Millimeter Wave Link Configuration with Hybrid MIMO Architectures

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Background & Motivation

1 — Millimeter Wave Link Configuration with Hybrid MIMO Architectures

Contribution 1

2 — Millimeter Wave Compressive Channel Estimation in the Frequency Domain

Contribution 2

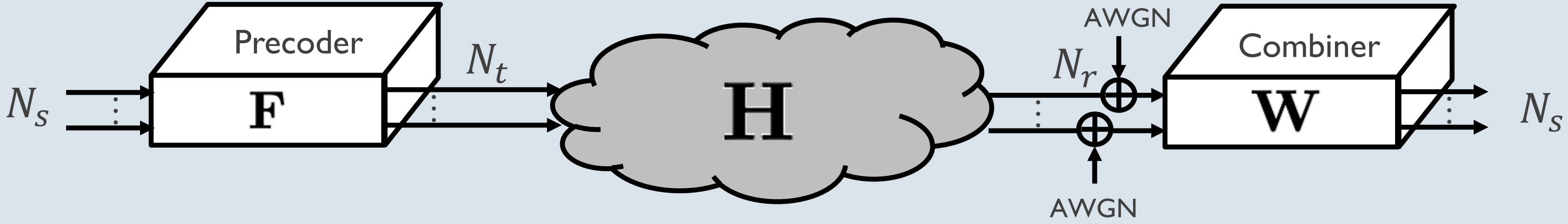
3 — Millimeter Wave Compressive Channel Estimation with Carrier Frequency Offset Uncertainties

Contribution 3

4 — Millimeter Wave Broadband Synchronization, Compressive Channel Estimation and Data Transmission

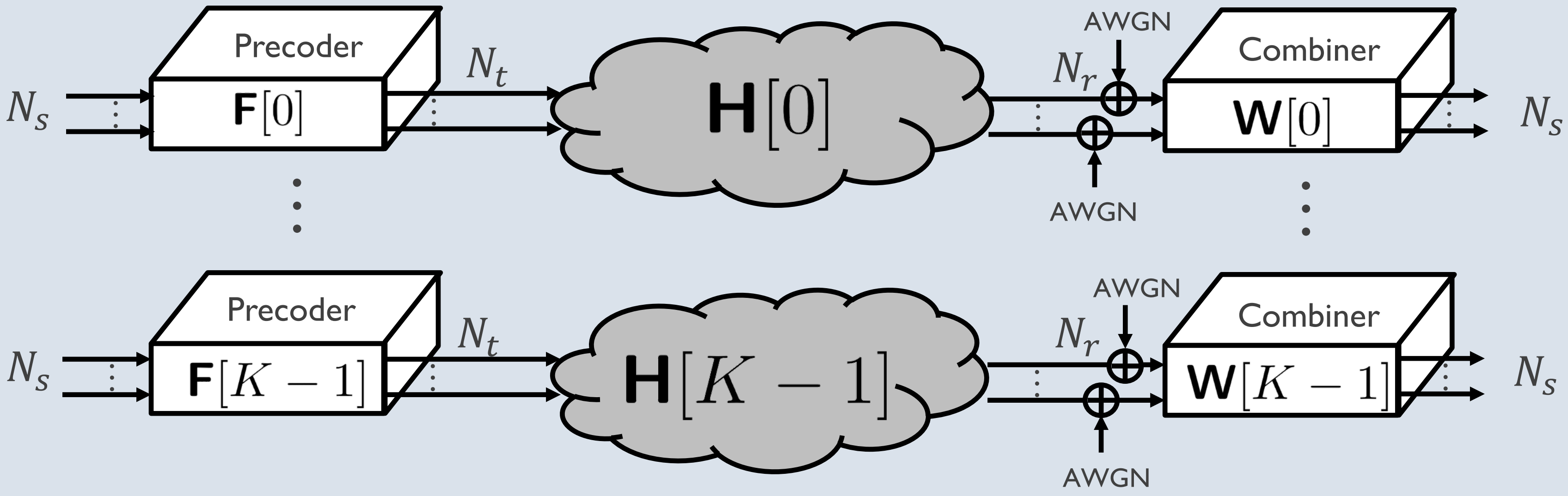
Narrowband MIMO communication

MIMO: Multiple-Input Multiple-Output



MIMO-OFDM communication

MIMO: Multiple-Input Multiple-Output
OFDM: Orthogonal Frequency Division Multiplexing



Spatial multiplexing

Channel estimation

Bit error rate

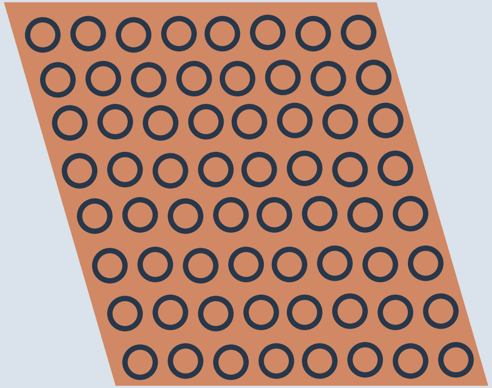
Synchronization

Beam alignment

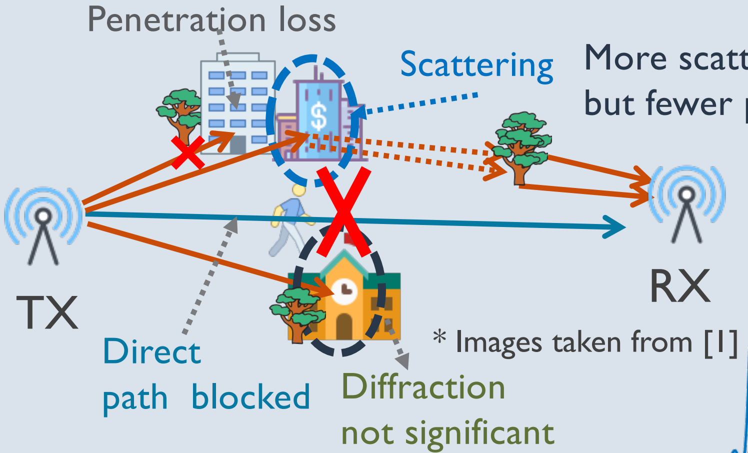
Mean squared error

Spectral efficiency

MIMO is different at mmWave vs. sub-6 GHz



Large antenna arrays

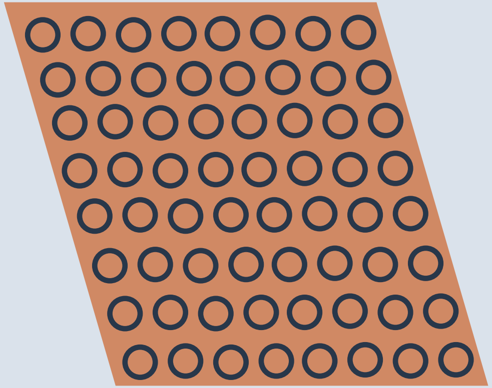


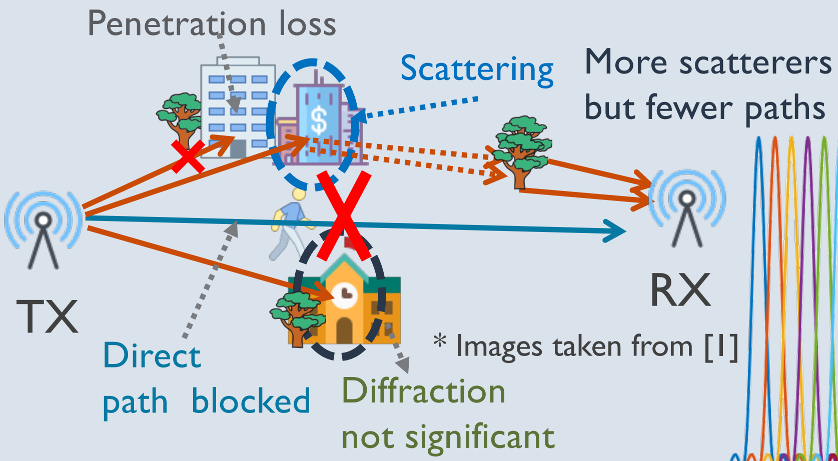
Small wavelength changes propagation

Large bandwidth

[1] https://icons8.com/icons/

MIMO is different at mmWave vs. sub-6 GHz





Large antenna arrays

Small wavelength changes propagation

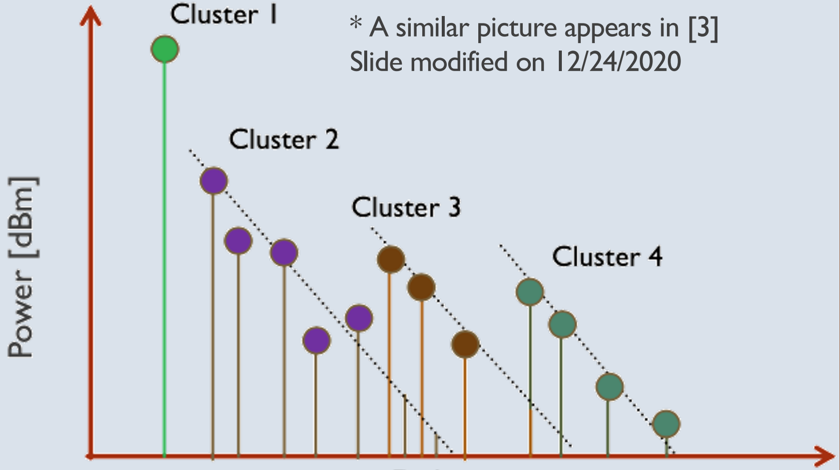
Large bandwidth

Signal processing problems are formulated and solved in a different way in mmWave bands

[1] https://icons8.com/icons/

Geometric channel model and sparsity

Sparsity in delay domain [1]

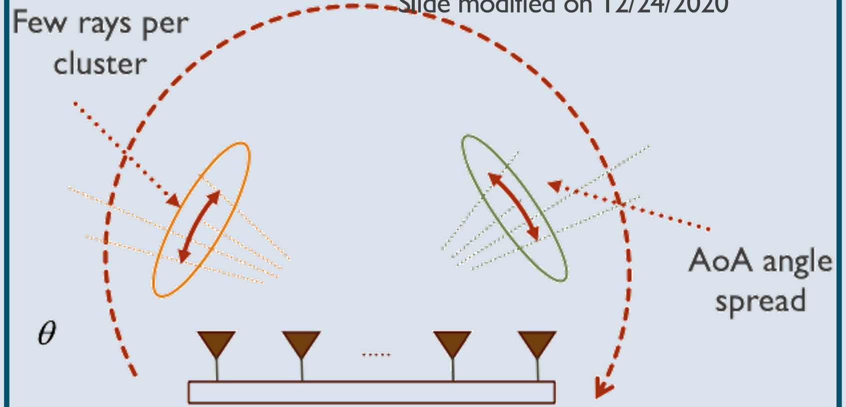


* A similar picture appears in [3]
Slide modified on 12/24/2020

Clusters in time domain

Sparsity in angular (spatial) domain [1,2]

* A similar picture appears in [3]
Slide modified on 12/24/2020



Clusters in spatial domain

Channel models are similar to lower frequency systems [2]

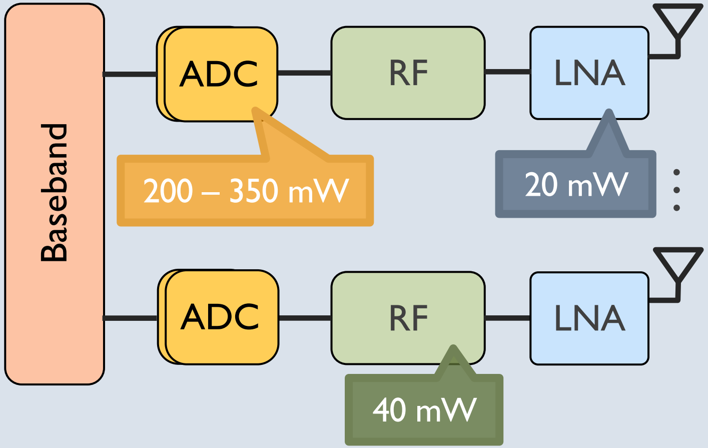
More sparsity in the channel due to larger bandwidth and larger arrays [2]

[1] P. Schniter and A. Sayeed, "Channel estimation and precoder design for millimeter-wave communications: The sparse way," 2014 48th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, 2014, pp. 273-277.
[2] 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," in IEEE Journal of Selected Topics in Signal Processing, vol. 10, no. 3, pp. 436-453, April 2016.
[3] R. W. Heath, "Millimeter Wave Wireless Communication: A Signal Processing Perspective", tutorial presented in IEEE SPAWC 2015.

mmWave communications for 5G: challenges

Power consumption challenge [1]

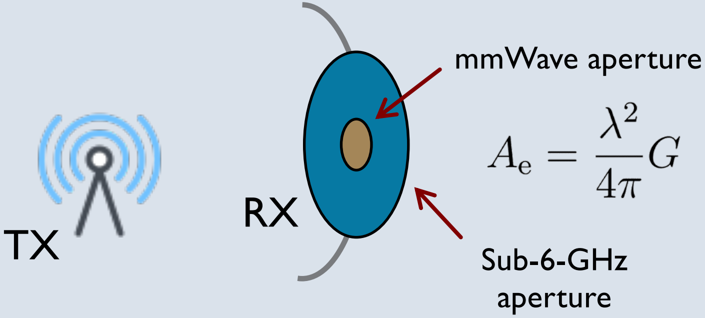
Power consumption at 60 GHz with 1 GHz BW



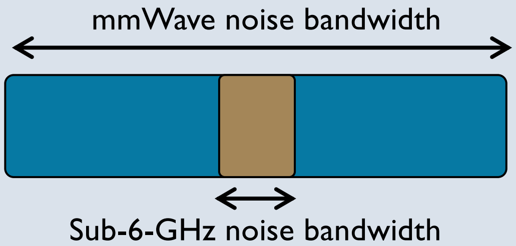
ADC: Analog-to-Digital Converter
LNA: Low-Noise Amplifier

Dedicated RF chain and high-resolution ADCs for each antenna are impractical

Propagation challenge [2]



$$A_e = \frac{\lambda^2}{4\pi} G$$



Directional beamforming is required to increase link quality through received SNR

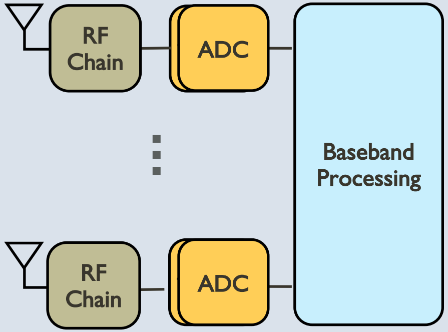
[1] R. Mendez-Rial, C. Rusu, N. Gonzalez-Prelcic, A. Alkhateeb, and R. W. Heath, Jr., "Hybrid MIMO architectures for millimeter wave communications: phase shifters or switches?" *IEEE Access*, vol. 4, pp. 247-267, Jan. 2016.

