RF}F_{BB}\|_F^2 \\
\text{subject to} & \quad \|F_{BB}\|_F^2 = \frac{N_{RF}^t N_s}{N_t}.
\end{align*}
\]

Reformulate as a non-convex QCQP problem

\[
\begin{align*}
\text{minimize}_{Y \in \mathbb{H}^n} & \quad \text{Tr}(CY) \\
\text{subject to} & \quad \begin{cases}
\text{Tr}(A_1 Y) = \frac{N_{RF}^t N_s}{N_t} \\
\text{Tr}(A_2 Y) = 1 \\
Y \succeq 0, \quad \text{rank}(Y) = 1
\end{cases}
\end{align*}
\]

SDR is tight so globally optimal solution is obtained [Z.-Q. Luo et al., 2010]

Converge to a local optimum
Simulation results

\[ N_t = 144, \quad N_r = 36, \quad N_{RF}^t = N_{RF}^r = N_s = 3 \]

Effectiveness of the proposed AltMin algorithms

The fully-connected mapping can easily approach the performance of the fully digital precoding.
Simulation results

\[ N_t = 144, \quad N_r = 36, \quad N_{RF}^t = N_{RF}^r = N_{RF}, \quad N_s = 2, \quad \text{SNR} = 0 \text{dB} \]

\(~N_s\) RF chains are enough for the fully-connected mapping

Employing fewer PSs, the partially-connected mapping needs more RF chains
Conclusion

- **Limited**: computational efficiency not good, thus difficult to extend to MU multicarrier settings
Double phase shifter (DPS) implementation

- Sum of two phase shifters: $|e^{j\theta_1} + e^{j\theta_2}| \leq 2$

Q: What is the benefit?

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Algorithm Design & Hardware Implementation II: DPS

- Fully-connected mapping
  - RF-only precoding
    \[
    \begin{align*}
    \text{minimize} & \quad \| F_{\text{opt}} - F_{\text{RF}} F_{\text{BB}} \|_F^2 \\
    \text{subject to} & \quad \left| (F_{\text{RF}})_{i,j} \right| \leq 2
    \end{align*}
    \]

- LASSO
  \[
  \text{minimize}_x \quad \frac{1}{2} \| Ax - b \|_2^2 + 2 \| x \|_1
  \]

- Closed-form solution for semi-unitary codebooks
  \[ F_{\text{BB}} F_{\text{BB}}^H = I_{N_{\text{RF}}^t} \]
  \[ F_{\text{RF}}^* = F_{\text{opt}} F_{\text{BB}}^H - \exp \left\{ j \angle (F_{\text{opt}} F_{\text{BB}}^H) \right\} \circ (|F_{\text{opt}} F_{\text{BB}}^H| - 2)^+. \]

- Hybrid precoding
  \[
  \begin{align*}
  \text{minimize}_{F_{\text{RF}}, F_{\text{BB}}} & \quad \| F_{\text{opt}} - F_{\text{RF}} F_{\text{BB}} \|_F^2 \\
  \end{align*}
  \]

- Redundant
Fully-connected mapping (cont’d)

- Optimality in single-carrier systems
  \[ F_{opt} = F_{RF} F_{BB} \] with \( N_{RF}^t = KN_s \) and \( N_{RF}^r = N_s \) when \( F = 1 \)

  Minimum number of RF chains

- Reduced the number of RF chains by half required for achieving the fully digital precoding

- Multi-carrier systems
  \[
  \text{minimize} \quad \| F_{opt} - F_{RF} F_{BB} \|_F^2
  \]

- Low-rank matrix approximation: SVD
  - Optimal solution
Partially-connected mapping

- Block diagonal structure

\[ F_{RF} = \begin{bmatrix}
p_1 & 0 & \cdots & 0 \\
0 & p_2 & 0 & \\
\vdots & \ddots & \ddots & \\
0 & \cdots & 0 & p_{N_{RF}}
\end{bmatrix} \]

- Decoupled for each RF chain

\[ p_j = \begin{bmatrix}
a_{(j-1)} \frac{N_t}{N_{RF}} + 1, & \cdots, & a_{j} \frac{N_t}{N_{RF}}
\end{bmatrix}^T \]

