Channel Estimation and Hybrid Precoding for Millimeter Wave Systems

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mmWave Cellular Systems

- Current systems live with limited microwave spectrum

- Potential large bandwidth available at high frequencies [1]

- mmWave band can enable multi-gigabit data rates
- Hardware technology advances make mmWave possible

[1] Z. Pi and F. Khan, "An introduction to millimeter-wave mobile broad- band systems," *IEEE Communications Magazine*, vol. 49, no. 6, pp. 101–107, 2011.

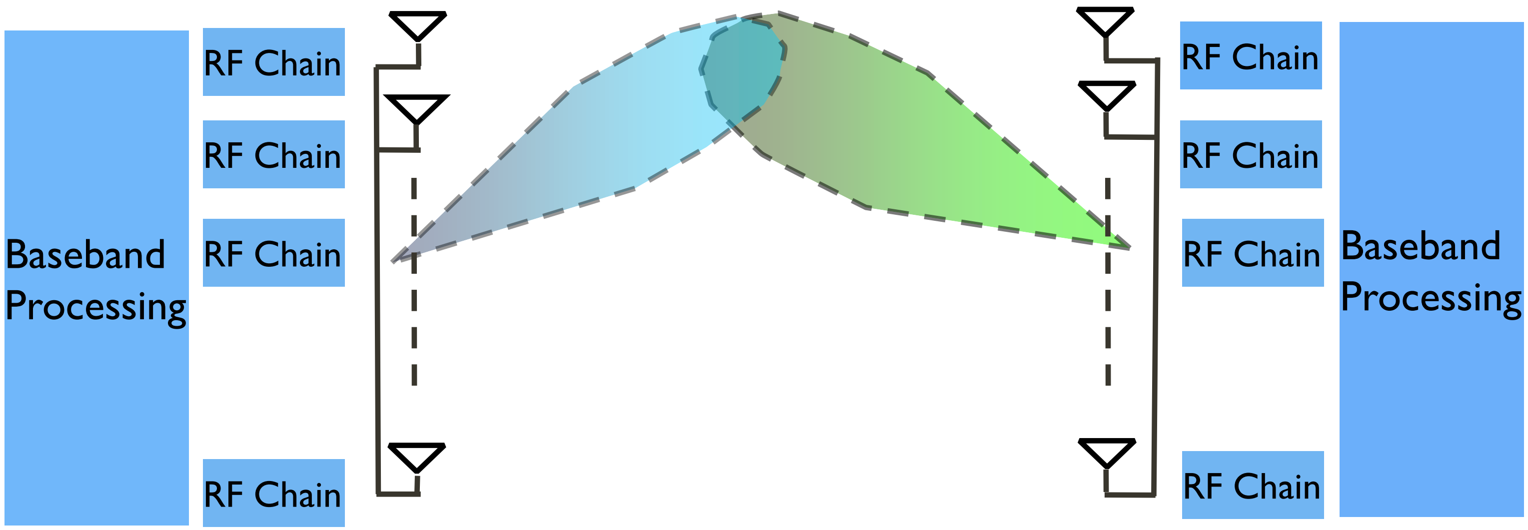
Directional Beamforming

- mmWave communication needs high beamforming gain

Why?

- High frequency signals experience severe path-loss
- Larger bandwidth at mmWave means higher noise power