[2] Z. Pi and F. Khan, "An introduction to millimeter-wave mobile broadband systems," *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 101-107, Jun. 2011.

Alternative MIMO architectures

Conventional MIMO:
all digital

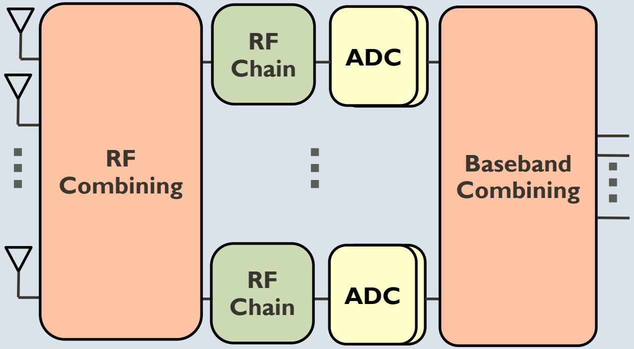
antennas = # RF chains = # pairs ADCs



Feasible with small antenna arrays

mmWave MIMO:
hybrid architecture

antennas ≥ # RF chains = # pairs ADCs



Split processing between analog and digital domains to reduce power consumption

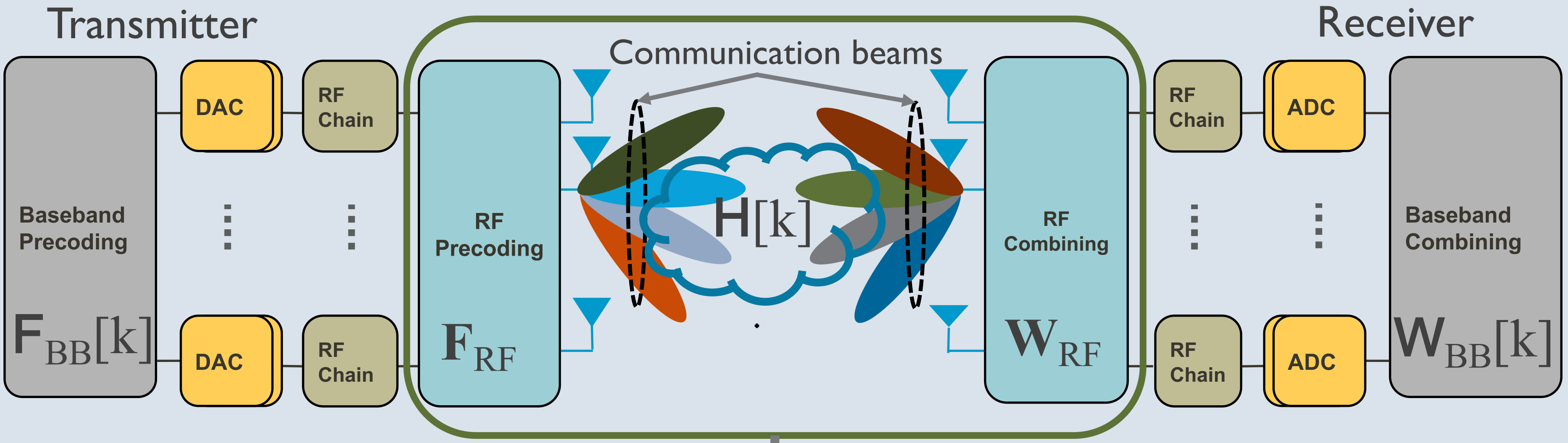
Hybrid mmWave architecture is considered in mmWave cellular deployments

[1] A. Alkhateeb, J. Mo, N. González-Prelcic and R. W. Heath, Jr., ``MIMO Precoding and Combining Solutions for Millimeter Wave Systems,'' IEEE Communications Magazine, vol. 52, no. 12, 122-131, December 2014.

[2] O. E. Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi and R. W. Heath, "Spatially Sparse Precoding in Millimeter Wave MIMO Systems," in IEEE Transactions on Wireless Communications, vol. 13, no. 3, pp. 1499-1513, March 2014.

*NR: New Radio

Array configuration with hybrid architectures



Synchronization at high SNR

Single-stream communication

Beam training
Choose beam pair that maximizes link quality (e.g. SINR)

Considered in 5G *NR

High overhead

Synchronization at low SNR

Multi-stream communication

Channel estimation
Reconstruct the channel and then design precoders and combiners

Legacy approach from LTE

Low overhead

Thesis Statement

Advanced hybrid analog-digital signal processing techniques can enable unprecedented communication performance while keeping training overhead low, even in the practical scenario of link configuration in the low SNR regime

Contribution 1

Millimeter Wave Compressive Channel Estimation in the Frequency Domain

- J. Rodriguez-Fernandez, N. Gonzalez-Prelcic, K. Venugopal and R. W. Heath, "Exploiting Common Sparsity for Frequency-Domain Wideband Channel Estimation at mmWave," *GLOBECOM 2017 - 2017 IEEE Global Communications Conference*, Singapore, 2017, pp. 1-6.
- J. Rodríguez-Fernández, N. González-Prelcic, K. Venugopal and R. W. Heath, "Frequency-Domain Compressive Channel Estimation for Frequency-Selective Hybrid Millimeter Wave MIMO Systems," in *IEEE Transactions on Wireless Communications*, vol. 17, no. 5, pp. 2946-2960, May 2018.
- J. P. González-Coma, J. Rodríguez-Fernández, N. González-Prelcic, L. Castedo and R. W. Heath, "Channel Estimation and Hybrid Precoding for Frequency Selective Multiuser mmWave MIMO Systems," in IEEE Journal of Selected Topics in Signal Processing, vol. 12, no. 2, pp. 353-367, May 2018.

Broadband open-loop channel estimation at mmWave

Approach	Computes/ exploits noise covariance	Pulse-shaping	Application to mmWave	Hybrid architecture	Online Complexity	Training Overhead	Communication Performance
SSAMP [1-2]					High	High	Medium
DGMP [3]					Low	High	Low
OMP [4]		✓	✓	✓	Medium	High	Medium
Proposed SW-OMP	✓	✓	✓	✓	Medium	Low	Very High
Proposed SS-SW-OMP+Th	✓	✓	✓	✓	Low	Medium	High

[1] Z. Gao, L. Dai, Z. Wang and S. Chen, "Spatially Common Sparsity Based Adaptive Channel Estimation and Feedback for FDD Massive MIMO," in *IEEE Transactions on Signal Processing*, vol. 63, no. 23, pp. 6169-6183, Dec.1, 2015.
[2] Z. Gao, L. Dai and Z. Wang, "Channel estimation for mmWave massive MIMO based access and backhaul in ultra-dense network," *2016 IEEE International Conference on Communications (ICC)*, Kuala Lumpur, 2016, pp. 1-6.
[3] Z. Gao, C. Hu, L. Dai and Z. Wang, "Channel Estimation for Millimeter-Wave Massive MIMO With Hybrid Precoding Over Frequency-Selective Fading Channels," in *IEEE Communications Letters*, vol. 20, no. 6, pp. 1259-1262, June 2016.
[4] K. Venugopal, A. Alkhateeb, N. González Prelcic and R. W. Heath, "Channel Estimation for Hybrid Architecture-Based Wideband Millimeter Wave Systems," in *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 9, pp. 1996-2009, Sept. 2017.

SSAMP: Structured Sparsity-Adaptive Matching Pursuit
DGMP: Distributed Grid-Matching Pursuit
OMP: Orthogonal Matching Pursuit
SW-OMP: Simultaneous Weighted – OMP
SS-SW-OMP+Th: Subcarrier Selection – SW-OMP + Thresholding

Broadband mmWave hybrid beamforming system model

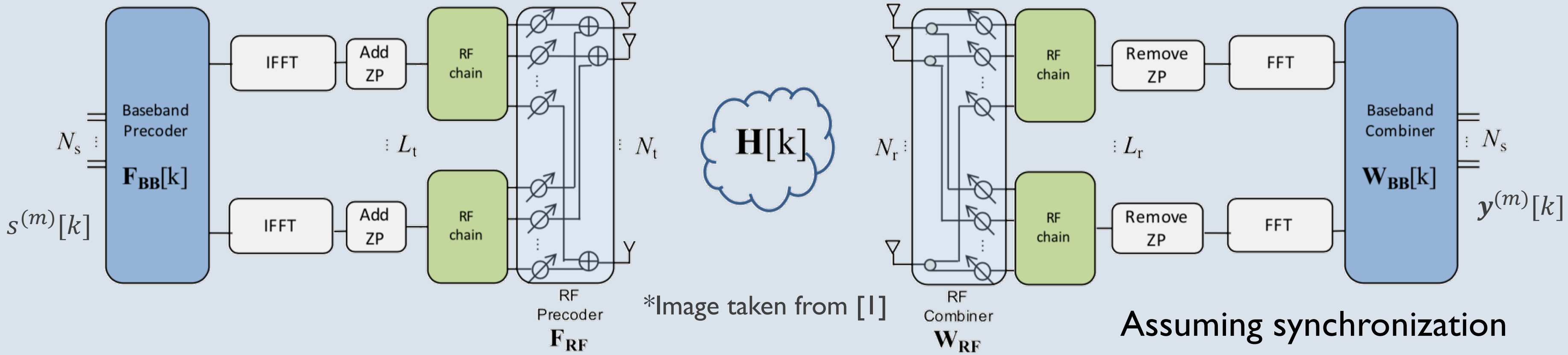


*Image taken from [1]

Assuming synchronization

Received signal — Transfer matrix — Received noise → $\mathbf{n}[k] \sim \mathcal{CN}(0, \sigma^2 \mathbf{W}_{\mathrm{BB}}^*[k]\mathbf{W}_{\mathrm{RF}}^*\mathbf{W}_{\mathrm{RF}}\mathbf{W}_{\mathrm{BB}}[k])$

$$\mathbf{y}[k] = \mathbf{A}[k]\ \mathbf{s}[k] + \mathbf{n}[k]$$

$$\mathbf{A}[k] = \mathbf{W}_{\mathrm{BB}}^*[k]\mathbf{W}_{\mathrm{RF}}^*\mathbf{H}[k]\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}[k]$$

kth subcarrier — OFDM symbol — Channel response

[1] **J. Rodriguez-Fernandez**, N. Gonzalez-Prelcic, K. Venugopal and R. W. Heath, "Frequency-Domain Compressive Channel Estimation for Frequency-Selective Hybrid Millimeter Wave MIMO Systems," in *IEEE Transactions on Wireless Communications*, vol. 17, no. 5, pp. 2946-2960, May 2018.

Broadband channel estimation using pilot symbols

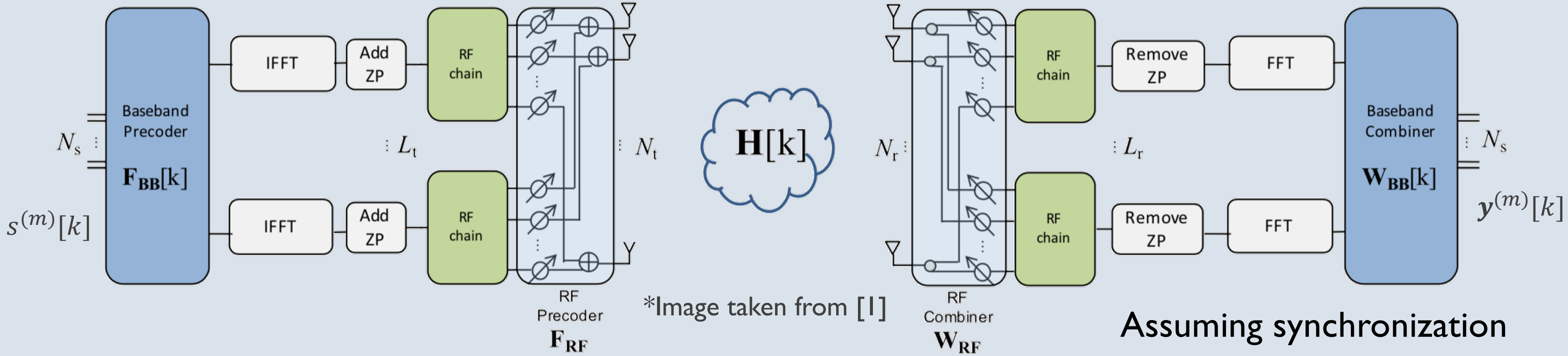


*Image taken from [1]

Assuming synchronization

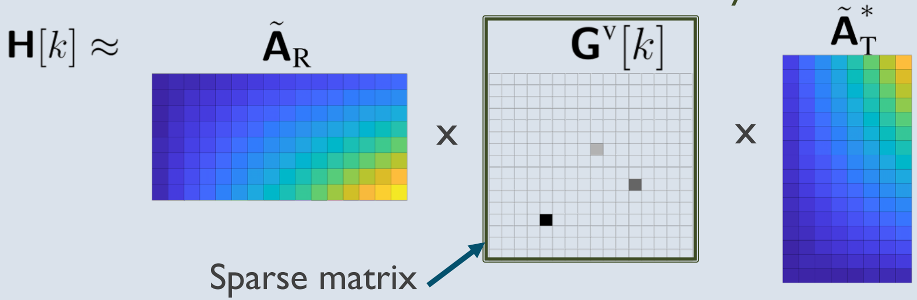
- Offline design of training pilot symbols, precoders, and combiners known at Tx and Rx
- Estimate vectorized channel $\mathbf{h}[k] = \mathrm{vec}\{\mathbf{H}[k]\}$ in $\mathbf{y}[k] = \mathbf{\Phi}[k]\ \mathbf{h}[k] + \mathbf{n}[k]$
- Synchronization grants orthogonality among subcarriers and preserves Fisher information
- Frequency-flat precoders/combiners give frequency-flat $\mathbf{\Phi}[k]$ to reduce complexity
- Estimate vectorized channel in $\mathbf{y}[k] = \mathbf{\Phi}\ \mathbf{h}[k] + \mathbf{n}[k]$

Sparse channel matrix and common sparsity at mmWave

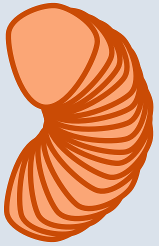
Channel matrix at kth subcarrier [1] → $\mathbf{H}[k] = \mathbf{A}_{\mathrm{R}}(\phi)\,\mathbf{G}[k]\mathbf{A}_{\mathrm{T}}^{*}(\boldsymbol{\theta})$

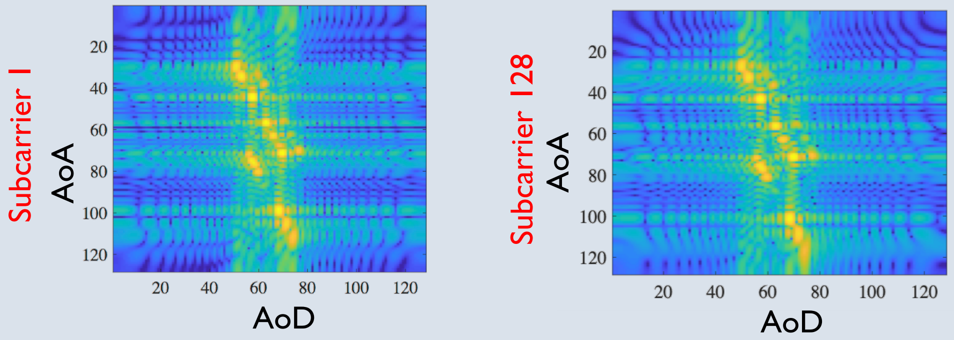
Diagonal matrix of size $N_{\mathrm{p}} \times N_{\mathrm{p}}$

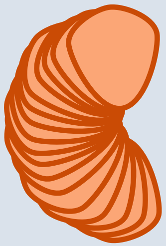
Receive & Transmit array matrices evaluated on *AoAs/*AoDs



Sparse channel matrix $\boldsymbol{G}^{v}[k]$ for 256 subcarriers, 500 MHz bandwidth, using NYUSIM channel simulator [2]







*AoAs: Angles-of-Arrival
AoDs: Angles-of-Departure

[1] **J. Rodriguez-Fernandez**, N. Gonzalez-Prelcic, K. Venugopal and R. W. Heath, "Frequency-Domain Compressive Channel Estimation for Frequency-Selective Hybrid Millimeter Wave MIMO Systems," in *IEEE Transactions on Wireless Communications*, vol. 17, no. 5, pp. 2946-2960, May 2018.