- Eigenvalue problem

\[ x_j^* = \lambda_1 \left( \sum_{i \in F_j} y_i y_i^H \right), \quad a_i^* = \frac{x_j^H y_i}{\|x_j\|^2} \]
Partially-connected mapping (cont’d)

Dynamic mapping

Adaptively separate all the antennas into $N_{RF}$ groups

Problem formulation

$$\begin{align*}
\text{maximize} & \quad \sum_{j=1}^{N_{RF}} \lambda_1 \left( \sum_{i \in \mathcal{D}_j} y_iy_i^H \right) \\
\text{subject to} & \quad \bigcup_{j=1}^{N_{RF}} \mathcal{D}_j = \{1, \ldots, N_t\} \\
& \quad \mathcal{D}_j \cap \mathcal{D}_k = \emptyset, \quad \forall j \neq k \\
\end{align*}$$

$$\begin{align*}
\text{maximize} & \quad \sum_{j=1}^{N_{RF}} x_j^H \left( \sum_{i \in \mathcal{D}_j} y_iy_i^H \right) x_j \\
\text{subject to} & \quad \bigcup_{j=1}^{N_{RF}} \mathcal{D}_j = \{1, \ldots, N_t\} \\
& \quad \mathcal{D}_j \cap \mathcal{D}_k = \emptyset, \quad \forall j \neq k \\
\end{align*}$$

Modified K-means algorithm

- Centroid: $x_j^* = \lambda_1 \left( \sum_{i \in \mathcal{D}_j} y_iy_i^H \right)$
- Clustering: $j^* = \arg \max_j \left| y_i^H x_j \right|^2$

Converge to a local optimum
Inter-user interference

- Approximating the fully digital precoder leads to a near-optimal performance in single-user single-carrier, single-user multicarrier, and multiuser single-carrier mmWave MIMO systems.

- Inter-user interference will be more prominent in the multicarrier system as the analog precoder is shared by a large number of subcarriers.

- Cascade an additional block diagonalization (BD) precoder

  - Effective channel: \( \hat{\mathbf{H}}_{k,f} = \mathbf{W}_{BB_{k,f}}^H \mathbf{W}_{RF_k}^H \mathbf{H}_{k,f} \mathbf{F}_{RF} \mathbf{F}_{BB_f} \)

  - BD: \( \hat{\mathbf{H}}_{j,f} \mathbf{F}_{BD_{k,f}} = 0, \quad k \neq j \)
Simulation results (Fully-connected)

\[ N_t = 256, \ N_r = 16, \ K = 3, \ F = 128, \ N_s = 3, \ N_{RF}^t = 9, \text{ and } N_{RF}^r = 3 \]

Achieve near-optimal spectral efficiency and optimal multiplexing gain with low-complexity algorithms

Effectiveness of the proposed DPS implementation and cascaded BD precoder
Simulation results (Partially-connected)

\[ N_t = 256, \ N_r = 16, \ K = 4, \ F = 128, \ N_s = 2, \ N_{RF}^t = 8, \text{ and } N_{RF}^r = 2 \]

Simply doubling PSs in the partially-connected mapping is far from satisfactory.

Superiority of the modified K-means algorithm with lower complexity than the greedy one.
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Algorithm Design & Hardware Implementation II: DPS

✿ Conclusion

✿ Limitations
- Too many phase shifters needed
- Adaptive high-resolution phases needed
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Algorithm Design & Hardware Implementation III: FPS

- Fixed phase shifter (FPS) implementation

Hybrid Precoding for mm-Wave MIMO Systems
Algorithm Design & Hardware Implementation III: FPS

❖ Problem formulation

\[
\text{minimize}_{S,F_{BB}} \quad \|F_{opt} - SCF_{BB}\|^2_F \\
\text{subject to} \quad S \in B
\]

