Time-domain channel estimation for wideband millimeter wave systems with hybrid architecture

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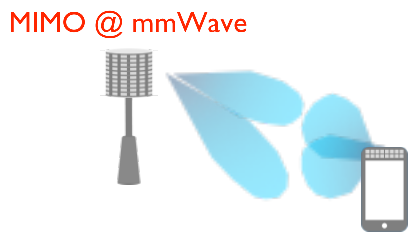
MIMO and massive MIMO systems at mmWave



mmWave and massive MIMO are key ingredients of 5G

Large antenna arrays needed at Tx and Rx

Leverage beamforming gain to realize large data rates

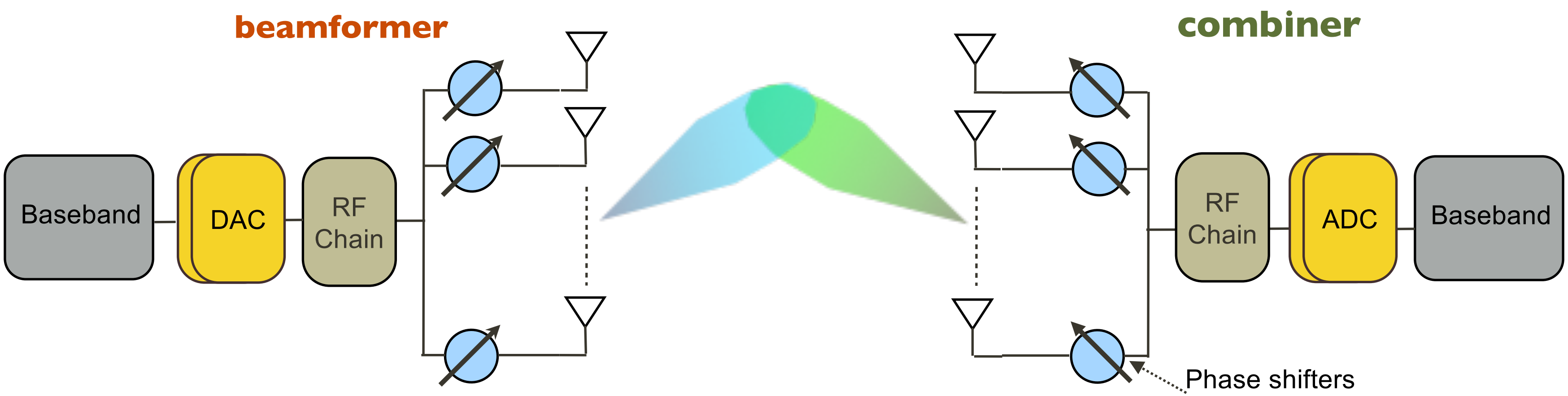
Low-overhead channel estimation techniques needed

Crucial for efficient precoder/combiner design in both mmWave MIMO and mmWave massive MIMO systems

Large matrix sizes also complicate channel estimation

MIMO channel estimation at mmWave is complicated due to hardware constraints

MIMO architectures at mmWave: analog beamforming



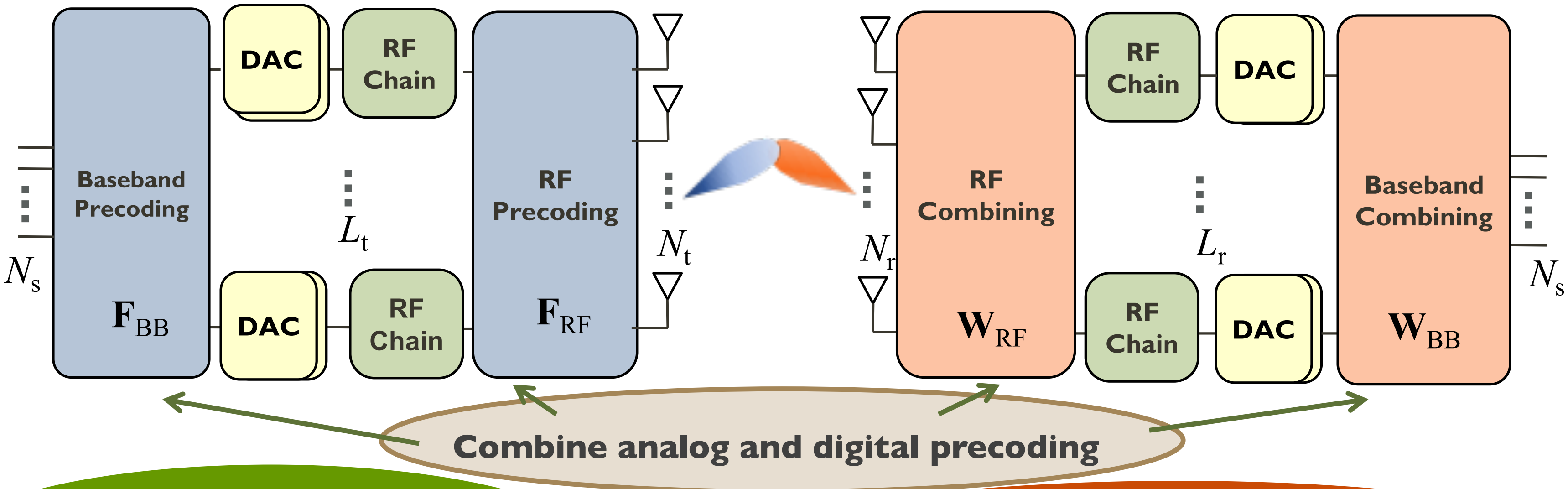
Phase shifters apply for the entire band