[2] S. Sun, G. R. MacCartney and T. S. Rappaport, "A novel millimeter-wave channel simulator and applications for 5G wireless communications," 2017 IEEE International Conference on Communications (ICC), Paris, 2017, pp. 1-7.

Problem formulation

Stack M Received OFDM symbols [1,2]

Hybrid precoders and combiners

Dictionary matrix

Received noise

Sparse channel

$$\underbrace{\begin{bmatrix} \mathbf{y}^{(1)}[k] \\ \vdots \\ \mathbf{y}^{(M)}[k] \end{bmatrix}}_{\mathbf{y}[k]} = \underbrace{\begin{bmatrix} \mathbf{\Phi}^{(1)} \\ \vdots \\ \mathbf{\Phi}^{(M)} \end{bmatrix}}_{\mathbf{\Phi}} \mathbf{\Psi}\mathbf{g}^{\mathrm{v}}[k] + \underbrace{\begin{bmatrix} \mathbf{n}_{\mathrm{c}}^{(1)}[k] \\ \vdots \\ \mathbf{n}_{\mathrm{c}}^{(M)}[k] \end{bmatrix}}_{\mathbf{n}_{\mathrm{c}}[k]}$$

Extended virtual channel model

$$\mathrm{vec}\{\mathbf{H}[k]\} \approx \underbrace{\left(\tilde{\mathbf{A}}_{\mathrm{T}}^{\mathrm{C}} \otimes \tilde{\mathbf{A}}_{\mathrm{R}}\right)}_{\mathbf{\Psi}} \mathbf{g}^{\mathrm{v}}[k]$$

Measurement matrix

$$\mathbf{\Upsilon} = \mathbf{\Phi}\mathbf{\Psi}$$

[1] **J. Rodriguez-Fernandez**, N. Gonzalez-Prelcic, K. Venugopal and R. W. Heath, "Frequency-Domain Compressive Channel Estimation for Frequency-Selective Hybrid Millimeter Wave MIMO Systems," in *IEEE Transactions on Wireless Communications*, vol. 17, no. 5, pp. 2946-2960, May 2018.

[2] J. P. González-Coma, **J. Rodríguez-Fernández**, N. González-Prelcic, L. Castedo and R. W. Heath, "Channel Estimation and Hybrid Precoding for Frequency Selective Multiuser mmWave MIMO Systems," in *IEEE Journal of Selected Topics in Signal Processing*, vol. 12, no. 2, pp. 353-367, May 2018

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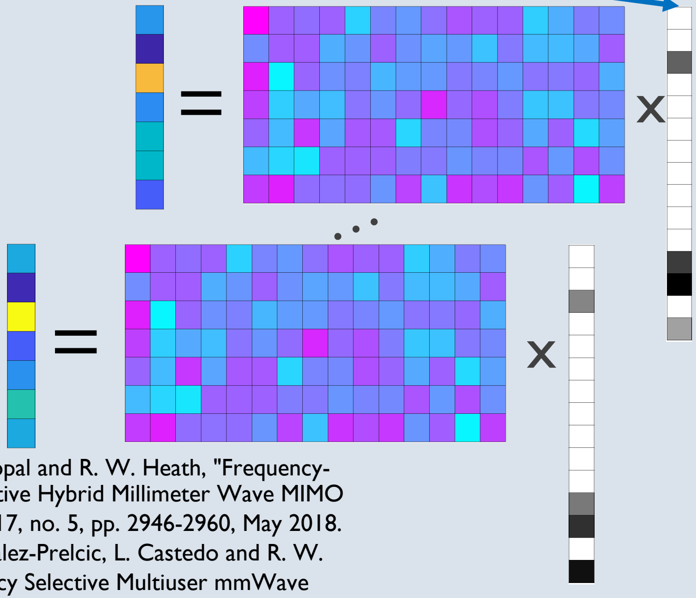

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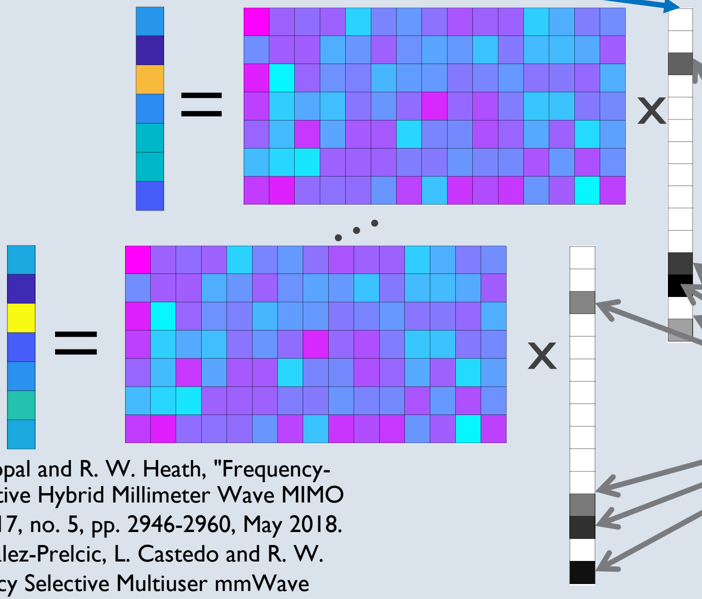

Non-zero positions characterize AoA/AoD and the channel gains

Common spatial sparsity pattern

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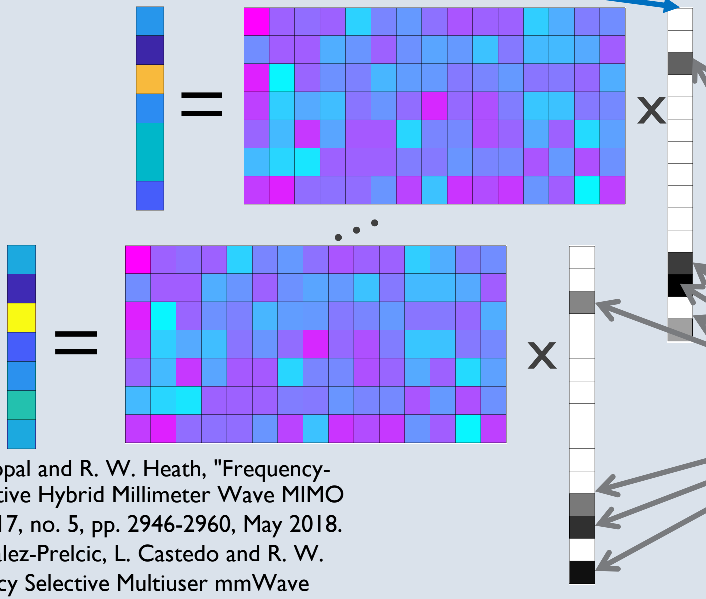
Measurement matrix

$$\mathbf{\Upsilon} = \mathbf{\Phi}\mathbf{\Psi}$$

Estimation of non-zero indexes + coefficients



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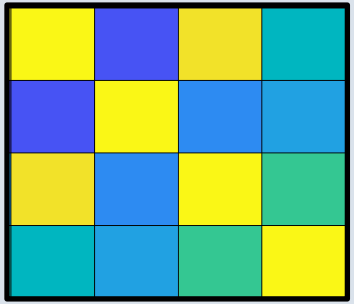
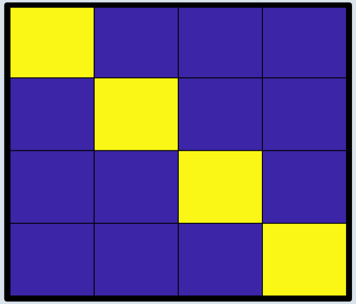
Proposed algorithms and key ingredients

Simultaneous Weighted – Orthogonal Matching Pursuit (SW-OMP)



Noise spatial covariance **before** whitening

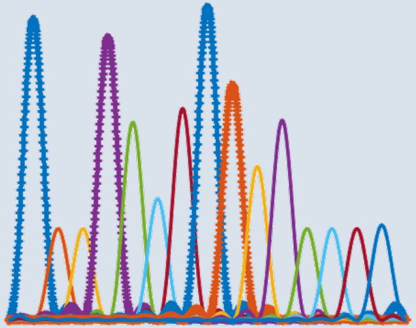


Noise spatial covariance **after** whitening

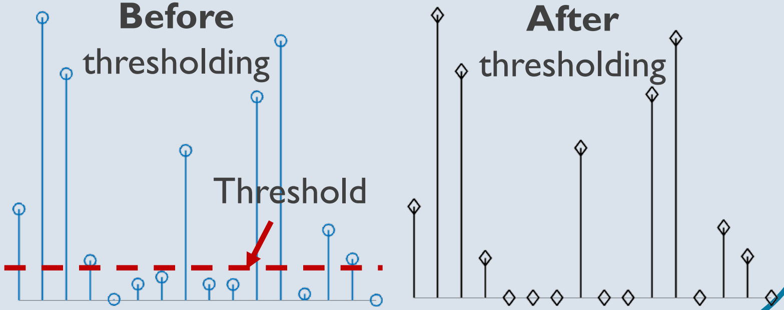
Cancelling spatial correlation reduces estimation error

Subcarrier Selection – SW – OMP + Thresholding (SS-SW-OMP+Th)

Select $K_P = 4$ strongest subcarriers



Spatial domain



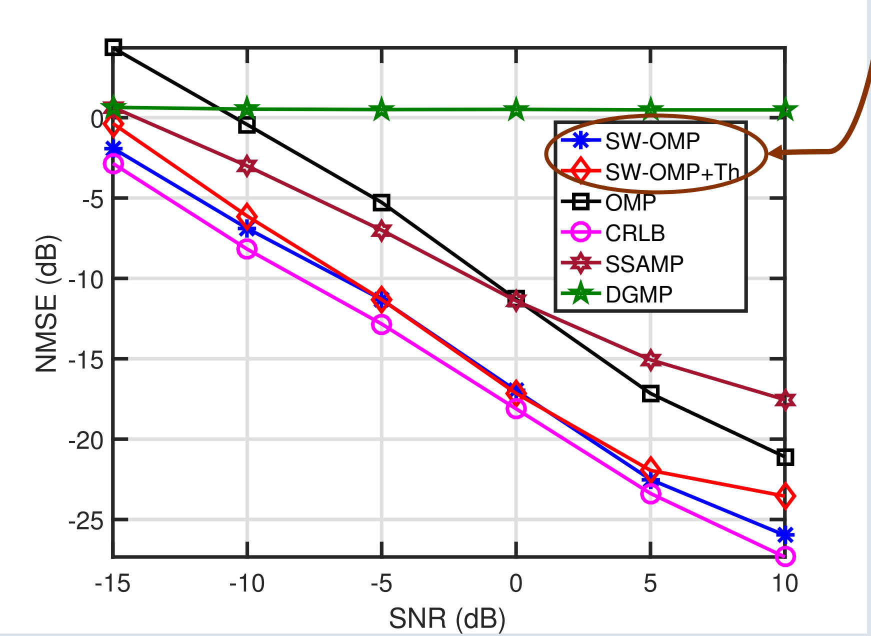
Estimation error performance

System parameters

32 Tx antennas
32 Rx antennas
Sampling period 1/1760 μs
4 Tx RF chains
4 Rx RF chains
64-point angular grid sizes
16 subcarriers
80 OFDM training symbols

Channel realizations from NYUSIM channel simulator

Proposed algorithms significantly outperform prior work on massive MIMO [1]



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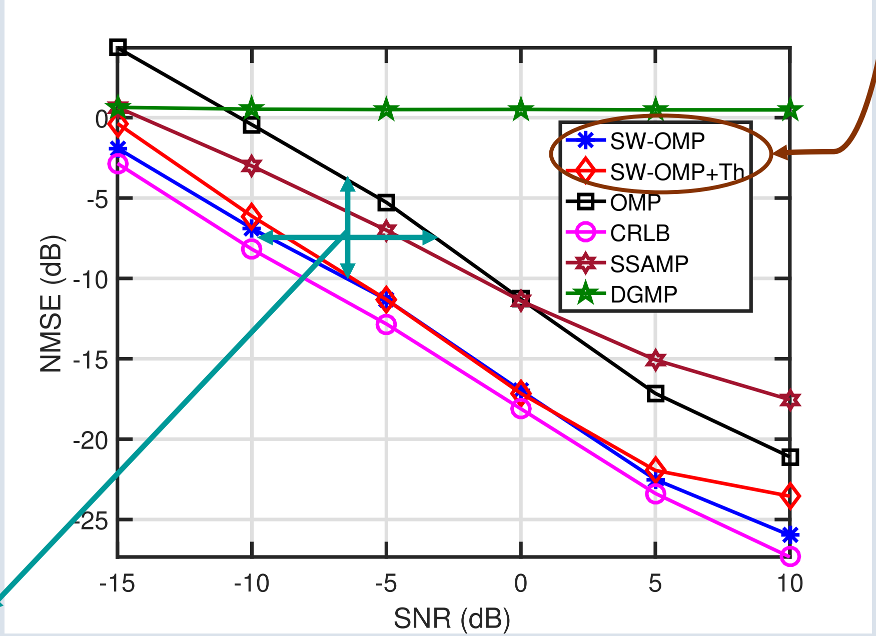
Channel realizations from NYUSIM channel simulator

Proposed algorithms significantly outperform prior work on massive MIMO [1]



Exploiting common spatial sparsity leads to ~7 dB error and SNR improvement [1]

[1] **J. Rodriguez-Fernandez**, N. Gonzalez-Prelcic, K. Venugopal and R. W. Heath, "Frequency-Domain Compressive Channel Estimation for Frequency-Selective Hybrid Millimeter Wave MIMO Systems," in *IEEE Transactions on Wireless Communications*, vol. 17, no. 5, pp. 2946-2960, May 2018.