Solution



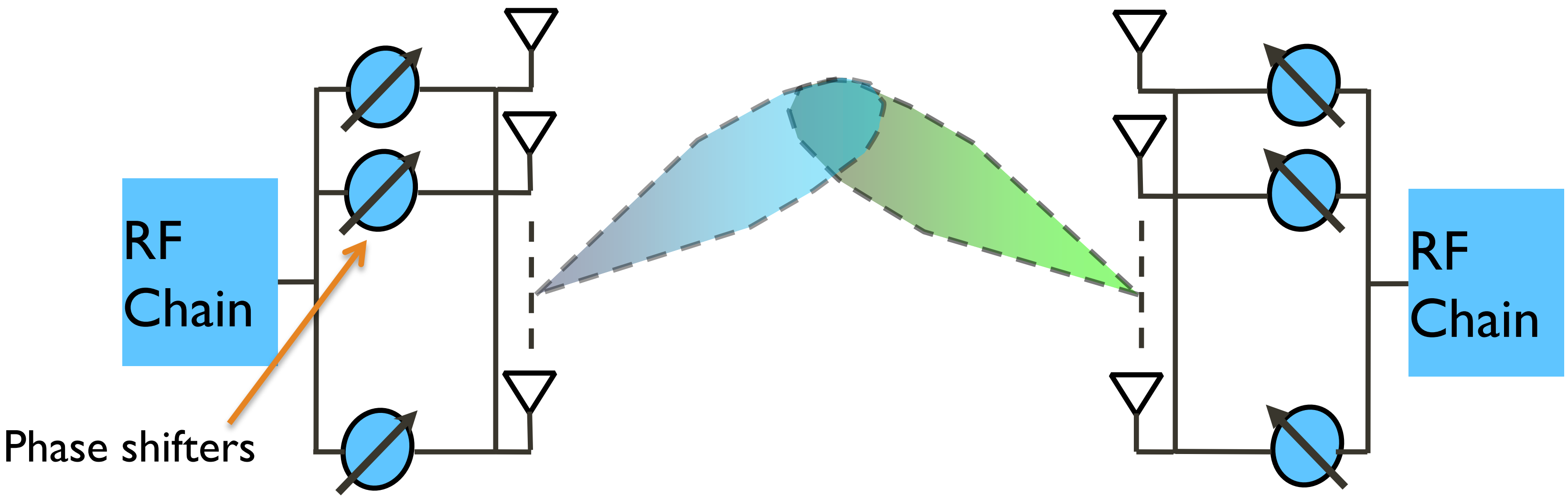
- Leverage array gain from large antenna arrays

Limitations of mmWave beamforming

- High cost of mixed-signal components limits RF chains

Possible solution

- Perform the beamforming processing in analog (RF) domain



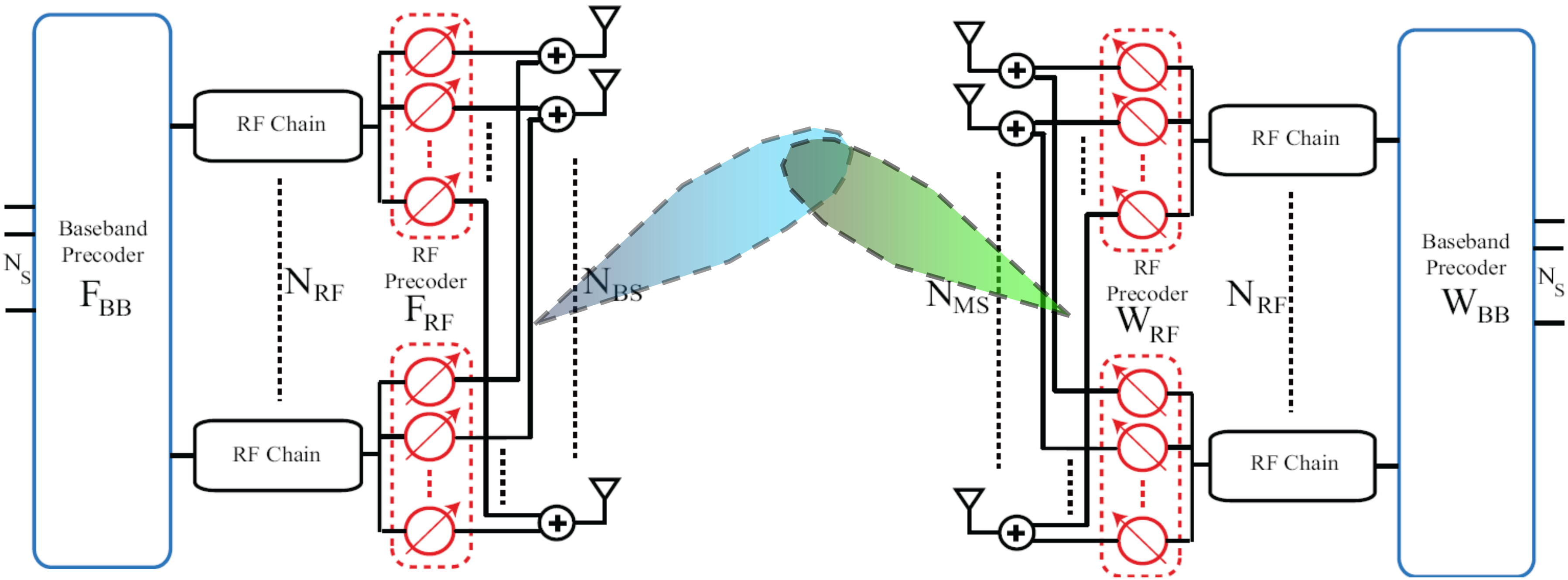
- But RF imposes other constraints that limits the performance

