Estimating Millimeter Wave Channels Using Out-of-Band Measurements

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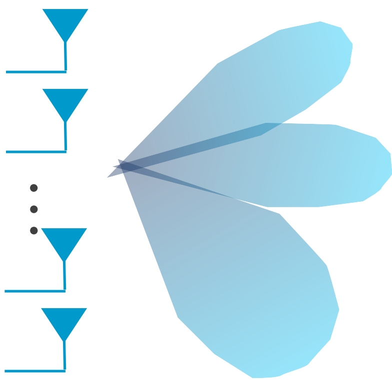
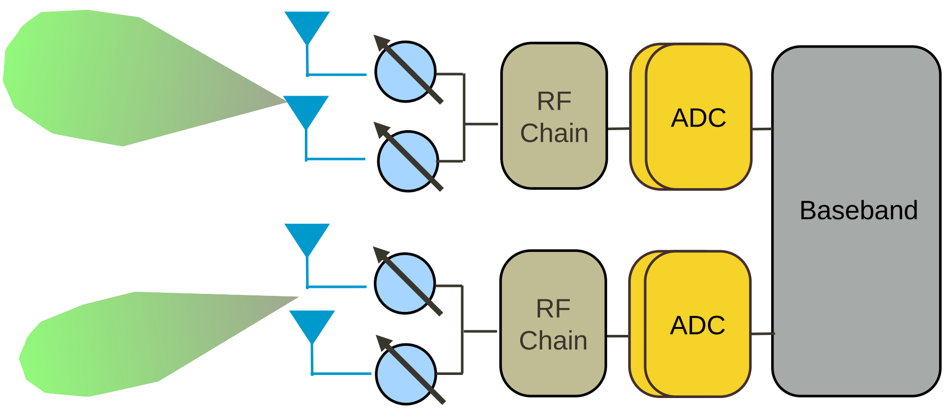
Millimeter wave wireless communication

Many antennas at the TX and RX

Hardware constraints impact how the antennas are used





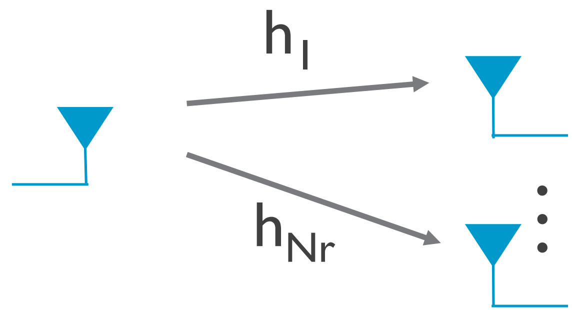
MmWave is finding applications to 5G, WLAN, and connected cars