Spectral efficiency performance

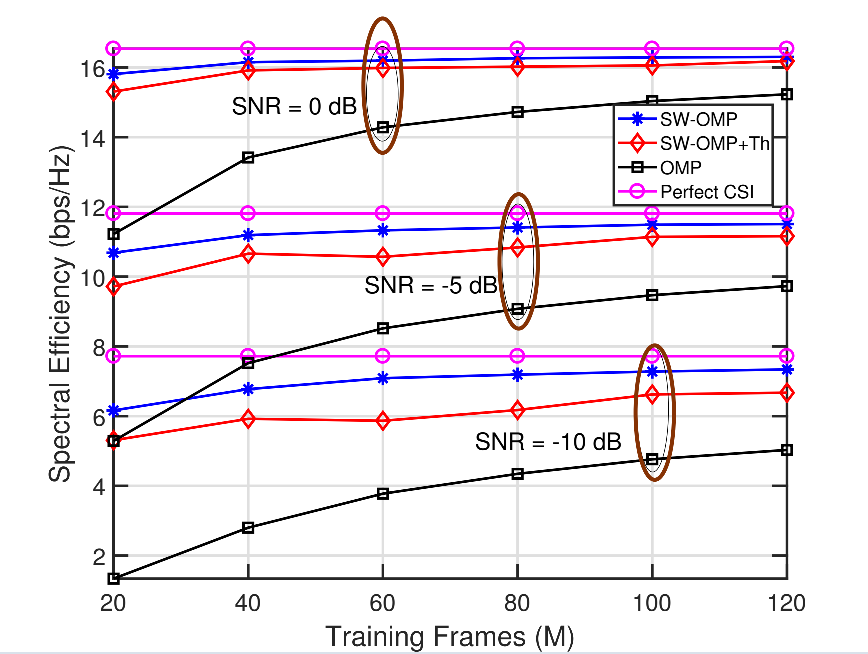
System parameters

32 Tx antennas
32 Rx antennas
Sampling period 1/1760 μs
4 Tx RF chains
4 Rx RF chains
128-point angular grid sizes
256 subcarriers
1 OFDM symbol/frame

Per-subcarrier estimation leads to poor spectral efficiency [1]

Near-optimum spectral efficiency at low SNR regime

20 training frames are enough to estimate the channel



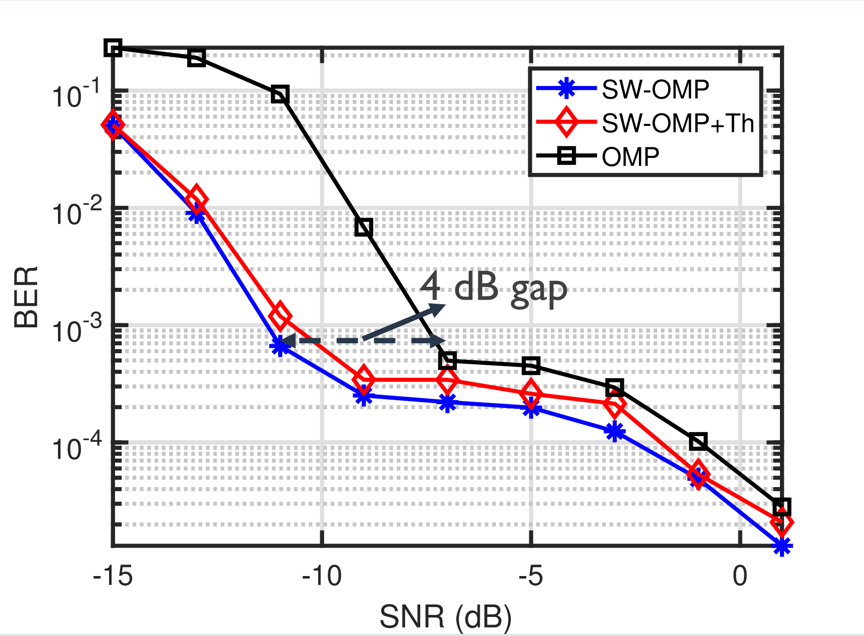
[1] **J. Rodriguez-Fernandez**, N. Gonzalez-Prelcic, K. Venugopal and R. W. Heath, "Frequency-Domain Compressive Channel Estimation for Frequency-Selective Hybrid Millimeter Wave MIMO Systems," in *IEEE Transactions on Wireless Communications*, vol. 17, no. 5, pp. 2946-2960, May 2018.

Bit Error Rate performance

System parameters

32 Tx antennas
32 Rx antennas
Sampling period 1/1760 μs
4 Tx RF chains
4 Rx RF chains
128-point angular grid sizes
512 subcarriers
1 OFDM symbol/frame, 60 frames
802.11ad OFDM-PHY parameters
Dual Carrier 16-QAM modulation
½ code rate

Proposed algorithms outperform prior work in terms of BER



Large performance gap at low SNR

Proposed algorithms enable data decoding with low overhead

[1] **J. Rodriguez-Fernandez**, N. Gonzalez-Prelcic, K. Venugopal and R. W. Heath, "Frequency-Domain Compressive Channel Estimation for Frequency-Selective Hybrid Millimeter Wave MIMO Systems," in *IEEE Transactions on Wireless Communications*, vol. 17, no. 5, pp. 2946-2960, May 2018.

Conclusion for Contribution 1

- ❖ Millimeter Wave Compressive Channel Estimation in the Frequency Domain
  - ✓ Proposed two algorithms to estimate broadband mmWave MIMO channels
  - ✓ Analyzed theoretical convergence guarantees
  - ✓ Derived CRLB* for broadband mmWave MIMO channel estimation with perfect angle retrieval
  - ✓ Showed frequency-flat training precoding attains CRLB at low SNR and reduces complexity
  - ✓ Conveniently selected only a few subcarrier signals to reduce complexity without loss in estimation or communication performance

*CRLB: Cramer-Rao Lower Bound

Contribution II

Millimeter Wave Compressive Channel Estimation with Carrier Frequency Offset (CFO) Uncertainties

- J. Rodriguez-Fernandez, N. Gonzalez-Prelcic and R. W. Heath, "Channel Estimation for Millimeter Wave MIMO Systems in the Presence of CFO Uncertainties," *2018 IEEE International Conference on Communications (ICC)*, Kansas City, MO, 2018, pp. 1-6.
- J. Rodriguez-Fernandez and N. Gonzalez-Prelcic, "Channel Estimation for Hybrid mmWave MIMO Systems With CFO Uncertainties," in *IEEE Transactions on Wireless Communications*, vol. 18, no. 10, pp. 4636-4652, Oct. 2019.

Narrowband open-loop channel estimation with impairments

Approach	Computes/ exploits noise covariance	Requires no prior info.	Application to mmWave	Hybrid architecture	Online Complexity	Training Overhead	Communication Performance
Narrowband w/ *PN [1]					Low	Medium	Medium
Tensor approach [2]			✓		High	Medium	Low
Channel est. w/ CFO [3]			✓		Low	Medium	Low
Swift-Link [4]		✓	✓		Medium	Medium	Medium
Beam training w/ CFO and PN [5]		✓	✓		Medium	Medium	Medium
Proposed	✓	✓	✓	✓	Low	Medium	High

[1] C. Zhang, Z. Xiao, L. Su, L. Zeng and D. Jin, "Iterative channel estimation and phase noise compensation for SC-FDE based mmWave systems," *2015 IEEE International Conference on Communication Workshop (ICCW)*, London, 2015, pp. 2133-2138.

[2] N. J. Myers and R. W. Heath, "A compressive channel estimation technique robust to synchronization impairments," *2017 IEEE 18th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Sapporo, 2017, pp. 1-5.

[3] M. Pajovic, P. Wang, T. Koike-Akino and P. Orlik, "Estimation of frequency unsynchronized millimeter-wave channels," *2017 IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, Montreal, QC, 2017, pp. 1205-1209.

[4] N. J. Myers, A. Mezghani and R. W. Heath, "Swift-Link: A Compressive Beam Alignment Algorithm for Practical mmWave Radios," in *IEEE Transactions on Signal Processing*, vol. 67, no. 4, pp. 1104-1119, 15 Feb.15, 2019.

[5] H. Yan and D. Cabria, "Compressive sensing based initial beamforming training for massive MIMO millimeter-wave systems," *2016 IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, Washington, DC, 2016, pp. 620-624.

Problem formulation

M training symbols

Equivalent beamformed channel $\tilde{\boldsymbol{\alpha}}^{(m)} = [\alpha_1^{(m)} e^{j\beta_1^{(m)}}, \ldots, \alpha_{L_r}^{(m)} e^{j\beta_{L_r}^{(m)}}]^T$

Index for training frame

Stacked received samples

$$\underbrace{\begin{bmatrix} \mathbf{y}^{(m)}[0] \\ \vdots \\ \mathbf{y}^{(m)}[N-1] \end{bmatrix}}_{\mathbf{y}^{(m)}} = \underbrace{\begin{bmatrix} \boldsymbol{\Omega}_0^{(m)} \tilde{\boldsymbol{\alpha}}^{(m)} & & \\ & \ddots & \\ & & \boldsymbol{\Omega}_{N-1}^{(m)} \tilde{\boldsymbol{\alpha}}^{(m)} \end{bmatrix}}_{\mathbf{T}(\boldsymbol{\xi}^{(m)})} \underbrace{\begin{bmatrix} s^{(m)}[0] \\ \vdots \\ s^{(m)}[N-1] \end{bmatrix}}_{\mathbf{s}^{(m)}} + \underbrace{\begin{bmatrix} \mathbf{v}^{(m)}[0] \\ \vdots \\ \mathbf{v}^{(m)}[N-1] \end{bmatrix}}_{\mathbf{v}^{(m)}}$$

Number of samples per frame

Training vector

Noise vector

Potentially different CFO for each equivalent channel

$$\boldsymbol{\Omega}_n^{(m)} = e^{j2\pi\Delta f^{(m)} n} \mathbf{I}_{L_r}$$

Sparsity level is unknown

Gains of the beamformed channel for every RF chain and *m*th training frame

Noise variance is unknown

Parameters to estimate

$$\boldsymbol{\xi}^{(m)} = [\alpha_1^{(m)}, \ldots, \alpha_{L_r}^{(m)}, \beta_1^{(m)}, \ldots, \beta_{L_r}^{(m)}, \Delta f^{(m)}, \sigma^2]^T$$

Phase of the beamformed channel for *m*th training frame and every RF chain

J. Rodriguez-Fernandez and N. Gonzalez-Prelcic, "Channel Estimation for Hybrid mmWave MIMO Systems With CFO Uncertainties," in *IEEE Transactions on Wireless Communications*, vol. 18, no. 10, pp. 4636-4652, Oct. 2019.

Stage 1: Maximum Likelihood (ML) estimators

Maximization of Log-Likelihood function

$$\hat{\boldsymbol{\xi}}_{\mathrm{ML}}^{(m)} = \underset{\boldsymbol{\xi}^{(m)}}{\arg\max} \log p\left(\mathbf{y}^{(m)}; \boldsymbol{\xi}^{(m)}\right)$$

CFO ML estimator

$$\widehat{\Delta f}_{\mathrm{ML}}^{(m)} = \underset{\Delta f}{\arg\max} \left\{ \frac{1}{N} \sum_{i=1}^{L_{\mathrm{r}}} \left| \sum_{n=0}^{N-1} y_i^{(m)}[n] s^{(m)\mathrm{C}}[n] e^{-\mathrm{j}2\pi\Delta f^{(m)} n} \right|^2 \right\}$$

Amplitude ML estimator

$$\hat{\hat{\alpha}}_{i,\mathrm{ML}}^{(m)} = \frac{1}{N} \sum_{n=0}^{N-1} y_i^{(m)}[n] s^{(m)\mathrm{C}}[n] e^{-\mathrm{j}2\pi\widehat{\Delta f}_{\mathrm{ML}}^{(m)} n}$$

Noise variance ML estimator

$$\widehat{\sigma^2}_{\mathrm{ML}} = \frac{1}{N L_{\mathrm{r}}} \left\| \mathbf{y}^{(m)} - \mathbf{T}\left(\hat{\boldsymbol{\xi}}^{(m)}\right) \mathbf{s}^{(m)} \right\|_2^2$$

J. Rodriguez-Fernandez and N. Gonzalez-Prelcic, "Channel Estimation for Hybrid mmWave MIMO Systems With CFO Uncertainties," in *IEEE Transactions on Wireless Communications*, vol. 18, no. 10, pp. 4636-4652, Oct. 2019.

Stage 2: Combining ML Optimality and CRLB [1]

Estimate high-dimensional MIMO channel using beamformed estimates and noise variance

$$\underbrace{\begin{bmatrix} \hat{\tilde{\boldsymbol{\alpha}}}_{\mathrm{ML}}^{(1)} \\ \vdots \\ \hat{\tilde{\boldsymbol{\alpha}}}_{\mathrm{ML}}^{(M)} \end{bmatrix}}_{\hat{\tilde{\boldsymbol{\alpha}}}_{\mathrm{ML}}} = \underbrace{\begin{bmatrix} \boldsymbol{\Phi}^{(1)} \\ \vdots \\ \boldsymbol{\Phi}^{(M)} \end{bmatrix}}_{\boldsymbol{\Phi}} \boldsymbol{\Psi}\, \mathbf{g}^{\mathrm{v}} + \begin{bmatrix} \tilde{\mathbf{v}}^{(1)} \\ \vdots \\ \tilde{\mathbf{v}}^{(M)} \end{bmatrix}$$

$$\mathrm{vec}\{\mathbf{H}\} \approx \underbrace{\left(\tilde{\mathbf{A}}_{\mathrm{T}}^{\mathrm{C}} \otimes \tilde{\mathbf{A}}_{\mathrm{R}}\right)}_{\boldsymbol{\Psi}} \underbrace{\mathrm{vec}\{\mathbf{G}^{\mathrm{v}}\}}_{\mathbf{g}^{\mathrm{v}}}$$

Dictionary matrix

Sparse channel

Beamformed channel estimates

Estimation error for different training frames

MIMO channel estimation problem [1]

$$\hat{\mathbf{g}}^{\mathrm{v}} = \arg\min_{\mathbf{g}^{\mathrm{v}}} \|\mathbf{g}^{\mathrm{v}}\|_1, \qquad \text{subject to}$$

$$\left(\hat{\tilde{\boldsymbol{\alpha}}}_{\mathrm{ML}} - \boldsymbol{\Phi}\boldsymbol{\Psi}\mathbf{g}^{\mathrm{v}}\right)^* \mathbf{C}_{\tilde{\mathbf{v}}\tilde{\mathbf{v}}}^{-1} \left(\hat{\tilde{\boldsymbol{\alpha}}}_{\mathrm{ML}} - \boldsymbol{\Phi}\boldsymbol{\Psi}\mathbf{g}^{\mathrm{v}}\right) \leq \epsilon$$

[1] J. Rodriguez-Fernandez and N. Gonzalez-Prelcic, "Channel Estimation for Hybrid mmWave MIMO Systems With CFO Uncertainties," in *IEEE Transactions on Wireless Communications*, vol. 18, no. 10, pp. 4636-4652, Oct. 2019.