Beam training used to get the best Tx and Rx beamforming directions

Limited to single stream and single user MIMO

* J. Wang et al, "Beam codebook based beamforming protocol for multi-Gbps millimeter-wave WPAN systems," in *IEEE JSAC*, October 2009.
** 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.

MIMO architectures at mmWave: hybrid precoding



Fully digital MIMO is not feasible at mmWave

# of DACs/ADCs << # of antennas

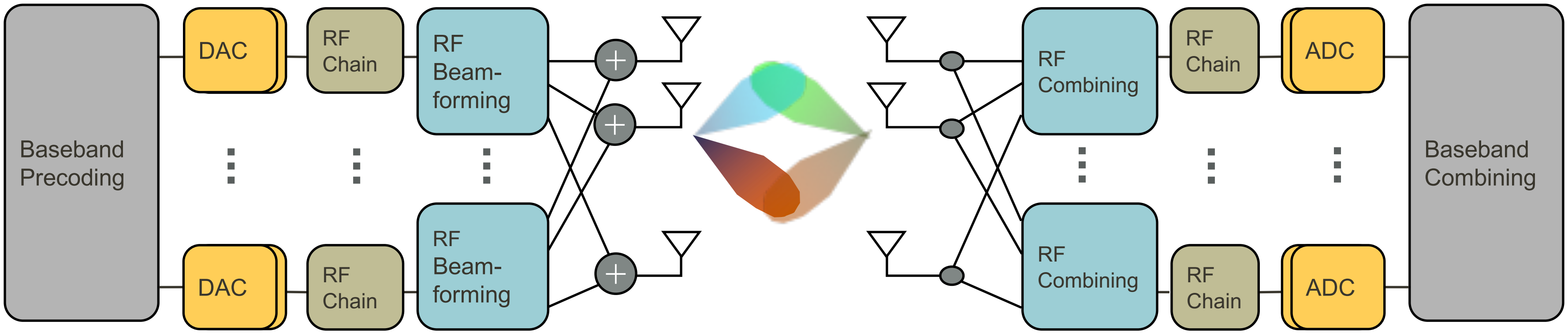
Rules out several digital channel estimation techniques

*Low resolution mixed circuit components not considered here

Hybrid precoding can support multi-stream and multi-user MIMO at mmWave

R. W. Heath, N. González-Prelcic, S. Rangan, W. Roh, and A. M. Sayeed, ``An overview of signal processing techniques for millimeter wave MIMO systems," JSAC, April 2016.