  Ex. Phase shifter may have constant gains and quantized angles

- Managing multi-stream and multi-user interference is difficult

Need new precoding solutions for mmWave systems

mmWave-suitable Precoding



Hybrid Analog/digital Precoding Architecture

- Hybrid precoding (HP) Enables
  - Multiplexing multiple data streams
  - Manage interference between multiple users
- Prior work considers designing HP with full channel knowledge [1]

But, is it simple to estimate mmWave channels?

[1] O. El Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. Heath, "Spatially sparse precoding in millimeter wave MIMO systems," IEEE Transactions on Wireless Communications, vol. 13, no. 3, pp. 1499–1513, March 2014

Hybrid Precoding Design

- The hybrid precoding matrices are jointly designed to solve[1]

Minimize the Frobenius norm of the error between the optimal precoder (singular value decomposition) and the constrained hybrid precoders

$$
\begin{aligned}
(\mathbf{F}_{\mathrm{RF}}^{\star}, \mathbf{F}_{\mathrm{BB}}^{\star}) = \arg\min \quad & \|\mathbf{F}_{\mathrm{opt}} - \mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}\|_F, \\
\text{s.t.} \quad & [\mathbf{F}_{\mathrm{RF}}]_{:,i} \in \left\{ [\mathbf{A}_{\mathrm{can}}]_{:,\ell} \mid 1 \leq \ell \leq N_{\mathrm{can}} \right\}, \\
& \|\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}\|_F^2 = N_{\mathrm{S}}.
\end{aligned}
$$

The set of quantized (candidate) array response vectors

- Main Idea: Approximate the optimal precoders
- This is a sparse approximation problem

Matching pursuit algorithms can be leveraged in the design

Matching Pursuit Based HP Design

Algorithm 1 Hybrid Analog-Digital Beamforming Design

$\mathcal{R} = \phi$

$\mathbf{F}_{\mathrm{res}} = \mathbf{F}_{\mathrm{opt}}$

for $i \le N_{\mathrm{RF}}$ **do**

$\quad \mathbf{\Psi} = \mathbf{A}_{\mathrm{can}}^{H} \mathbf{F}_{\mathrm{res}}$

$\quad k = \arg\max_{j=1,2,..N_{\mathrm{can}}} \left(\mathbf{\Psi}^{H} \mathbf{\Psi} \right)_{j,j}$

Find the direction from $\mathbf{A}_{\mathrm{can}}$ that has the maximum projection on $\mathbf{F}_{\mathrm{opt}}$

$\quad \mathcal{R} = \mathcal{R} \cup k$

$\quad \mathbf{F}_{\mathrm{RF}} = [\mathbf{A}_{\mathrm{can}}]_{:,\mathcal{R}}$

$\quad \mathbf{F}_{\mathrm{BB}} = \left({\mathbf{F}_{\mathrm{RF}}}^{H} \mathbf{F}_{\mathrm{RF}} \right)^{-1} {\mathbf{F}_{\mathrm{RF}}}^{H} \mathbf{F}_{\mathrm{opt}}$

Design the baseband precoder to approach $\mathbf{F}_{\mathrm{opt}}$

$\quad \mathbf{F}_{res} = \frac{\mathbf{F}_{\mathrm{res}} - \mathbf{F}_{\mathrm{RF}} \mathbf{F}_{\mathrm{BB}}}{\| \mathbf{F}_{\mathrm{res}} - \mathbf{F}_{\mathrm{RF}} \mathbf{F}_{\mathrm{BB}} \|_F}$