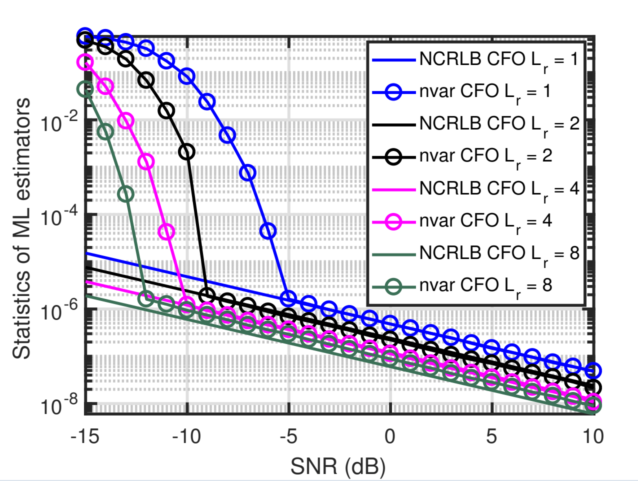
CFO estimation error performance

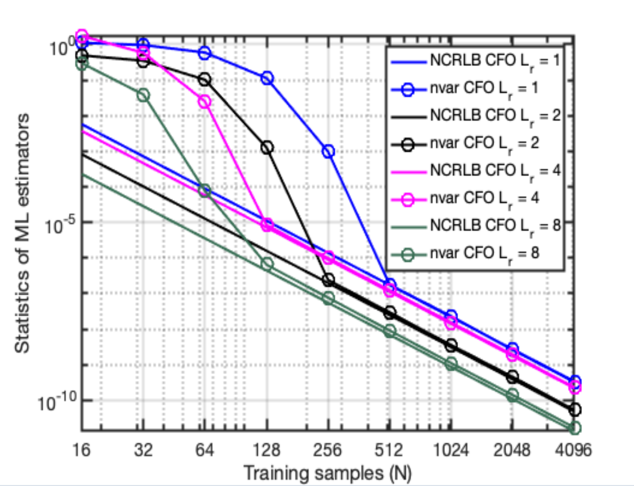
System parameters

32 Tx antennas
32 Rx antennas
Sampling period 1/1760 μs
4 Tx RF chains
{1,2,4,8} Rx RF chains
128-point angular grid sizes
128 samples per training frame
4 clusters with 15 rays/cluster
Angular Spread 15°

Increasing number of RF chains reduces minimum SNR for asymptotic efficiency

Asymptotic efficiency is obtained in the low SNR regime





SNR = -10 dB

128 training samples are enough to accurately estimate the CFO

[1] **J. Rodriguez-Fernandez**, N. Gonzalez-Prelcic, K. Venugopal and R. W. Heath, "Frequency-Domain Compressive Channel Estimation for Frequency-Selective Hybrid Millimeter Wave MIMO Systems," in *IEEE Transactions on Wireless Communications*, vol. 17, no. 5, pp. 2946-2960, May 2018.

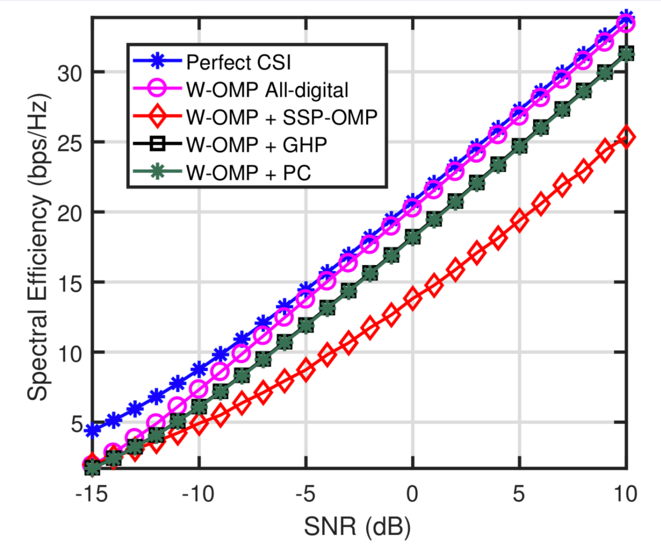
Spectral efficiency performance

System parameters

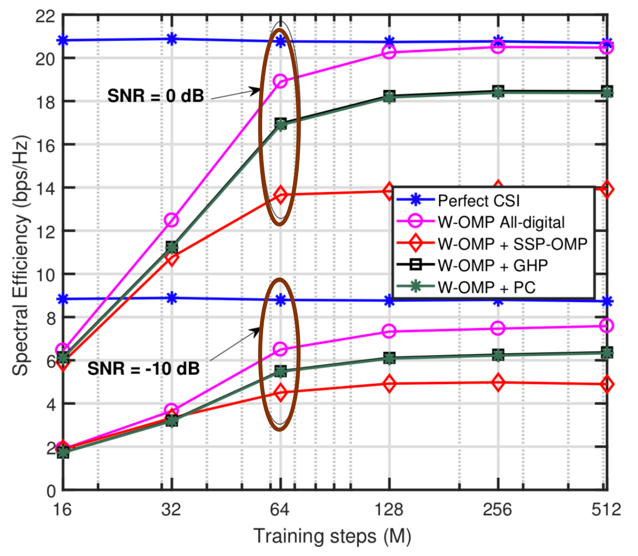
32 Tx antennas
32 Rx antennas
Sampling period 1/1760 μs
4 Tx RF chains
4 Rx RF chains
128-point angular grid sizes
128 samples per training frame
4 clusters with 15 rays/cluster
Angular Spread 15°

Small gap between all-digital and hybrid precoders/combiners [2-3]

Near-optimum spectral efficiency at low SNR regime



Marginal increase in spectral efficiency for $M > 128$



[1] **J. Rodriguez-Fernandez**, N. Gonzalez-Prelcic, K. Venugopal and R. W. Heath, "Frequency-Domain Compressive Channel Estimation for Frequency-Selective Hybrid Millimeter Wave MIMO Systems," in *IEEE Transactions on Wireless Communications*, vol. 17, no. 5, pp. 2946-2960, May 2018.
[2] R. Méndez-Rial, C. Rusu, N. González-Prelcic and R. W. Heath, "Dictionary-free hybrid precoders and combiners for mmWave MIMO systems," *2015 IEEE 16th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Stockholm, 2015, pp. 151-155.
[3] R. Lopez-Valcarce, N. Gonzalez-Prelcic, C. Rusu and R. W. Heath, "Hybrid Precoders and Combiners for mmWave MIMO Systems with Per-Antenna Power Constraints," *2016 IEEE Global Communications Conference (GLOBECOM)*, Washington, DC, 2016, pp. 1-6.

Hybrid Precoding Algorithms
SSP: Spatially Sparse Precoding
OMP: Orthogonal Matching Pursuit
GHP: Greedy Hybrid Precoding
PC: Per-antenna Constrained

Conclusion for Contribution 2

- ❖ Millimeter Wave Compressive Channel Estimation with CFO* Uncertainties
  - ✓ Derived multi-stage solution to joint CFO and channel estimation
  - ✓ Derived closed-form CRLB* expressions
  - ✓ Derived optimal ML* estimators attaining the CRLB
  - ✓ Combined frame-wise estimators to reduce complexity and preserve optimality
  - ✓ Leveraged ML estimates and CRLB to obtain CS*-based algorithm

*CFO: Carrier Frequency Offset
CRLB: Cramer-Rao Lower Bound
CS: Compressed-Sensing
ML: Maximum-Likelihood

Contribution III

Millimeter Wave Broadband Synchronization, Compressive Channel Estimation and Data Transmission

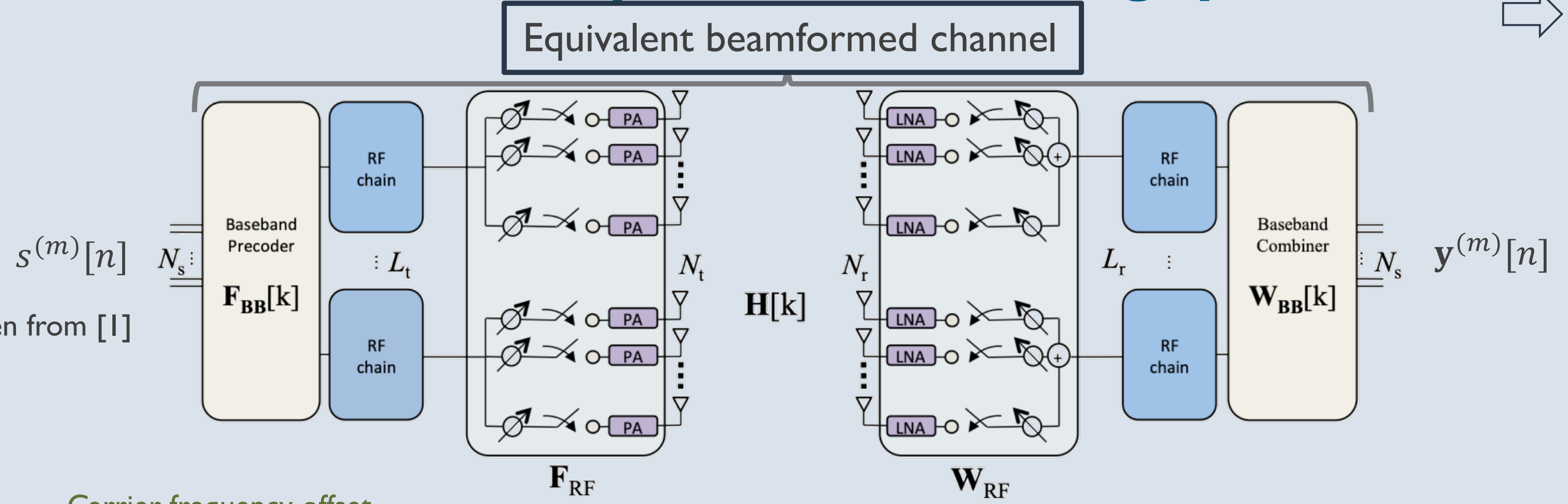
- J. Rodriguez-Fernandez and N. Gonzalez-Prelcic, "Joint Synchronization and Compressive Estimation for Frequency-Selective mmWave MIMO Systems," 2018 52nd Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, USA, 2018, pp. 1280-1286.
- J. Rodriguez-Fernandez, "Broadband Synchronization, Compressive Channel Estimation, and Data Transmission for Hybrid mmWave MIMO Systems," to be submitted to IEEE Transactions on Wireless Communications.

Broadband open-loop channel estimation with impairments

Approach	Exploits noise covariance	Considers Timing Offset	Considers phase noise	Considers CFO	Hybrid architecture	Online Complexity	Training Overhead	Communication Performance
Compressive initial access [1]		✓	?	✓		Low	Low-Medium	Low
Swift-Link [2]				✓		Medium	Low-Medium	Low
Proposed LMMSE-EM	✓	✓	✓	✓	✓	Medium-High	Low-Medium	High
Proposed EKF-RTS-EM	✓	✓	✓	✓	✓	Low-Medium	Low-Medium	Medium-High

[1] H. Yan and D. Cabric, "Compressive Initial Access and Beamforming Training for Millimeter-Wave Cellular Systems," in *IEEE Journal of Selected Topics in Signal Processing*, vol. 13, no. 5, pp. 1151-1166, Sept. 2019.
[2] N. J. Myers, A. Mezghani and R. W. Heath, "Swift-Link: A Compressive Beam Alignment Algorithm for Practical mmWave Radios," in *IEEE Transactions on Signal Processing*, vol. 67, no. 4, pp. 1104-1119, 15 Feb.15, 2019.

Broadband mmWave hybrid beamforming system model



* Image taken from [1]

Carrier frequency offset (CFO)

Equivalent beamformed channel

Timing offset (TO)

Post-combining noise

$$\mathbf{y}^{(m)}[n] = e^{\mathrm{j}(2\pi\Delta f^{(m)} n + \theta^{(m)}[n])} \sum_{d=0}^{D-1} \mathbf{g}^{(m)}[d] \; s^{(m)}[n-d-n_0] + \mathbf{v}^{(m)}[n]$$

Received signal for *m*th frame

Training pilot

Phase noise (PN)

$$n = 0, \ldots, N + D + n_0 - 1$$

Goal is to estimate the MIMO channel $\{\mathbf{H}[k]\}_{k=0}^{K-1}$

[1] J. Rodríguez-Fernández and N. González-Prelcic, "Joint Synchronization and Compressive Estimation for Frequency-Selective mmWave MIMO Systems," 2018 52nd Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, USA, 2018, pp. 1280-1286.

Joint synchronization and channel estimation formulation

Received signal for *m*th frame

Carrier frequency offset (CFO)

Equivalent beamformed channel *m*th training frame, *d*th delay tap

Timing offset (TO)

Post-combining noise

$$\mathbf{y}^{(m)}[n] = e^{\mathrm{j}(2\pi\Delta f^{(m)} n + \theta^{(m)}[n])} \sum_{d=0}^{D-1} \mathbf{g}^{(m)}[d]\, s^{(m)}[n-d-n_0] + \mathbf{v}^{(m)}[n]$$

$$n = 0, \ldots, N + D + n_0 - 1$$

Phase noise (PN)

Training OFDM symbols

Unknown CFO

Channel sparsity is unknown

Known PN covariance [1]

Unknown TO

$$\boldsymbol{\xi}^{(m)} \triangleq \left[\ \Delta f^{(m)} \quad \{\mathbf{g}^{(m)T}[d]\}_{d=0}^{D-1} \quad \boldsymbol{\theta}^{(m)T} \quad n_0\ \right]^T$$

Parameters to estimate

[1] IEEE 802.11ad standard, “Part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications - amendment 3: Enhancements for very high throughput in the 60 GHz band,” IEEE P802.11ad/D8.0, May 2012 (Draft Amendment based on IEEE 802.11-2012), pp. 1–667, June 2012.