❖ FPS matrix \( C = \text{diag} \left( \underbrace{c, c, \ldots, c}_{N_{RF}^k} \right), \quad c = \frac{1}{\sqrt{N_c}} \left[ e^{j\theta_1}, e^{j\theta_2}, \ldots, e^{j\theta_{N_c}} \right]^T \)

❖ Switch matrix \( S \in \{0, 1\}^{N_c \times N_c N_{RF}^k} \)

❖ An objective upper bound enables a low-complexity algorithm

❖ Enforce a semi-orthogonal constraint of \( F_{BB} \) [X. Yu et al., 2016]

\[
F_{BB}^H F_{BB} = \alpha^2 F_{DD}^H F_{DD} = \alpha^2 I_{KN_s}
\]

\[
\|F_{opt} - SCF_{BB}\|^2_F \leq \|F_{opt}\|^2_F - 2\alpha \Re \text{Tr} (F_{DD} F_{opt}^H SC) + \alpha^2 \|S\|^2_F
\]
Alternating minimization

- **Digital precoder**
  \[
  \text{maximize} \quad \text{Tr} \left( F_{DD} F_{opt}^H S C \right) \\
  \text{subject to} \quad F_{DD}^H F_{DD} = I_{K N_a}
  \]

- **Semi-orthogonal Procrustes solution**
  \[ F_{DD} = V_1 U^H \]

- **Switch matrix optimization**
  \[
  \text{minimize}_{\alpha, S} \quad \| \text{Tr} \left( F_{opt} F_{DD}^H C^H \right) - \alpha S \|_F^2 \\
  \text{subject to} \quad S \in \mathcal{B}
  \]

- Once \( \alpha \) is optimized, the optimal \( S \) is determined correspondingly

\[
S^* = \begin{cases} 
\mathcal{I} \left\{ \text{Tr} \left( F_{opt} F_{DD}^H C^H \right) > \frac{\alpha}{2} 1_{N_t \times N_c N_{RF}^t} \right\} & \alpha > 0 \\
\mathcal{I} \left\{ \text{Tr} \left( F_{opt} F_{DD}^H C^H \right) < \frac{\alpha}{2} 1_{N_t \times N_c N_{RF}^t} \right\} & \alpha < 0
\end{cases}
\]
Alternating minimization (cont’d)

Optimization of $\alpha$

$$\alpha^* = \text{arg} \min_{\{\tilde{x}_i, \bar{x}_i\}_{i=1}^n} \{f(\tilde{x}_i), f(\bar{x}_i)\}$$

$$\tilde{x} = \text{sort}(\text{vec}(\mathbf{F}_{\text{opt}} \mathbf{F}_{\text{DD}}^H \mathbf{C}^H))$$

$$\bar{x}_i \triangleq \begin{cases} \frac{\sum_{j=1}^i \tilde{x}_j}{\sum_{j=i+1}^n \bar{x}_j} & \alpha < 0 \text{ and } \frac{\sum_{j=1}^i \tilde{x}_j}{n-i} \in [2\tilde{x}_i, 2\tilde{x}_{i+1}] \\ \infty & \alpha > 0 \text{ and } \frac{\sum_{j=i+1}^n \bar{x}_j}{n-i} \in [2\tilde{x}_i, 2\tilde{x}_{i+1}] \\ \end{cases}$$

Search dimension: $2N_tN_{\text{RF}}N_c$

Optimal point can only be finite $\bar{x}_i$

$$\alpha^* = \text{arg} \min_{\bar{x}_i \in \mathcal{X}} f(\bar{x}_i)$$

Search dimension: $|\mathcal{X}| \ll 2N_tN_{\text{RF}}N_c$

Converge to a local optimum

Q: How to reduce # phase shifters?
New mapping strategy

- Group-connected mapping

\[ F_{RF} = \begin{bmatrix} R_1 & 0 & \cdots & 0 \\ 0 & R_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & R_\eta \end{bmatrix} \]

- \( \eta = 1 \): fully-connected mapping
- \( \eta = N_{RF} \): partially-connected

Designed by directly migrating the design for the fully-connected mapping
Simulation results: SU-SC systems

\[ N_t = 144, \quad N_r = 16, \quad N_{RF}^t = N_{RF}^r = N_s = 4, \quad \text{and} \quad N_c = 30 \]