MmWave channel estimation with hybrid architecture



Multistream beam training → large training overhead

Low link SNR without beamforming

Large bandwidth → frequency selective channel

No direct access to antenna outputs

Channel estimates are an alternative to beam training, work with multi-stream

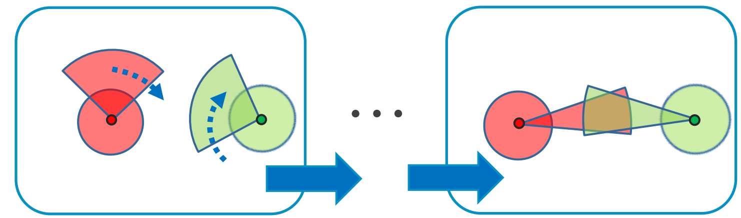
Prior work

Hierarchical beam training

Single stream support only

Works for wideband channel

Used for analog architectures



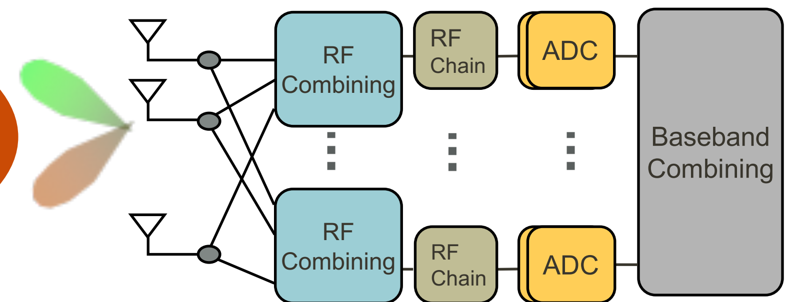
Avoids explicit channel estimation

Sparsity-based channel estimation

Support for multi stream

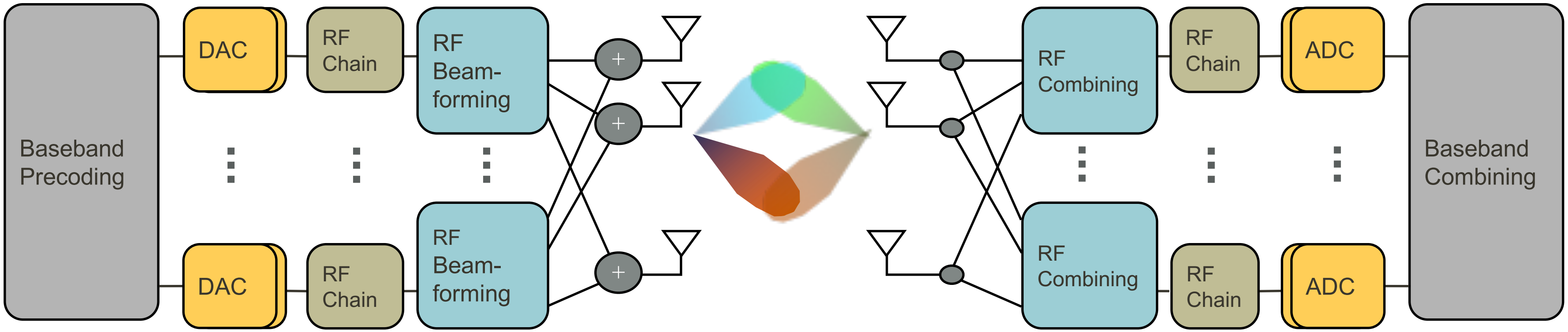
Most prior work on narrowband channel model

Wideband systems assumed ideal setting



Works for any architecture

Contributions



Wideband mmWave channel estimation technique

Sparse problem formulation in time domain

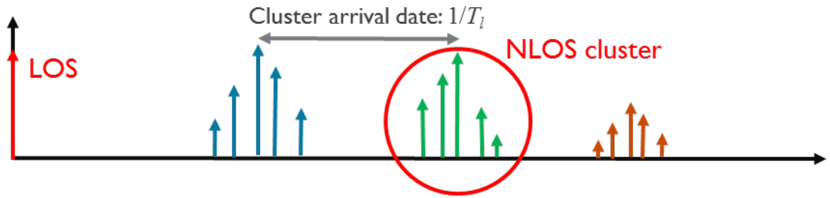
Include system constraints
- Frame structure
- Finite bandwidth of pulse shaper
- Hybrid architecture

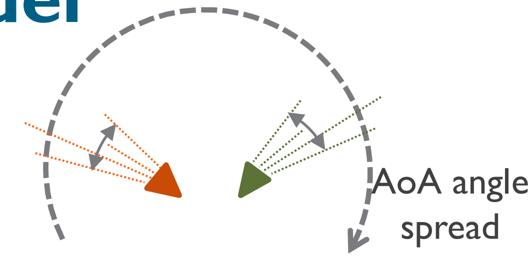
Useful in single-carrier mmWave systems

Works for both MIMO and massive MIMO wideband mmWave systems

Wideband mmWave channel model

Clustered in time:





Clustered in space

$$L \ll N_\mathrm{r} N_\mathrm{t}$$

$$\mathbf{H}_d \in \mathbb{C}^{N_r \times N_t}$$
$$d = 0,\ 1,\ \ldots\ N_c - 1$$

# of tap channel

$$\mathbf{H}_d = \sum_{\ell=1}^{L} \alpha_\ell p_\mathrm{rc}(dT_s - \tau_\ell)\mathbf{a}_\mathrm{R}(\phi_\ell)\mathbf{a}_\mathrm{T}^*(\theta_\ell)$$