Multi-stage Expectation-Maximization solution

Deterministic and random parameters

$$\boldsymbol{\xi}_{\mathrm{D}}^{(m)} = [\Delta f^{(m)}, \mathbf{g}_1^{(m)T}, \ldots, \mathbf{g}_{L_r}^{(m)T}]^T$$

$$\boldsymbol{\xi}_{\mathrm{R}}^{(m)} = [\boldsymbol{\theta}_0^{(m)T}, \ldots, \boldsymbol{\theta}_{N_{\mathrm{tr}}-1}^{(m)T}]^T$$

Algorithm initialization

$\hat{n}_0$ $\widehat{\Delta f}^{(1,0)}$

For M training frames do
    For N_{iter} iterations do
        Stage 1
    Compute Hybrid *CRLB

$\hat{\boldsymbol{\xi}}_{\mathrm{D}}^{(m)}$ $\hat{\boldsymbol{\xi}}_{\mathrm{R}}^{(m)}$

For N_{SIC} iterations do
    Stage 2

$\hat{\mathbf{H}}[k]$

Stage 1

E-Step: approximate current Log-Likelihood Function

$$Q\left(\boldsymbol{\xi}_{\mathrm{D}}^{(m)}, \hat{\boldsymbol{\xi}}_{\mathrm{D}}^{(m,n-1)}\right) \triangleq \mathbb{E}_{\boldsymbol{\xi}_{\mathrm{R}}^{(m)}|\mathbf{y}^{(m)}, \hat{\boldsymbol{\xi}}_{\mathrm{D}}^{(m,n-1)}} \left\{\log p\left(\mathbf{y}^{(m)}, \boldsymbol{\xi}_{\mathrm{R}}^{(m)}; \boldsymbol{\xi}_{\mathrm{D}}^{(m)}\right)\right\}$$

M-Step: maximize current Log-Likelihood Function

$$\hat{\boldsymbol{\xi}}_{\mathrm{D}}^{(m,n)} = \arg\max_{\boldsymbol{\xi}_{\mathrm{D}}^{(m)}} Q\left(\boldsymbol{\xi}_{\mathrm{D}}^{(m)}, \hat{\boldsymbol{\xi}}_{\mathrm{D}}^{(m,n-1)}\right)$$

Conditional MMSE estimator →

$$\hat{\boldsymbol{\theta}}_{\mathrm{MMSE}}^{(m,n)} \triangleq \mathbb{E}_{\boldsymbol{\xi}_{\mathrm{R}}^{(m)}|\mathbf{y}^{(m)}, \hat{\boldsymbol{\xi}}_{\mathrm{D}}^{(m,n-1)}} \{\boldsymbol{\theta}^{(m)}\}$$

Stage 2

M-step: mmWave MIMO channel estimation

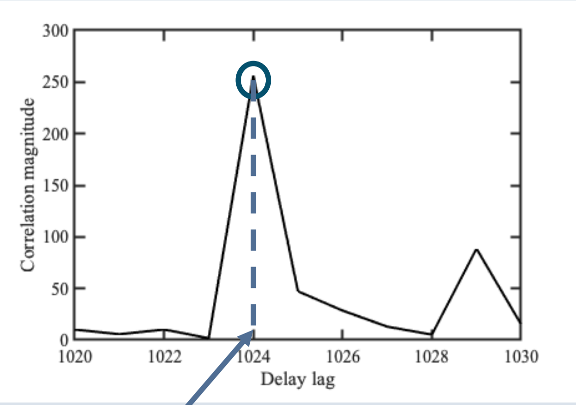
$$\mathrm{vec}\{\hat{\mathbf{H}}[k]\} = \left(\tilde{\mathbf{A}}_{\mathrm{T}}^{\mathrm{C}} \otimes \tilde{\mathbf{A}}_{\mathrm{R}}\right) \mathrm{vec}\{\hat{\mathbf{G}}^{\mathrm{v}}[k]\}$$

*CRLB: Cramer-Rao Lower Bound

Algorithm initialization: *TO and coarse CFO estimation

Preliminary steps to kick off EM algorithm

Received signal → Low complexity estimator for TO, approximating the ML estimator [1] →



Golay sequence

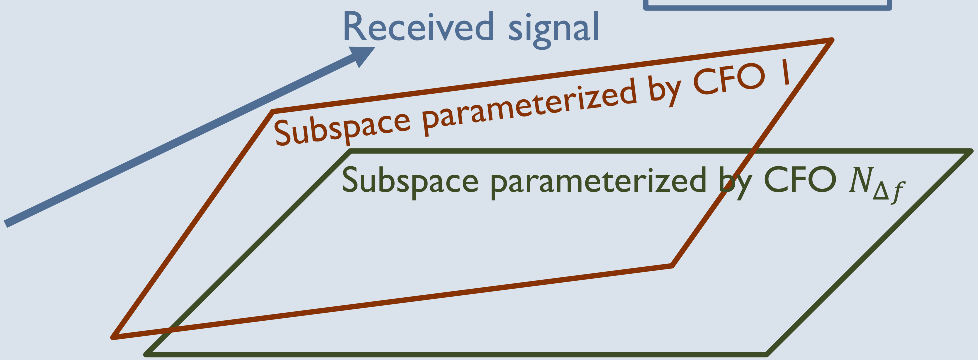
$$\hat{n}_0 = \arg\max_{n_0} \sum_{i=1}^{L_r} \sum_{n=0}^{63} \left| y_i^{(m)*}[n] s^{(m)}[n-d-n_0] \right|$$

Exploits information coming from all the RF chains [1]

$\hat{n}_0$ estimate

* PN: Phase Noise
TO: Timing Offset
CFO: Carrier Frequency Offset

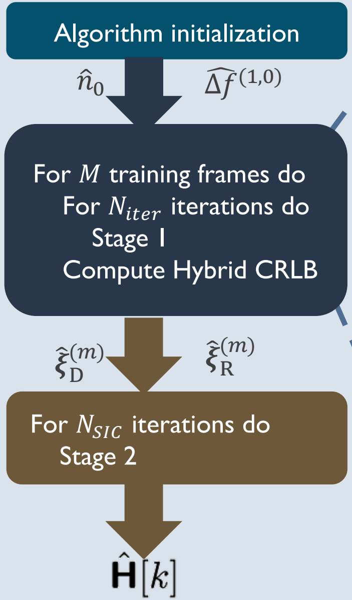
Key idea: Find subspace in which signal belongs through coarse *CFO search



[1] J. Rodríguez-Fernández and N. González-Prelcic, "Joint Synchronization and Compressive Estimation for Frequency-Selective mmWave MIMO Systems," 2018 52nd Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, USA, 2018, pp. 1280-1286.

Stage 1: E-Step

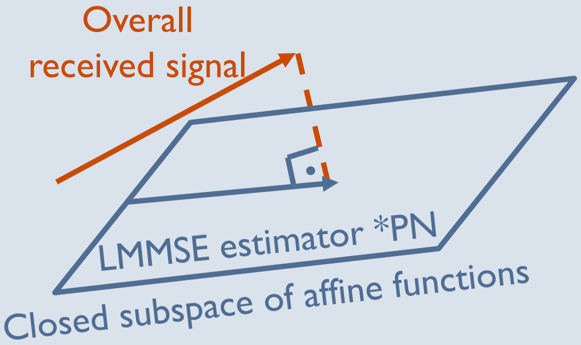
*PN: Phase Noise
LMMSE: Linear Minimum Mean Square Error
MMSE: Minimum Mean Square Error
EKF: Extended Kalman Filter
RTS: Rauch-Tung-Striebel
TO: Timing Offset
CFO: Carrier Frequency Offset

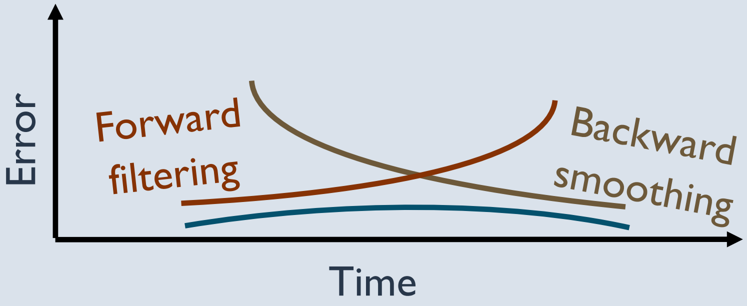


Key idea: Statistical linearization of *MMSE estimator [1]

Single-shot batch estimation
***LMMSE-EM algorithm**

***EKF and *RTS sequential estimation**
***EKF-RTS-EM algorithm**

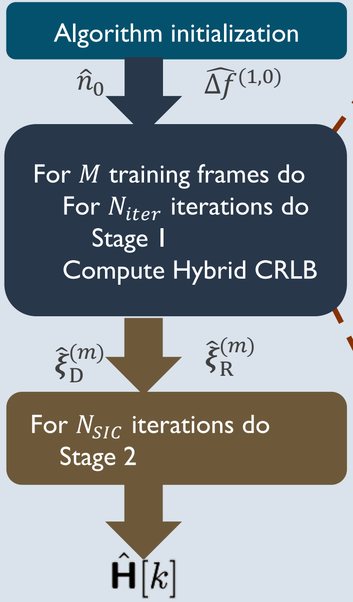




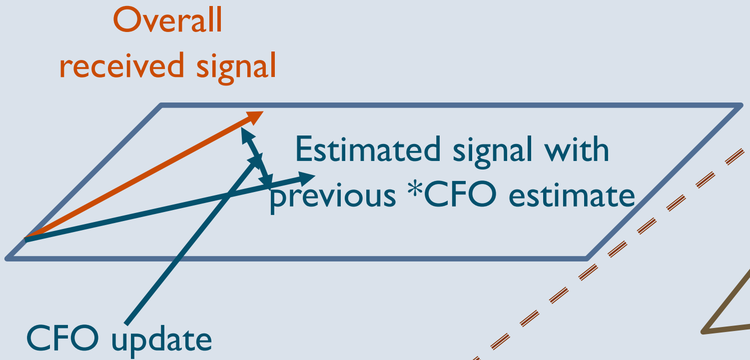
[1] J. Rodríguez-Fernández, “Broadband Synchronization, Compressive Channel Estimation, and Data Transmission for Hybrid mmWave MIMO Systems,” to be submitted to IEEE Transactions on Wireless Communications.

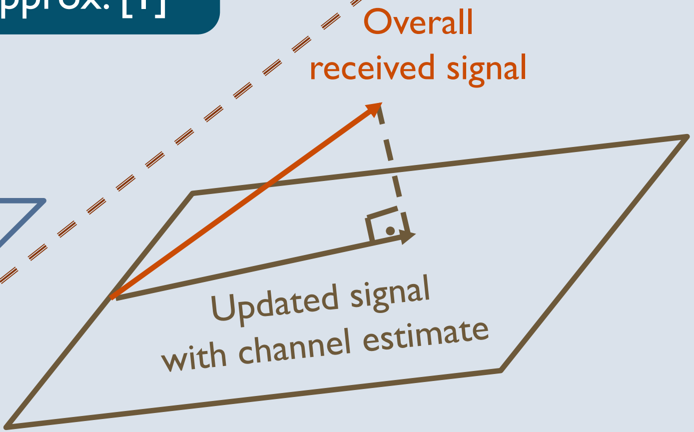
Stage 1: M-Step

*PN: Phase Noise
LMMSE: Linear Minimum Mean Square Error
EKF: Extended Kalman Filter
RTS: Rauch-Tung-Striebel
TO: Timing Offset
CFO: Carrier Frequency Offset



Key idea *CFO estimation: make *LLF convex through second-order approx. [1]





Key idea channel estimation: *ML estimation using last estimate of *CFO

[1] J. Rodríguez-Fernández, "Broadband Synchronization, Compressive Channel Estimation, and Data Transmission for Hybrid mmWave MIMO Systems," to be submitted to IEEE Transactions on Wireless Communications.

Stage 2: Combining *ML Optimality and Hybrid *CRLB

*ML: Maximum-Likelihood
CRLB: Cramer-Rao Lower Bound
SW-OMP: Simultaneous Weighted – Orthogonal Matching Pursuit

Algorithm initialization

$\hat{n}_0$ $\widehat{\Delta f}^{(1,0)}$

For M training frames do
For N_{iter} iterations do
Stage 1
Compute Hybrid CRLB

$\hat{\xi}_{\mathrm{D}}^{(m)}$ $\hat{\xi}_{\mathrm{R}}^{(m)}$

For N_{SIC} iterations do
Stage 2

$\hat{\mathbf{H}}[k]$

$$\underbrace{\begin{bmatrix} \hat{\mathbf{g}}_{\mathrm{ML}}^{(1,N)}[k] \\ \vdots \\ \hat{\mathbf{g}}_{\mathrm{ML}}^{(M,N)}[k] \end{bmatrix}}_{\hat{\mathbf{g}}_{\mathrm{ML}}^{(N)}} = \underbrace{\begin{bmatrix} \mathbf{\Phi}^{(1)} \\ \vdots \\ \mathbf{\Phi}^{(M)} \end{bmatrix}}_{\mathbf{\Phi}} \mathrm{vec}\{\mathbf{H}[k]\} + \underbrace{\begin{bmatrix} \tilde{\mathbf{v}}^{(1,N)}[k] \\ \vdots \\ \tilde{\mathbf{v}}^{(M,N)}[k] \end{bmatrix}}_{\mathbf{v}^{(N)}[k]}$$

Estimated equivalent beamformed channels

Measurement matrix

Estimation error (noise) vector

Extended virtual channel model

$$\mathrm{vec}\{\mathbf{H}[k]\} \approx \mathbf{\Psi}\mathbf{g}^{\mathrm{v}}[k]$$

$$\underset{\{\mathbf{g}^{\mathrm{v}}[\ell]\}_{\ell=0}^{K-1}}{\arg\min} \sum_{k=0}^{K-1} \|\mathbf{g}^{\mathrm{v}}[k]\|_1, \quad \text{subject to } \frac{1}{K}\sum_{k=0}^{K-1} \left\| \mathbf{D}_{\tilde{\mathbf{v}}^{(N)}[k]}^{-*} \left(\hat{\mathbf{g}}_{\mathrm{ML}}^{(N)}[k] - \mathbf{\Phi}\mathbf{\Psi}\mathbf{g}^{\mathrm{v}}[k] \right) \right\|_2^2 \leq \epsilon$$

Covariance of estimation error

Maximum reconstruction error

Iterative *SW-OMP algorithm can be used to solve the channel estimation problem [1]

[1] J. Rodríguez-Fernández, “Broadband Synchronization, Compressive Channel Estimation, and Data Transmission for Hybrid mmWave MIMO Systems,” to be submitted to IEEE Transactions on Wireless Communications.