Outperforms the MO-AltMin with lower computational complexity

Effectiveness of the proposed FPS implementation and the FPS-AltMin algorithm
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Algorithm Design & Hardware Implementation III: FPS

Simulation results: MU-MC systems

\[ N_t = 144, \, N_r = 16, \, K = 4, \, F = 128, \, N_s = 2, \, N_{RF}^t = 8, \text{ and } N_{RF}^r = 2 \]

Slightly inferior to the DPS fully-connected mapping with much fewer PSs

Significant improvement over the OMP algorithm
Simulation results: How many PSs are needed?

\[ N_t = 256, \quad N_r = 16, \quad K = 4, \quad F = 128, \quad N_s = 2, \quad N_{RF}^t = 8, \quad \text{and} \quad N_{RF}^r = 2 \]

Only \( \sim 15 \) fixed phase shifters are sufficient!

200 times reduction compared with the DPS implementation
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Algorithm Design & Hardware Implementation III: FPS

- **Simulation results**

\[ N_t = 256, \quad N_r = 16, \quad K = 4, \quad F = 128, \quad N_s = 2, \quad N_{RF}^t = 8, \quad \text{and} \quad N_{RF}^r = 2 \]

A flexible approach to balance the achievable performance and hardware efficiency.
Conclusion

- Spectral efficiency
- Hardware efficiency
- Computational efficiency

FPS group-connected
Hybrid Precoding for mm-Wave MIMO Systems

Takeaways

- **Q1**: Can hybrid precoder provide performance close to the fully digital one? **YES**

- **Q2**: How many RF chains are needed? **Kn**

- **Q3**: How to connect the RF chains and antennas? **Group-connected**

- **Q4**: How many phase shifters are needed? **~15 FPSs**

- **Q5**: How to efficiently design hybrid precoding algorithms? **Alternating minimization, implementation dependent**
Hybrid Precoding for mm-Wave MIMO Systems

Takeaways

❖ Comparisons

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<th>Hardware complexity (No. of phase shifters)</th>
<th>Computational complexity</th>
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<td>SPS</td>
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<td>MO-AltMin</td>
<td>$N_{RF}^tN_t$</td>
<td>Extremely high</td>
<td>✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td></td>
<td>Partially-connected</td>
<td>SDR-AltMin</td>
<td>$N_t$</td>
<td>High</td>
<td>✓</td>
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<td>DPS</td>
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<td>Matrix decomposition</td>
<td>$2N_{RF}^t(N_t - N_{RF}^t)$</td>
<td>$O\left(N_{RF}^t N_t^t F\right)$</td>
<td>✓ ✓ ✓ ✓ ✓</td>
</tr>
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<td></td>
<td>Partially-connected</td>
<td>Modified K-means</td>
<td>$2N_t$</td>
<td>$O\left( NN_{RF}^t N_t^t F\right)$</td>
<td>✓ ✓</td>
</tr>
<tr>
<td>FPS</td>
<td>FPS-Alt-Min</td>
<td>$N_c \ll N_t$</td>
<td>Medium</td>
<td></td>
<td>✓ ✓ ✓ ✓ ✓</td>
</tr>
</tbody>
</table>

❖ The current **SPS implementation** is not a good choice due to the high design complexity caused by the strict hardware limitation

❖ The **DPS implementation** is an excellent candidate if high-performance hybrid precoders are required with low design complexity

❖ The **FPS implementation** finds a trade-off between the hardware and computational complexity, while with satisfactory performance
The Hybrid Precoder Landscape

Baseline: SPS fully-connected with OMP

SPS fully-connected

SPS partially-connected

DPS fully-connected

DPS partially-connected

FPS group-connected
Hybrid Precoding for mm-Wave MIMO Systems
Future Research Directions

- Joint design with CSI acquisition
- Performance evaluation of hybrid precoding algorithms
- Further reduction in computational complexity
- Hardware implementation and testing
- Hybrid precoding with low-precision ADCs
- ……
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References


Thanks