Complex path gain

Pulse shaping function

Path delay

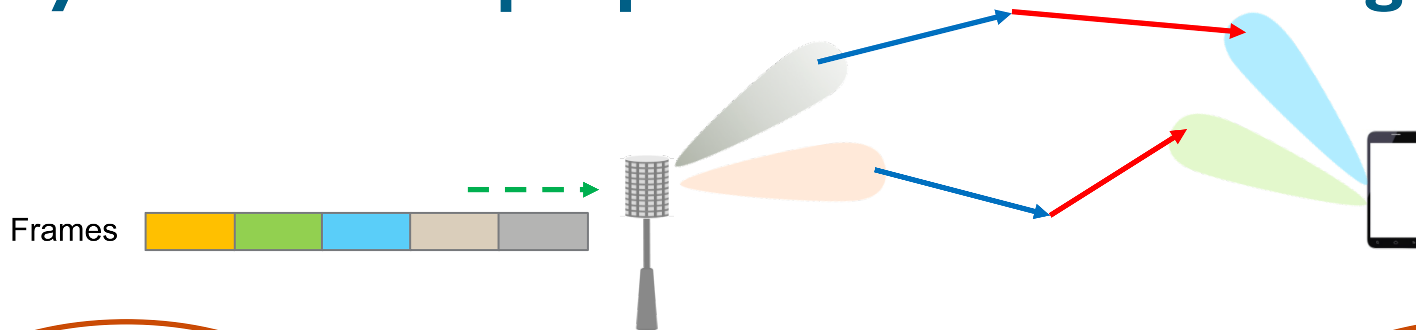
Antenna array response

Angle of arrival/departure

Obtain $\{\phi_\ell,\ \theta_\ell,\ \alpha_\ell,\ \tau_\ell\}$ for channel estimation

Exploit sparsity in the angular and delay domain in the problem formulation

Key idea of the proposed channel training



Uniform random phase from quantized angles → Hybrid precoding for training-frame transmission ← Fixed RF precoder/combiner for the whole frame

↓

Estimate AoA/AoD and ToA using sparse recovery

Leverage the sparse structure in the mmWave channel & the hybrid architecture

Channel training stages

(zeros used for beam switching)

$N_c - 1$ | Length N training data

ZP	Training sequence

precoder $\mathbf{f}_{\mathrm{RF}}^{(m)}$ combiner $\mathbf{w}_{\mathrm{RF}}^{(m)}$ → Discard ZP

m^{th} training frame $[\underbrace{0 \cdots 0}_{N_c-1} \; s_m[1] \cdots s_m[N]]$

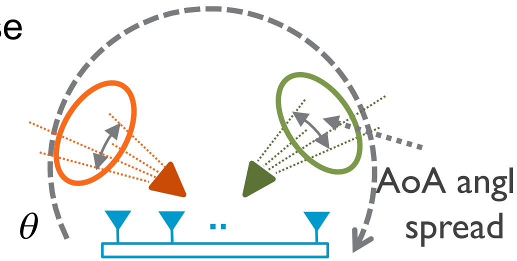
$$\begin{bmatrix} y_m[1] \\ y_m[2] \\ \vdots \\ y_m[N] \end{bmatrix}^T = \mathbf{w}_{\mathrm{RF}}^{(m)*} [\mathbf{H}_0 \quad \cdots \quad \mathbf{H}_{N_c-1}] \begin{bmatrix} \mathbf{f}_{\mathrm{RF}}^{(m)} s_m[1] & \mathbf{f}_{\mathrm{RF}}^{(m)} s_m[2] & \cdots & \mathbf{f}_{\mathrm{RF}}^{(m)} s_m[N] \\ 0 & \mathbf{f}_{\mathrm{RF}}^{(m)} s_m[1] & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 \cdots & \mathbf{f}_{\mathrm{RF}}^{(m)} s_m[N - N_c + 1] \end{bmatrix} + \mathbf{e}^{(m)}$$

Zero-padding facilitates RF circuit reconfiguration across frames

Exploiting sparsity in the angular domain

$$\mathbf{y}_m = \underbrace{\left(\mathbf{S}_m \otimes \mathbf{f}_{\mathrm{RF}}^{(m)^T} \otimes \mathbf{w}_{\mathrm{RF}}^{(m)^*}\right)}_{\boldsymbol{\Phi}_m} \begin{bmatrix} \mathrm{vec}(\mathbf{H}_0) \\ \mathrm{vec}(\mathbf{H}_1) \\ \vdots \\ \mathrm{vec}(\mathbf{H}_{N_c-1}) \end{bmatrix} + \mathbf{e}_m$$

Noise



Clustered in space

Training data matrix

$$\begin{bmatrix} s_m[1] & 0 & \cdots & 0 \\ s_m[2] & s_m[1] & \cdots & . \\ \vdots & \vdots & \ddots & \vdots \\ s_m[N] & \cdots & \cdots & s_m[N-N_c+1] \end{bmatrix}$$

$$\mathrm{vec}(\mathbf{H}_d) = \overbrace{\left(\bar{\mathbf{A}}_{\mathrm{T}} \circ \mathbf{A}_{\mathrm{R}}\right)}^{N_r N_t \times L} \begin{bmatrix} a_1 \\ \vdots \\ a_L \end{bmatrix}$$

Channel gain

Sparse formulation

$$\overbrace{\left(\bar{\mathbf{A}}_{\mathrm{tx}} \otimes \mathbf{A}_{\mathrm{rx}}\right)}^{N_r N_t \times G_r G_t} \mathbf{x}$$