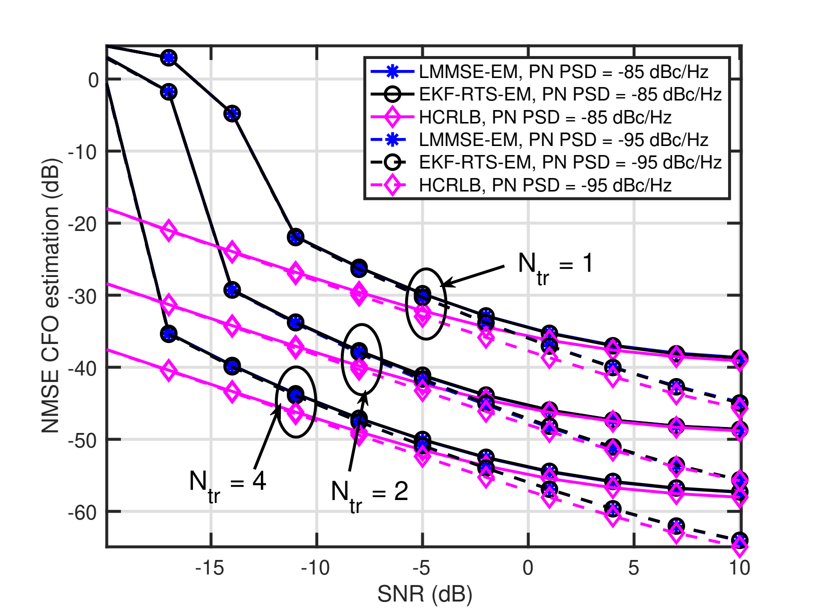
*CFO estimation performance

System parameters

64 Tx antennas
32 Rx antennas
Sampling period 1/30.72 μs
8 Tx RF chains
4 Rx RF chains
256 subcarriers
32 samples *CP
*3GPP *UMi channel model [1,2]
*CFO magnitude up to 5ppm [3]

Reducing complexity in EKF-RTS-EM algorithm does not result in estimation performance loss

Small gap with Hybrid *CRLB in low SNR



*CFO: Carrier Frequency Offset
CP: Cyclic Prefix
3GPP: 3rd Generation Partnership Protocol
UMi: Urban Microcell
CRLB: Cramer-Rao Lower Bound

Doubling N_{tr} results in 9 dB estimation gain

[1] S. Jaeckel, L. Raschkowski, K. Borner, and L. Thiele, "QuaDRiGa: A 3-D multi-cell channel model with time evolution for enabling virtual field trials," IEEE Transactions on Antennas Propagation, vol. 62, pp. 3242-3256, 2014.
[2] 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz (release 14.3.0)," Technical Report, Dec 2017.
[3] H. Yan and D. Cabric, "Compressive initial access and beamforming training for millimeter-wave cellular systems," IEEE Journal of Selected Topics in Signal Processing, vol. 13, no. 5, pp. 1151-1166, Sep. 2019.

Beamformed channel estimation performance

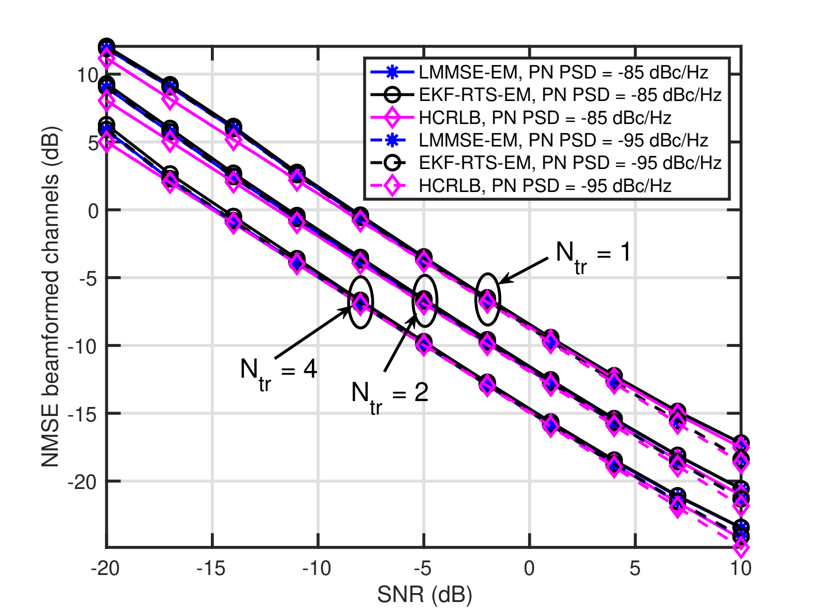
System parameters

64 Tx antennas
32 Rx antennas
Sampling period 1/30.72 μs
8 Tx RF chains
4 Rx RF chains
256 subcarriers
32 samples *CP
*3GPP *UMi channel model [1,2]
*CFO magnitude up to 5ppm [3]

*CFO: Carrier Frequency Offset
CP: Cyclic Prefix
3GPP: 3rd Generation Partnership Protocol
UMi: Urban Microcell
CRLB: Cramer-Rao Lower Bound

mmWave system is noise-limited for a wide range of SNR

Small gap with Hybrid *CRLB in low SNR



Doubling N_{tr} results in 3 dB estimation gain

[1] S. Jaeckel, L. Raschkowski, K. Borner, and L. Thiele, “QuaDRiGa: A 3-D multi-cell channel model with time evolution for enabling virtual field trials,” IEEE Transactions on Antennas Propagation, vol. 62, pp. 3242-3256, 2014.
[2] 3GPP, “Study on channel model for frequencies from 0.5 to 100 GHz (release 14.3.0),” Technical Report, Dec 2017.
[3] H. Yan and D. Cabric, “Compressive initial access and beamforming training for millimeter-wave cellular systems,” IEEE Journal of Selected Topics in Signal Processing, vol. 13, no. 5, pp. 1151-1166, Sep. 2019.

Phase noise estimation performance

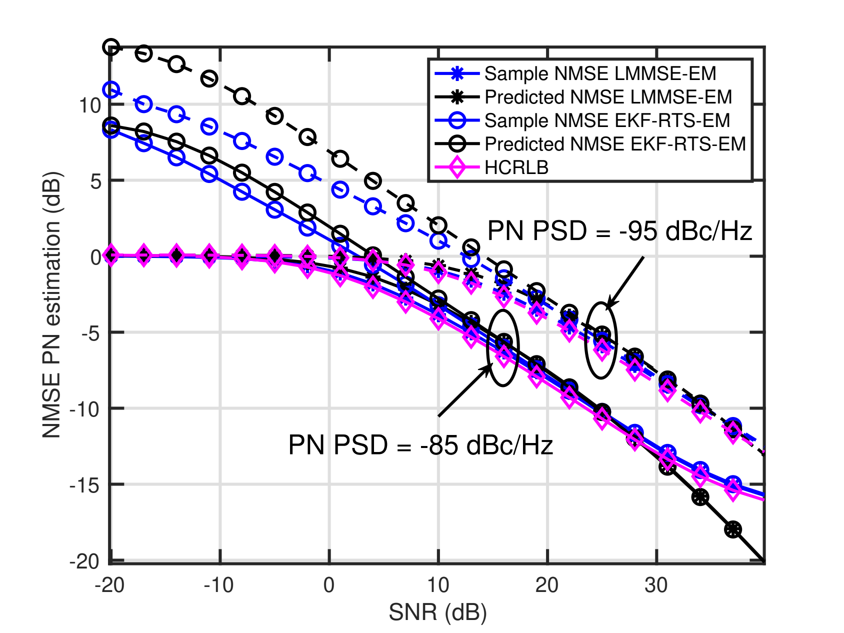
System parameters

64 Tx antennas
32 Rx antennas
Sampling period 1/30.72 μs
8 Tx RF chains
4 Rx RF chains
256 subcarriers
32 samples *CP
*3GPP *UMi channel model [1,2]
*CFO magnitude up to 5ppm [3]

*CFO: Carrier Frequency Offset
CP: Cyclic Prefix
3GPP: 3rd Generation Partnership Protocol
UMi: Urban Microcell
CRLB: Cramer-Rao Lower Bound

Small gap with Hybrid *CRLB in low SNR

mmWave system is noise-limited for a wide range of SNR



Sensitivity of Jacobians affects EKF-RTS-EM performance

[1] S. Jaeckel, L. Raschkowski, K. Borner, and L. Thiele, "QuaDRiGa: A 3-D multi-cell channel model with time evolution for enabling virtual field trials," IEEE Transactions on Antennas Propagation, vol. 62, pp. 3242-3256, 2014.
[2] 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz (release 14.3.0)," Technical Report, Dec 2017.
[3] H. Yan and D. Cabric, "Compressive initial access and beamforming training for millimeter-wave cellular systems," IEEE Journal of Selected Topics in Signal Processing, vol. 13, no. 5, pp. 1151-1166, Sep. 2019.

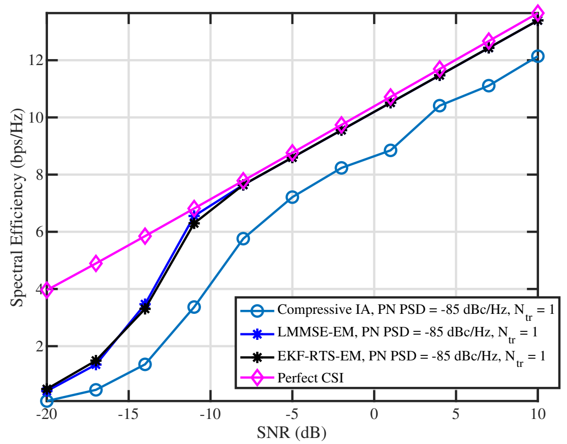
Spectral efficiency performance

System parameters

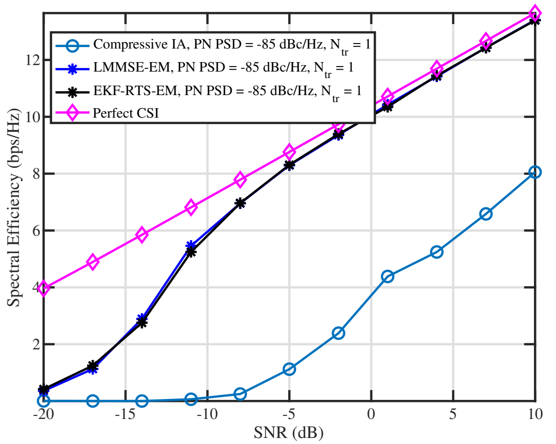
64 Tx antennas
32 Rx antennas
Sampling period 1/30.72 μs
1 Tx RF chains
1 Rx RF chains
256 subcarriers
32 samples *CP
32 training frames
1 OFDM symbol/frame
*3GPP *UMi channel model [1,2]
*CFO magnitude up to 5ppm [3]

*CFO: Carrier Frequency Offset
CP: Cyclic Prefix
3GPP: 3rd Generation Partnership Protocol
UMi: Urban Microcell

Near-optimum spectral efficiency in the very low SNR regime



Line-Of-Sight



Rician factor -10 dB

Proposed algorithms outperform prior work on compressive beam training [3]

[1] S. Jaeckel, L. Raschkowski, K. Borner, and L. Thiele, "QuaDRiGa: A 3-D multi-cell channel model with time evolution for enabling virtual field trials," IEEE Transactions on Antennas Propagation, vol. 62, pp. 3242-3256, 2014.
[2] 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz (release 14.3.0)," Technical Report, Dec 2017.
[3] H. Yan and D. Cabric, "Compressive initial access and beamforming training for millimeter-wave cellular systems," IEEE Journal of Selected Topics in Signal Processing, vol. 13, no. 5, pp. 1151-1166, Sep. 2019.

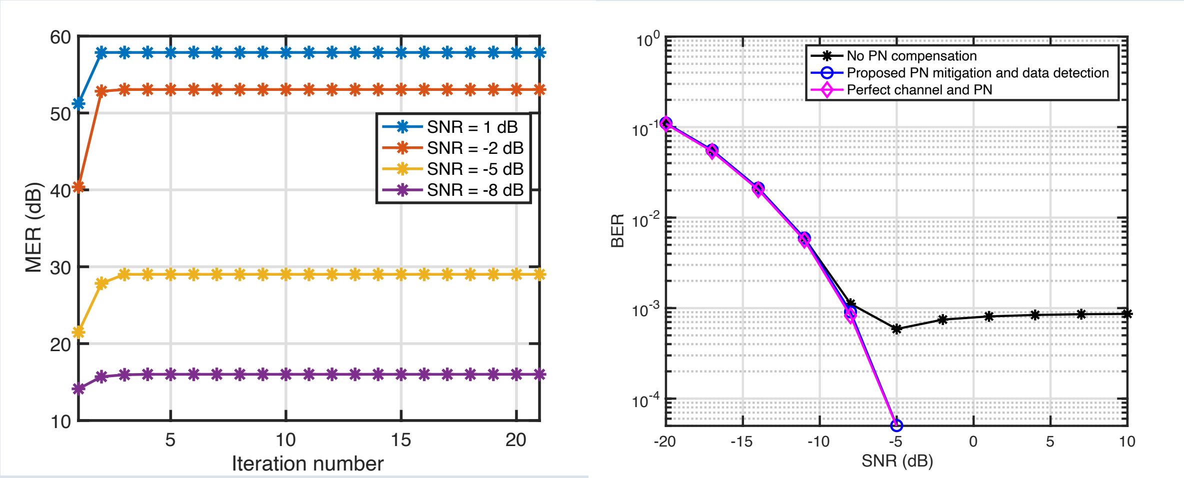
Modulation Error Ratio and Bit Error Rate

System parameters

64 Tx antennas
32 Rx antennas
Sampling period 1/30.72 μs
8 Tx RF chains
4 Rx RF chains
16-QAM modulation
Coding rate 2/3
256 subcarriers
32 samples *CP
32 training frames
*3GPP *UMi channel model [1,2]
*CFO magnitude up to 5ppm [3]
2 data streams

*CFO: Carrier Frequency Offset
CP: Cyclic Prefix
3GPP: 3rd Generation Partnership Protocol
UMi: Urban Microcell
MER: Modulation Error Ratio
BER: Bit Error Rate
PN: Phase Noise

Average *MER monotonically increases owing to LMMSE estimation and detection



Rician factor -10 dB

Achievable *BER is close to genie-aided perfect channel w/o *PN

[1] S. Jaeckel, L. Raschkowski, K. Borner, and L. Thiele, "QuaDRiGa: A 3-D multi-cell channel model with time evolution for enabling virtual field trials," IEEE Transactions on Antennas Propagation, vol. 62, pp. 3242-3256, 2014.
[2] 3GPP, "Study on channel model for frequencies from 0.5 to 100 GHz (release 14.3.0)," Technical Report, Dec 2017.
[3] H. Yan and D. Cabric, "Compressive initial access and beamforming training for millimeter-wave cellular systems," IEEE Journal of Selected Topics in Signal Processing, vol. 13, no. 5, pp. 1151-1166, Sep. 2019.