Project out the chosen precoders from $\mathbf{F}_{\mathrm{res}}$;

$\mathbf{F}_{\mathrm{BB}} = \sqrt{N_{\mathrm{S}}} \frac{\mathbf{F}_{\mathrm{BB}}}{\| \mathbf{F}_{\mathrm{RF}} \mathbf{F}_{\mathrm{BB}} \|_F}$

mmWave Channel Estimation

- mmWave channel estimation is challenging
  - Large transmit and receive antenna arrays
  - Low signal-to-noise ratio before beamforming
  - Limited number of RF chains imposes constraints on training signal design
- Prior work avoids explicit mmWave channel estimation

  Idea: Beam training by searching for the best beamforming directions [1],[2]

Limitations of beam training

- It supports only single-stream transmission
- It requires high training overhead to search for the best beams

Note. Some ideas considered hierarchical search to minimize the training overhead.

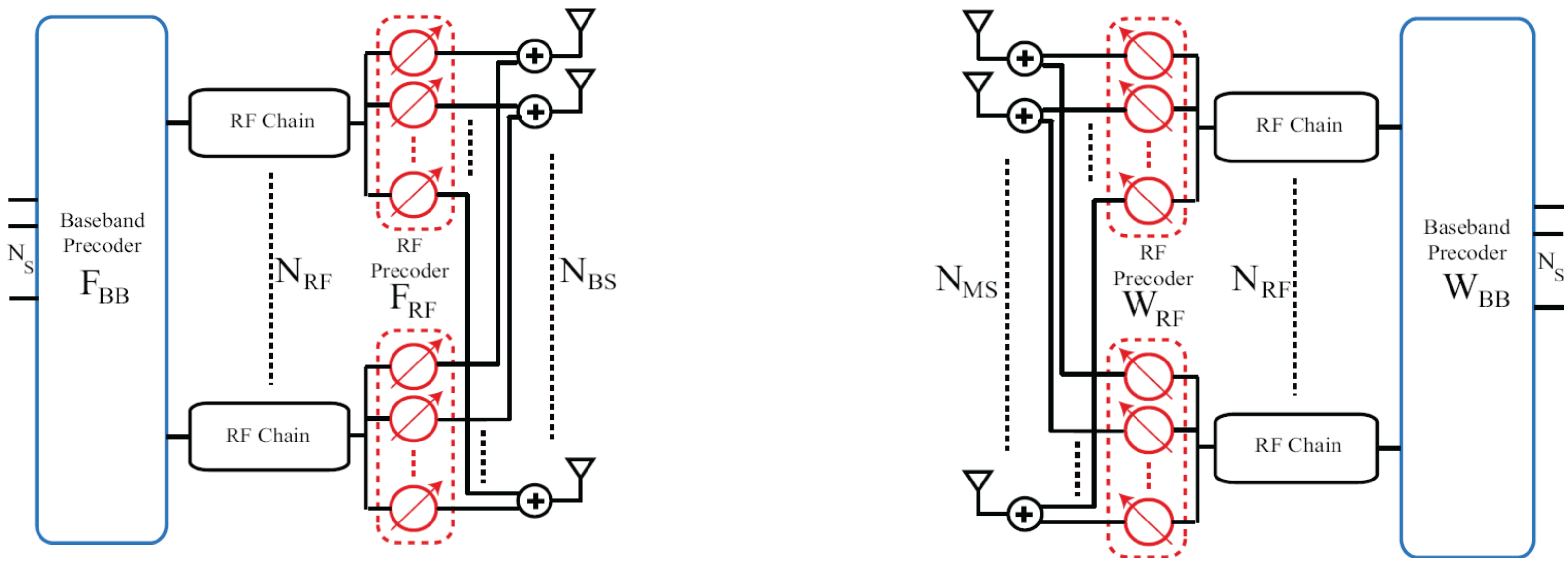
- It lacks the ability to manage multi-user transmissions

Need to design new mmWave channel estimation algorithms

[1] J. Wang, Z. Lan, C. Pyo, T. Baykas, C. Sum, M. Rahman, J. Gao, R. Funada, F. Kojima, H. Harada *et al.*, "Beam codebook based beamforming protocol for multi-Gbps millimeter-wave WPAN systems," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 8, pp. 1390–1399, 2009.
[2] S. Hur, T. Kim, D. Love, J. Krogmeier, T. Thomas, and A. Ghosh, "Millimeter wave beamforming for wireless backhaul and access in small cell networks," IEEE Transactions on Communications, vol. 61, no. 10, pp. 4391–4403, 2013.