Angle domain dictionary

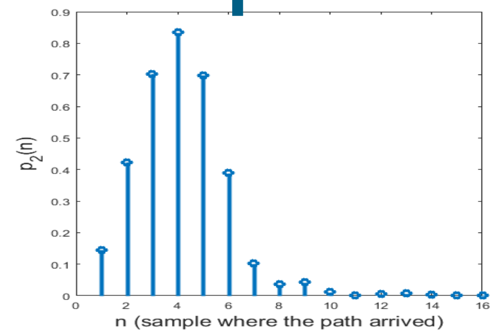
Evaluated on the angle grid

Angle grid sizes

$$G_r G_t >> L$$

Goal: Estimate the non-zeros elements of the sparse vector x

Exploiting group sparsity due to pulse shaping



$G_c >> N_c$

Delay grid sizes

$$p_d(n) = p_{\rm rc}\left((d - n\frac{N_c}{G_c})T_s\right)$$

Pulse shaping function

Sampled version

$$\mathbf{y}_m = \mathbf{\Phi}_m \left(\mathbf{I}_{N_c} \otimes \bar{\mathbf{A}}_{\rm tx} \otimes \mathbf{A}_{\rm rx}\right) \mathbf{\Gamma}\mathbf{x} + \mathbf{e}_m,$$

where
$$\mathbf{\Gamma} = \begin{bmatrix} \mathbf{I}_{G_r G_t} \otimes \mathbf{p}_0^T \\ \mathbf{I}_{G_r G_t} \otimes \mathbf{p}_1^T \\ \vdots \\ \mathbf{I}_{G_r G_t} \otimes \mathbf{p}_{N_c-1}^T \end{bmatrix},$$

Delay domain dictionary

Evaluated on the delay grid

$\mathbf{p}_d$ has entries $p_d(n)$ $\quad n = 1, 2, \cdots, G_c$

$d = 0, 1, \cdots, N_c - 1$

Unknown **x** is $G_t G_r G_c$ X *1*, *L*-sparse vector containing the complex channel gains

Compressive channel estimation

Stack M measurements → $\mathbf{y} = \sqrt{\rho}\boldsymbol{\Phi}\boldsymbol{\Psi}\mathbf{x} + \mathbf{e}$

- $\boldsymbol{\Psi}$: Effective dictionary matrix
- $\boldsymbol{\Phi}$: Measurement matrix

Measurement 1 $\quad \mathbf{y}_1 = \sqrt{\rho}\left(\mathbf{S}_1 \otimes {\mathbf{f}_{\mathrm{RF}}^{(1)}}^T \otimes {\mathbf{w}_{\mathrm{RF}}^{(1)}}^*\right)\left(\mathbf{I}_{N_c} \otimes \bar{\mathbf{A}}_{\mathrm{tx}} \otimes \mathbf{A}_{\mathrm{rx}}\right)\boldsymbol{\Gamma}\mathbf{x} + \mathbf{e}_1$

⋮

Measurement M $\quad \mathbf{y}_M = \sqrt{\rho}\left(\mathbf{S}_M \otimes {\mathbf{f}_{\mathrm{RF}}^{(M)}}^T \otimes {\mathbf{w}_{\mathrm{RF}}^{(M)}}^*\right)\left(\mathbf{I}_{N_c} \otimes \bar{\mathbf{A}}_{\mathrm{tx}} \otimes \mathbf{A}_{\mathrm{rx}}\right)\boldsymbol{\Gamma}\mathbf{x} + \mathbf{e}_M$

- $\mathbf{f}_{\mathrm{RF}}$, $\mathbf{w}_{\mathrm{RF}}$: Random beamforming matrices
- $\boldsymbol{\Gamma}$: Contains quantized grid of ToA
- $\bar{\mathbf{A}}_{\mathrm{tx}} \otimes \mathbf{A}_{\mathrm{rx}}$: Dictionary with columns $\mathsf{a}_{\mathrm{T}}^{c}(\tilde{\phi}_x) \otimes \mathsf{a}_{\mathrm{R}}(\tilde{\theta}_y)$
- $\tilde{\phi}_x$, $\tilde{\theta}_y$: Quantized grid of AoA/AoD