Conclusion for Contribution 3

- ❖ Millimeter Wave Broadband Synchronization, Compressive Channel Estimation, and Data Transmission
  - ✓ Derived multi-stage solutions to joint *TO, *CFO, *PN, and channel estimation
  - ✓ Derived closed-form hybrid CRLB* expressions
  - ✓ Derived two *EM-based algorithms to find the optimal *ML and *MMSE estimates
  - ✓ Combined frame-wise estimators to reduces complexity and preserve optimality
  - ✓ Leveraged *ML estimates and hybrid CRLB to obtain *CS-based algorithm
  - ✓ Designed joint *PN mitigation and data detection algorithm suitable for 5G NR

*TO: Timing Offset
CFO: Carrier Frequency Offset
PN: Phase noise
CRLB: Cramer-Rao Lower Bound
EM: Expectation-Maximization
MMSE: Minimum Mean Square Error
CS: Compressed-Sensing
ML: Maximum-Likelihood

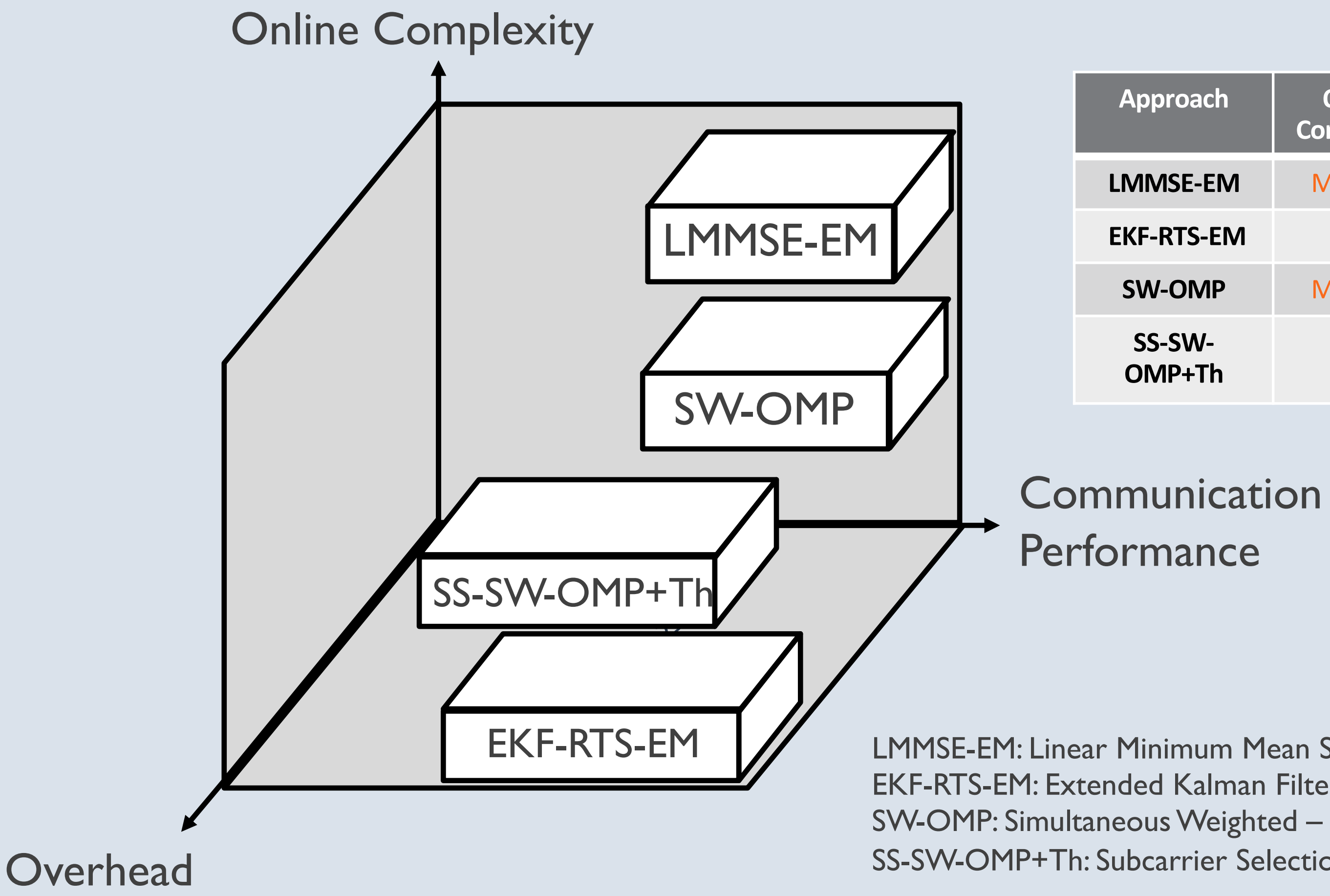
Dissertation Contributions

- 1. Millimeter Wave Compressive Channel Estimation in the Frequency Domain
  - ✓ Low-complexity broadband channel estimation algorithms
  - ✓ Derived theoretical CRLB and analyzed convergence
- 2. Millimeter Wave Compressive Channel Estimation with CFO Uncertainties
  - ✓ Low-complexity multi-stage joint CFO and channel estimation algorithm
  - ✓ Derived theoretical CRLB and showed convergence
- 3. Millimeter Wave Broadband Synchronization, Compressive Channel Estimation and Data Transmission
  - ✓ Low-complexity multi-stage joint synchronization and channel estimation
  - ✓ Convergence guarantees due to using EM algorithm and hybrid CRLB
  - ✓ Joint PN tracking and multi-stream data transmission under 5G NR frame structure

Takeaways in link configuration

- A millimeter wave MIMO channel can support multiple data streams
- Channel estimation
  - Strong dependence on timing offset and carrier frequency offset (CFO) estimation
  - Weak dependence on phase noise (PN) estimation at low-medium SNR (-10 to 10 dB)
- Timing offset estimation using Golay sequences accurate for SNR as low as -20 dB
- CFO estimation variance
  - Proportional to thermal noise variance
  - Inversely proportional to cube of number of training symbols and subcarriers
  - Inversely proportional to number of RF chains
- Thermal noise estimation variance
  - Proportional to square of thermal noise power
  - Inversely proportional to number of training symbols and RF chains
- PN creates floors in CFO, channel, PN estimation and bit error rate at SNR > 10 dB
- Low-SNR CFO estimation at a fourth of the 5G NR training overhead

Trade-offs in broadband synchronization and channel estimation algorithms



Approach	Online Complexity	Training Overhead	Comm. Perf.
LMMSE-EM	Medium	Low	High
EKF-RTS-EM	Low	Low	High
SW-OMP	Medium	Medium	High
SS-SW-OMP+Th	Low	Medium	Medium-High

LMMSE-EM: Linear Minimum Mean Square Error – Expectation Maximization
EKF-RTS-EM: Extended Kalman Filter – Rauch-Tung-Striebel – EM
SW-OMP: Simultaneous Weighted – Orthogonal Matching Pursuit
SS-SW-OMP+Th: Subcarrier Selection – SW-OMP + Thresholding

Publications

Journal papers

[1] **J. Rodríguez-Fernández**, N. Gonzalez-Prelcic, K. Venugopal and R. W. Heath, ”Frequency-Domain Compressive Channel Estimation for Frequency-Selective Hybrid Millimeter Wave MIMO Systems,” in IEEE Transactions on Wireless Communications, vol. 17, no. 5, pp. 2946-2960, May 2018.
[2] J. P. Gonzalez-Coma, **J. Rodríguez-Fernández**, N. Gonzalez-Prelcic, L. Castedo and R. W. Heath, ”Channel Estimation and Hybrid Precoding for Frequency Selective Multiuser mmWave MIMO Systems,” in IEEE Journal of Selected Topics in Signal Processing, vol. 12, no. 2, pp. 353-367, May 2018.
[3] **J. Rodríguez-Fernández** and N. González-Prelcic, "Channel Estimation for Hybrid mmWave MIMO Systems With CFO Uncertainties," in IEEE Transactions on Wireless Communications, vol. 18, no. 10, pp. 4636-4652, Oct. 2019.
[4] **J. Rodríguez-Fernández**, ”Broadband Synchronization, Compressive Channel Estimation, and Data Transmission for Hybrid mmWave MIMO Systems,” under preparation.

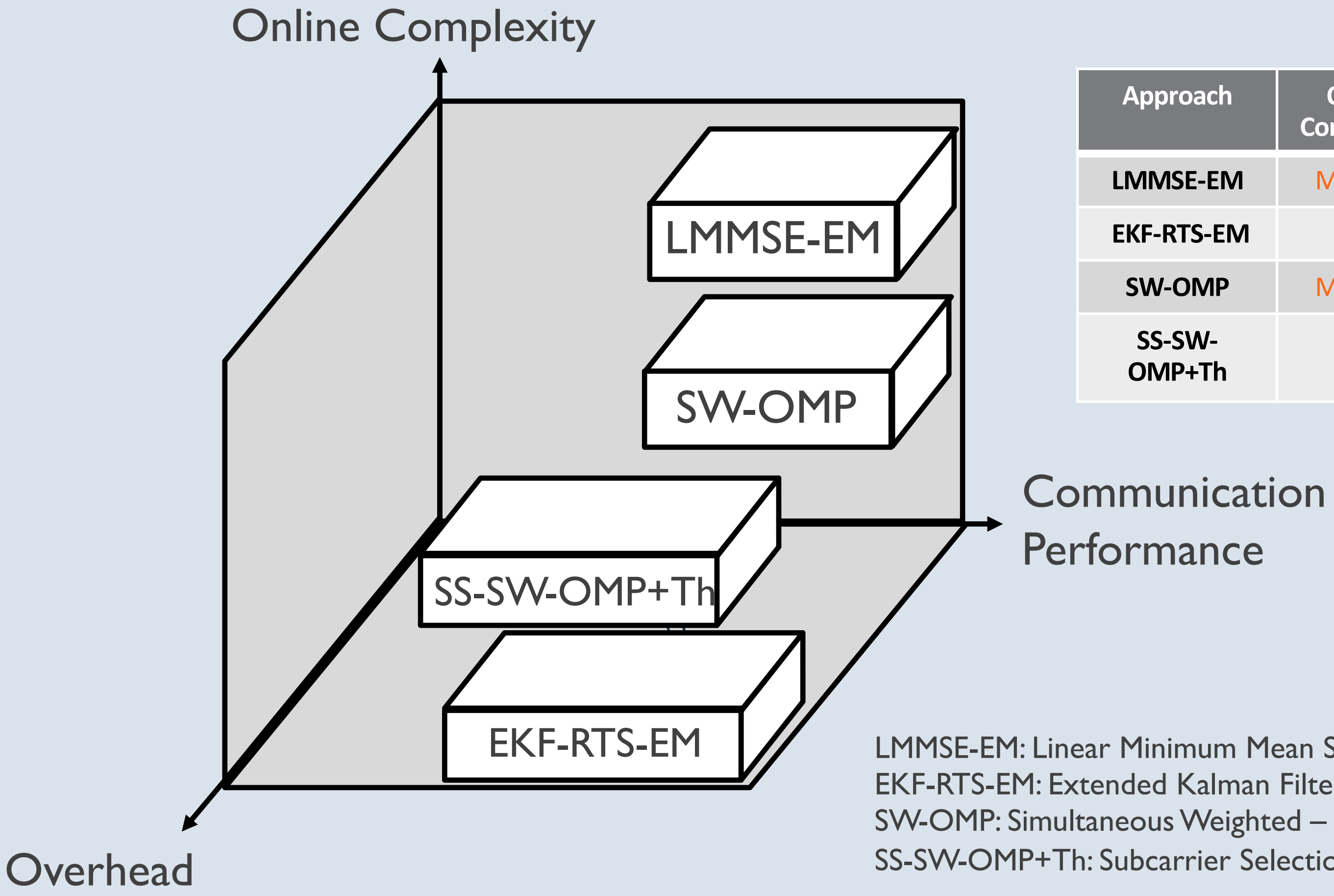
Conference papers

[1] **J. Rodríguez-Fernández**, N. Gonzalez-Prelcic, and R. W. Heath, ”Channel estimation in mixed hybrid-low resolution MIMO architectures for mmWave communication,” 2016 50th Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, 2016, pp. 768-773.
[2] **J. Rodríguez-Fernández**, K. Venugopal, N. Gonzalez-Prelcic, and R. W. Heath, ”A frequency-domain approach to wideband channel estimation in millimeter wave systems,” 2017 IEEE International Conference on Communications (ICC), Paris, 2017, pp. 1-7.
[3] **J. Rodríguez-Fernández**, N. Gonzalez-Prelcic, K. Venugopal and R. W. Heath, ”Exploiting Common Sparsity for Frequency-Domain Wideband Chan- nel Estimation at mmWave,” GLOBECOM 2017 - 2017 IEEE Global Communications Conference, Singapore, 2017, pp. 1-6.
[4] J. P. Gonzalez-Coma, **J. Rodríguez-Fernández**, N. Gonzalez-Prelcic and L. Castedo, ”Channel Estimation and Hybrid Precoding/Combining for Frequency-Selective Multiuser mmWave Systems,” GLOBECOM 2017 - 2017 IEEE Global Communications Conference, Singapore, 2017, pp. 1-6.

Conference papers (continued)

[5] **J. Rodríguez-Fernández**, N. Gonzalez-Prelcic and R. W. Heath, "A compressive sensing-maximum likelihood approach for off-grid wideband channel estimation at mmWave," 2017 IEEE 7th International Workshop on Computational Advances in Multi-Sensor Adaptive Processing (CAMSAP), Curacao, 2017, pp. 1-5.
[6] **J. Rodríguez-Fernández**, N. Gonzalez-Prelcic and R. W. Heath, "Channel Estimation for Millimeter Wave MIMO Systems in the Presence of CFO Uncertainties," 2018 IEEE International Conference on Communications (ICC), Kansas City, MO, 2018, pp. 1-6.
[7] **J. Rodríguez-Fernández**, N. Gonzalez-Prelcic and R. W. Heath, "Frequency- domain wideband channel estimation and tracking for hybrid MIMO systems," 2017 51st Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, 2017, pp. 1829-1833.
[8] **J. Rodríguez-Fernández**, N. Gonzalez-Prelcic and R. W. Heath, "Position- Aided Compressive Channel Estimation and Tracking for Millimeter Wave Multi- User MIMO Air-to-Air Communications," 2018 IEEE International Conference on Communications Workshops (ICC Workshops), Kansas City, MO, 2018, pp. 1-6.
[9] **J. Rodríguez-Fernández** and N. Gonzalez-Prelcic, "Low-Complexity Multiuser Hybrid Precoding and Combining for Frequency Selective Millimeter Wave Systems," 2018 IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), Kalamata, 2018, pp. 1-5.
[10] **J. Rodríguez-Fernández** and N. Gonzalez-Prelcic, "Channel Estimation for Frequency-Selective mmWave MIMO Systems with Beam-Squint", GLOBECOM 2018 - 2018 IEEE Global Communications Conference , Abu Dhabi, 2018, pp. 1-6.
[11] **J. Rodríguez-Fernández**, R. Lopez-Valcarce and N. Gonzalez-Prelcic, "Frequency-selective Hybrid Precoding and Combining for Mmwave MIMO Systems with Per-antenna Power Constraints," ICASSP 2019 - 2019 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Brighton, United Kingdom, 2019, pp. 4794-4798.
[12] **J. Rodríguez-Fernández**, N. Gonzalez-Prelcic and T. Shimizu, "Position-Aided Compressive Channel Tracking for mmWave Multi-User Cellular Communications via Bayesian Filtering", in Proc. of 2019 International Conference in Communications (ICC), Shanghai, China, 2019.
[13] **J. Rodríguez-Fernández** and N. Gonzalez-Prelcic, "Joint Synchronization and Compressive Estimation for Frequency-Selective mmWave MIMO Systems," 2018 52nd Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, USA, 2018, pp. 1280-1286.

Trade-offs in broadband synchronization and channel estimation algorithms



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