System Model

- Consider hybrid precoding architecture



Received signal: $\mathbf{y} = \mathbf{W}^H \mathbf{H} \mathbf{F} \mathbf{s} + \mathbf{W}^H \mathbf{n}$

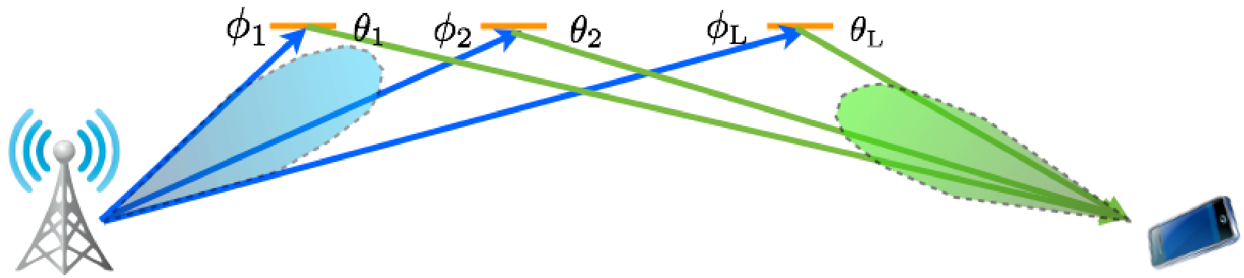
$\mathbf{W} = \mathbf{W}_{\mathrm{RF}} \mathbf{W}_{\mathrm{BB}}$ $\mathbf{F} = \mathbf{F}_{\mathrm{RF}} \mathbf{F}_{\mathrm{BB}}$

Ns: Number of streams
N_{RF}: Number of RF chains
N_{BS}: Number of BS antennas
N_{MS}: Number of MS antennas

- Phase shifters have constant modulus and quantized angles
- RF chains are much less than the number of antennas

mmWave Channels

- We adopt a geometric channel model



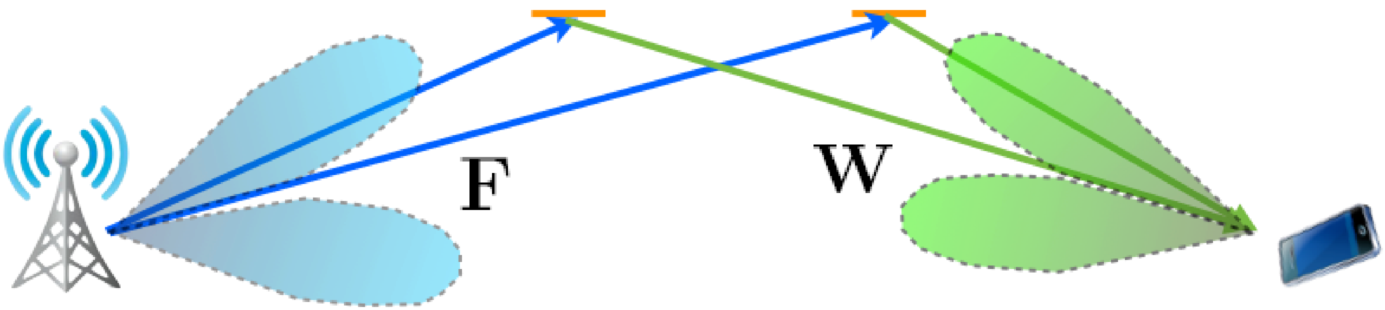
$$\mathbf{H} = \sqrt{\frac{N_{\mathrm{BS}} N_{\mathrm{MS}}}{\rho}} \sum_{\ell=1}^{L} \alpha_\ell \mathbf{a}_{\mathrm{MS}} \left(\theta_\ell\right) \mathbf{a}_{\mathrm{BS}}^{H} \left(\phi_\ell\right)$$