Dictionary matrix constructed using antenna array response

Angle grid & delay quantization can be made as fine as required for sparsity

Extends directly to multiple RF chains during training

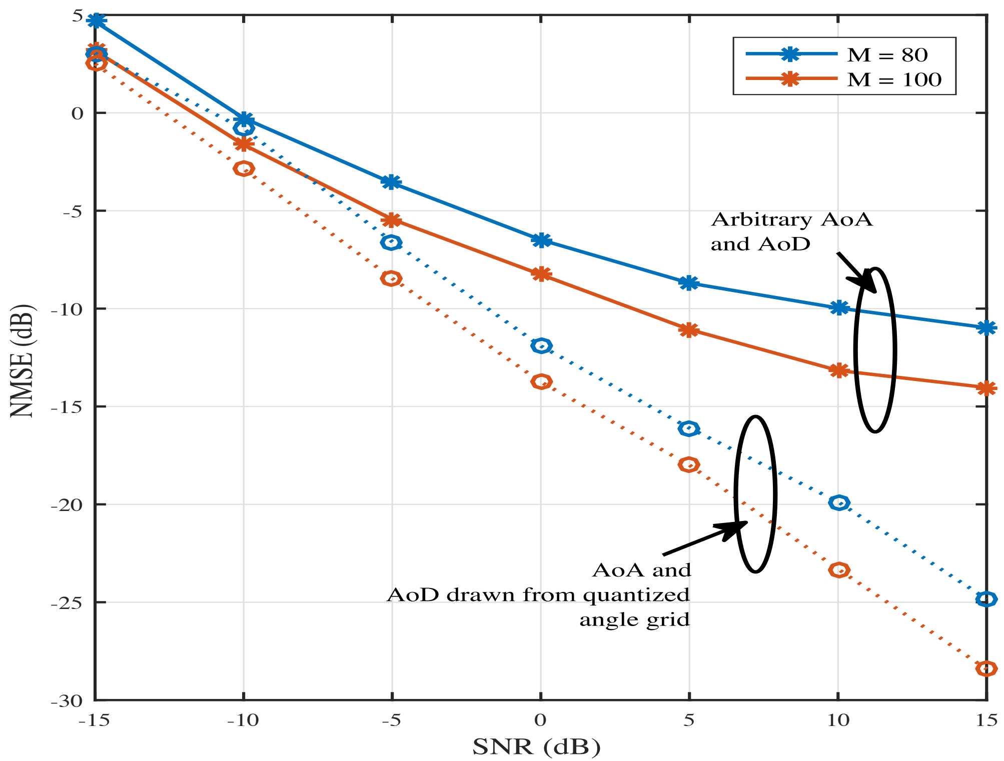
Simulation results

With 1 RF chain

Setup

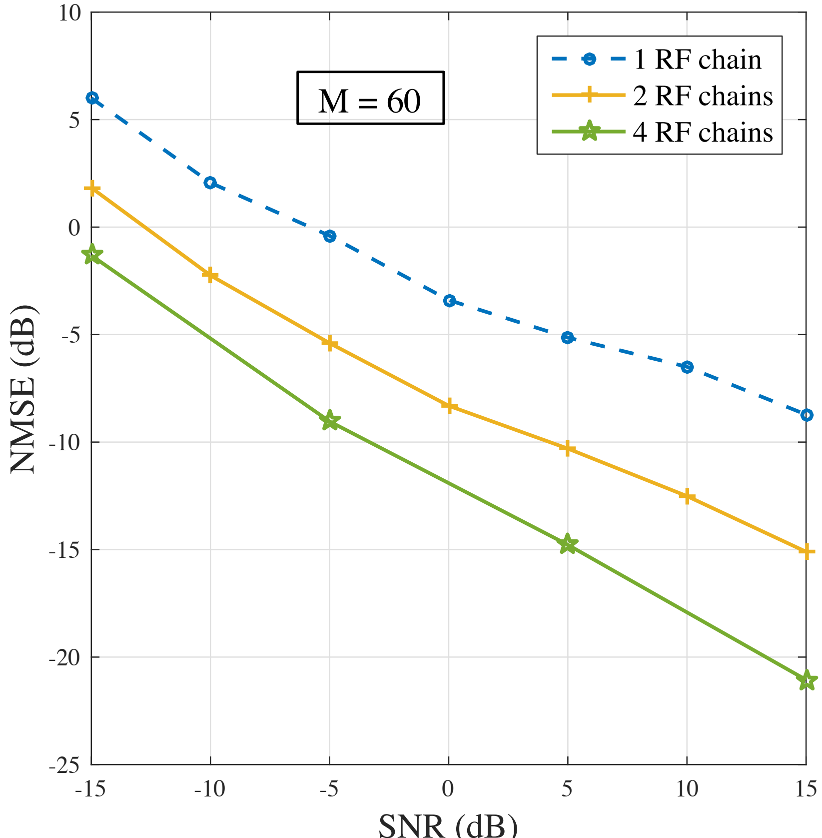
- Tx has **32** antennas, Rx has 32 antennas
- Dictionary generated using AoD/AoA with grid size = 64
- Frequency selective channel with 4 delay taps and 2 paths
- Pulse shaping filter with 0.8 roll-off factor
- Frame length = 16
- 2 bit quantization for precoder and combiner phase shifters
- Orthogonal Matching pursuit followed by least square estimation