Channel path-loss | Complex path gain | Steering vectors | Angles of arrival/departure (AoA/AoD)

- Assumption
  - Channels are sparse, a few paths exist [1]
  - Arrays are generally non-uniform
  - One of the channel paths is LOS

[1] M. Riza Akdeniz, Y. Liu, S. Sun, S. Rangan, T. S. Rappaport, and E. Erkip, "Millimeter Wave Channel Modeling and Cellular Capacity Evaluation," Dec. 2013. [Online]. Available: http://arxiv.org/abs/1312.4921

Sparse Formulation



- The derived formulation captures the channel sparsity

$$\mathbf{y}_{\mathrm{V}} = \sqrt{P}\left(\mathbf{F}^T \otimes \mathbf{W}^H\right)\mathbf{A}_{\mathrm{D}}\mathbf{z} + \mathbf{n}_{\mathrm{Q}}$$

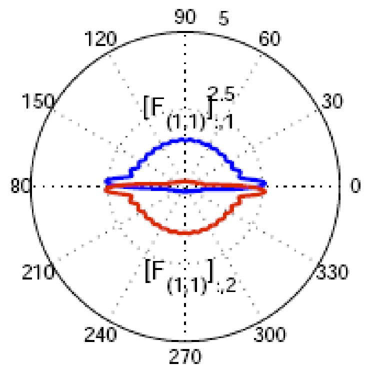
Dictionary of steering vectors. Its columns of the form $\left(\mathbf{a}_{\mathrm{BS}}^{*}\left(\bar{\phi}_u\right) \otimes \mathbf{a}_{\mathrm{MS}}\left(\bar{\theta}_v\right)\right)$

Sparse vector L non-zeros

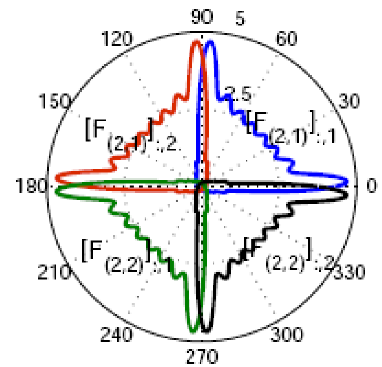
- Advantages of the sparse formulation
  - Enables using tools from (adaptive) compressed sensing
  - Enables estimating multi-path channels
- We will adaptively design training precoders/combiners

Hierarchical Codebook Design

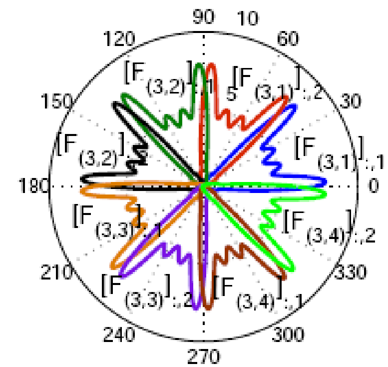
- Construct multi-resolution beamforming codebooks



Codebook level 1



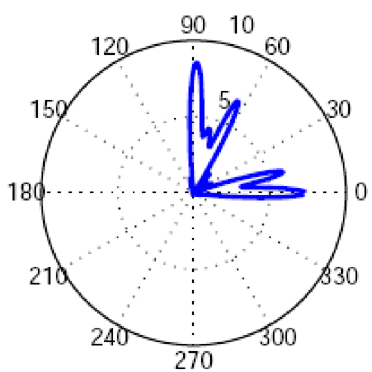
Codebook level 2



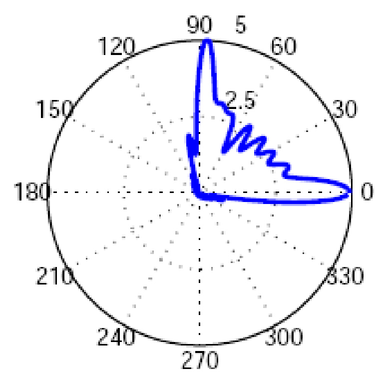
Codebook level 3

These patterns are generated with unconstrained (digital-only) precoders

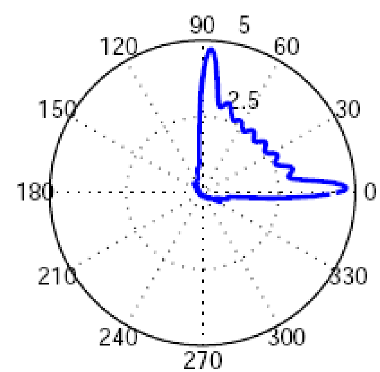
- Approximation using hybrid analog/digital precoding