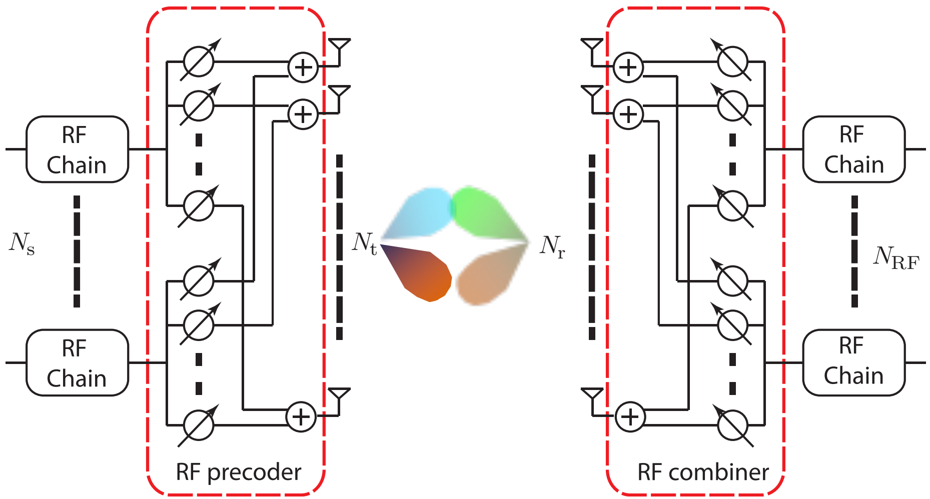
$$\mathrm{NMSE} = \frac{\sum_{d=0}^{N_c} ||\mathbf{H}_d - \hat{\mathbf{H}}_d||_F^2}{\sum_{d=0}^{N_c} ||\mathbf{H}_d||_F^2}$$



80-100 training frames are enough to ensure low channel estimation error

Employing hybrid architecture





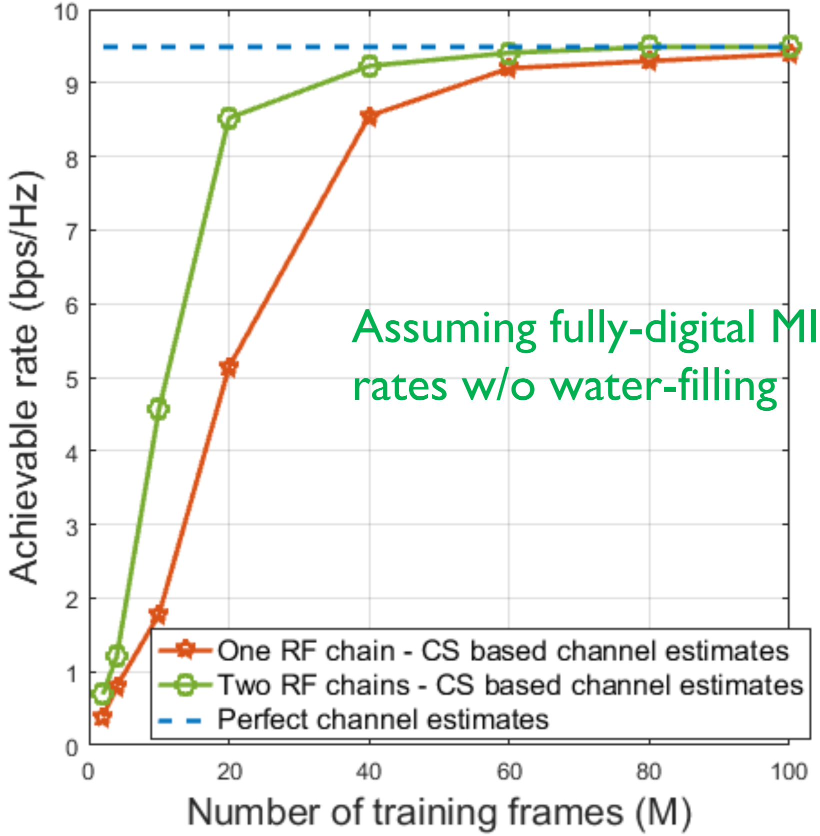
Effectively increases the precoding and combining beam patterns

Using multiple RF chains at Tx and Rx gives better channel estimates

Reducing the training overhead

Leverage multiple RF chains

Increased number of measurements per training frame



Assuming fully-digital MIMO rates w/o water-filling

Hybrid precoding can give rates close to fully-digital MIMO

Using multiple RF chains reduces training overhead

Conclusion and future work

Wideband mmWave channel estimation needs to consider hardware constraints

- Fewer number of baseband measurements
- Effective baseband channel is less sparse