$N_{RF}=5$



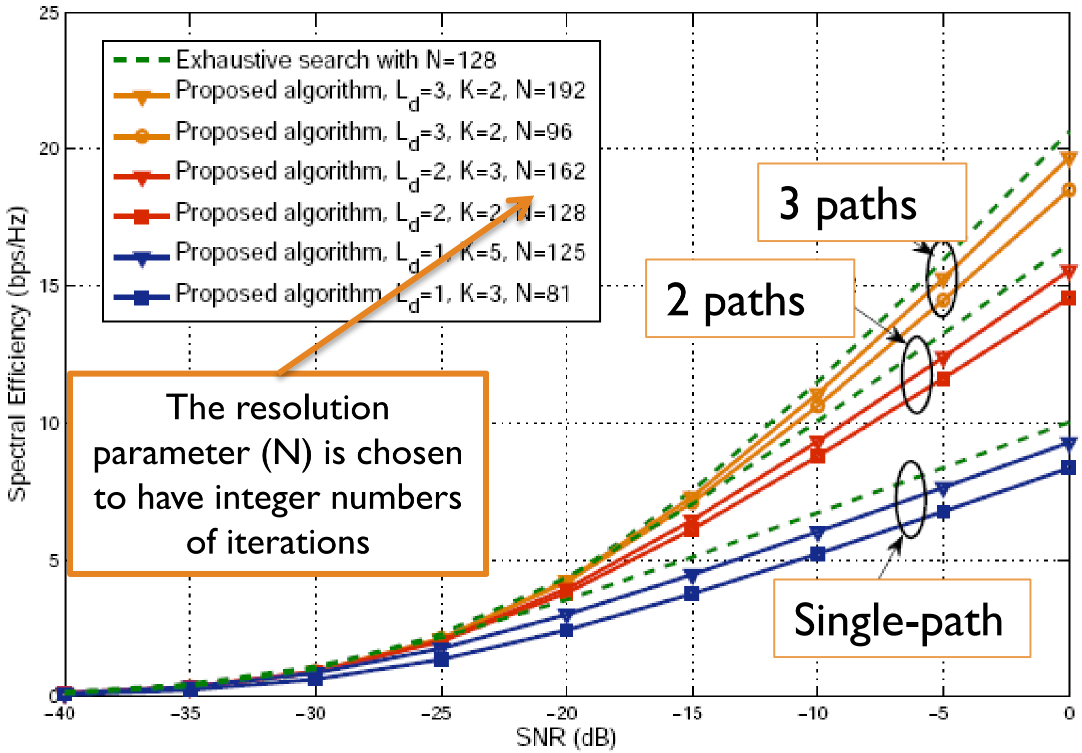
$N_{RF}=10$



$N_{RF}=15$

Each beam pattern is approximated using hybrid analog/digital architecture.

Simulation Results



Setup:
(Single-user model)
BS has - 64 antennas
- 10 RF chains*
MS has - 32 antennas
- 5 RF chains
Operating at 28 GHz
Bandwidth 100MHz
3 NLOS paths in the channel

- Achieve comparable performance to exhaustive search solutions
- Efficiently estimate multipath channels
- Quantized angles assumption has a small impact on performance

*Note: the numbers of the RF chains are chosen just to be have reasonable values.

Conclusion

- Channel sparsity enables low-complexity hybrid precoding designs
- Exploiting channel sparsity, we developed efficient channel training and estimation algorithms
- The developed algorithm
  - estimates multipath channels
  - is more robust to angles quantization compared with analog-only solutions
  - considers practical mmWave hardware (hybrid precoding architecture)
- The performance of the proposed algorithm approaches that of exhaustive search
- Future work:
  - Extend the proposed algorithm to multi-user mmWave systems
  - Consider other training beamforming designs (random beamforming)

Thank you