Proposed time domain channel estimation using hybrid architecture

- Sparse formulation enables use of compressive sensing tools
- Multiple RF chains at the transceivers reduce the number of training step

Future work

- Compare complexity with frequency domain channel estimation techniques
- Comparison of performance between beam training and CS based approaches

References

1. F. Boccardi *et al*, ``Five disruptive technology directions for 5G," *IEEE Commun. Mag.*, vol. 52, pp. 74--80, Feb. 2014.
2. J. Andrews *et al*, ``What will 5G be?," *IEEE J. Sel. Areas Commun.*, vol. 32, pp. 1065--1082, June 2014.
3. Z. Pi and F. Khan, ``An introduction to millimeter-wave mobile broadband systems," *IEEE Commun. Mag.*, vol. 49, pp. 101--107, June 2011.
4. T. Rappaport *et al*, ``Millimeter wave mobile communications for 5G cellular: It will work!," *IEEE Access*, vol. 1, pp. 335--349, May 2013.
5. W. Roh *et al*, ``Millimeter-wave beamforming as an enabling technology for 5G cellular communications: theoretical feasibility and prototype results," *IEEE Commun. Mag.*, vol. 52, pp. 106--113, Feb. 2014.
6. A. Alkhateeb, G. Leus, and R. W. Heath, ``Compressed sensing based multi-user millimeter wave systems: How many measurements are needed?," in *Proc. IEEE Int. Conf. Acoustics, Speech and Sig. Process. (ICASSP)*, pp.2909--2913, April 2015.
7. Z. Gao, L. Dai, and Z. Wang, ``Channel estimation for mmwave massive MIMO based access and backhaul in ultra-dense network," in *Proc. IEEE Int. Conf. on Commun. (ICC)*, pp. 1--6, May 2016.
8. T. E. Bogale and L. B. Le, ``Massive MIMO and mmwave for 5G wireless hetnet: Potential benefits and challenges," *IEEE Veh. Technol. Mag.*, vol. 11, pp. 64--75, March 2016.
9. R. W. Heath, N. González-Prelcic, S. Rangan, W. Roh, and A. M. Sayeed, ``An overview of signal processing techniques for millimeter wave MIMO systems," *IEEE J. Sel. Areas Commun.*, vol. 10, pp. 436--453, April 2016.
10. J. Wang, ``Beam codebook based beamforming protocol for multi-Gbps millimeter-wave WPAN systems," *IEEE J. Sel. Areas Commun.*, vol. 27, pp. 1390--1399, Oct. 2009.

References

11. S. Hur, T. Kim, D. J. Love, J.V. Krogmeier, T.A. Thomas, and A. Ghosh, ``Millimeter wave beamforming for wireless backhaul and access in small cell networks,'' IEEE Trans. Commun., vol. 61, pp. 4391--4403, Oct. 2013.
12. A. Alkhateeb, O. E. Ayach, G. Leus, and R.W. Heath Jr., ``Channel estimation and hybrid precoding for millimeter wave cellular systems,'' IEEE J. Sel. Topics Signal Process., vol. 8, pp. 831--846, Oct. 2014.
13. R. M. Rial, C. Rusu, A. Alkhateeb, N. G. Prelcic, and R.W. Heath Jr., ``Hybrid MIMO architectures for millimeter wave communications: Phase shifters or switches?,'' IEEE Access, Jan. 2016.
14. S. Kashyap, C. Mollen, E. Bjornson, and E. G. Larsson, ``Frequency-domain interpolation of the zero-forcing matrix in massive MIMO-OFDM,'' in IEEE Int. Workshop Signal Process. Advances Wireless Commun. (SPAWC), pp. 1--5, July 2016.
15. A. Alkhateeb and R.W. Heath Jr., ``Frequency selective hybrid precoding for limited feedback millimeter wave systems'' IEEE Trans. Commun., vol. 64, pp. 1801--1818, May 2016.
16. A. Ghosh et al, ``Millimeter-wave enhanced local area systems: A high-data-rate approach for future wireless networks,'' IEEE J. Sel. Areas Commun., vol.~32, pp.~1152--1163, June 2014.
17. O. E. Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R.W. Heath Jr., ``Spatially sparse precoding in millimeter wave MIMO systems,'' IEEE Trans. Commun., vol. 13, pp. 1499--1513, Mar. 2014.
18. P. Schniter and A. Sayeed, ``Channel estimation and precoder design for millimeter-wave communications: The sparse way,'' in Proc. Asilomar Conf. Signals, Syst., Comput., pp. 273--277, Nov. 2014.
19. K. Venugopal, A. Alkhateeb, N. G. Prelcic, and R.W. Heath Jr., ``Channel estimation for hybrid architecture based wideband millimeter wave systems,'' CoRR, vol. abs/1611.03046, 2016. http://arxiv.org/abs/1611.03046.