Challenge of channel estimation in mmWave

Conventional SIMO

Send N_{tr} training

train

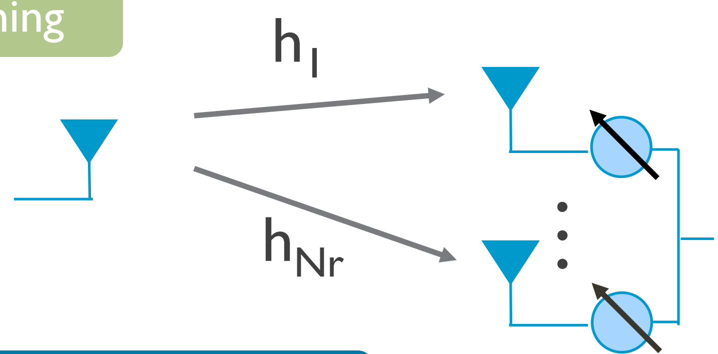


Estimate all coefficients at the same time

SIMO w/ analog beamforming

Send N_r N_{tr} training

train	train	• • •	train



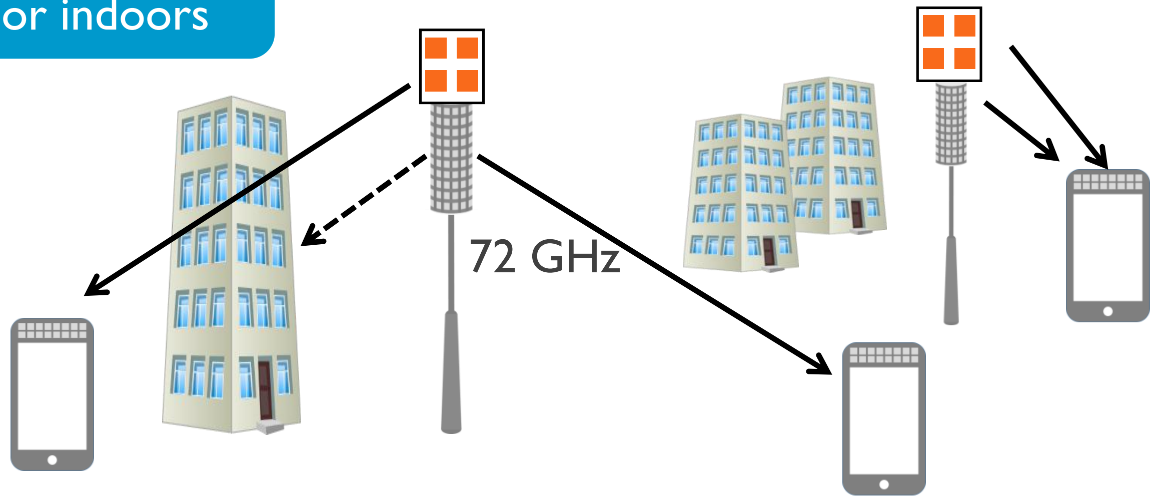
Estimate each coefficient separately (sparsity can reduce measurements)

SNR is low at mmWave ⟶ Ntr is big

Multiband operation for mmWave

Fallback to low frequency when blocked or indoors

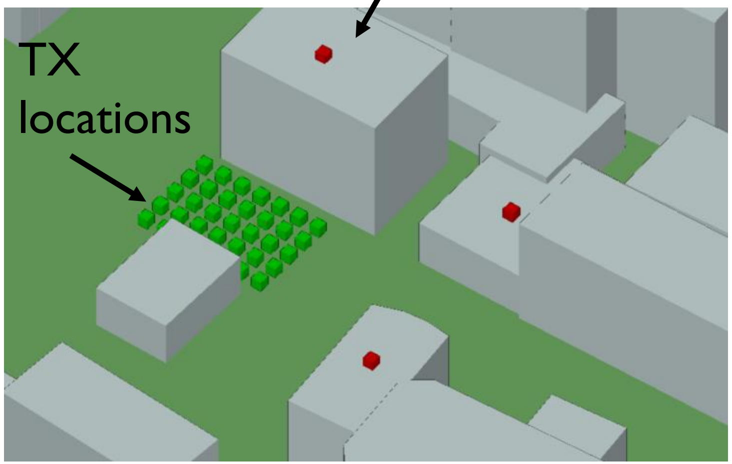
Use low frequency for control plane, high for data

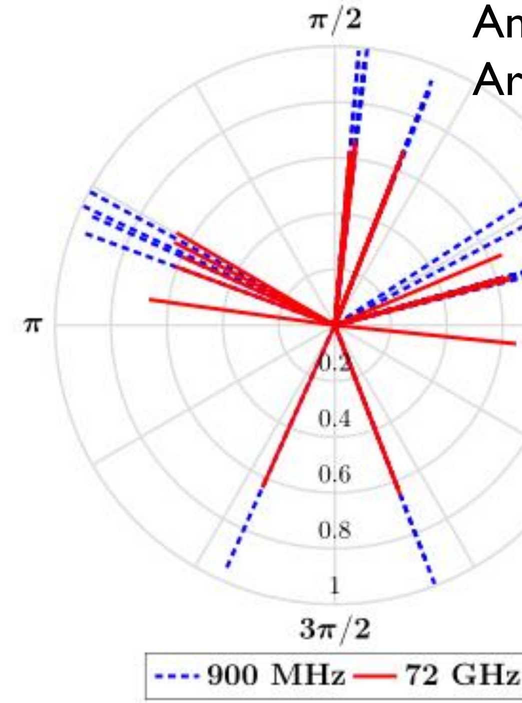


What can be exploited from the sub 6 GHz channel measurements to improve mmWave channel estimation?

Related work: Nitsche, T.; Flores, A.B.; Knightly, E.W.; Widmer, J., "Steering with eyes closed: Mm-Wave beam steering without in-band measurement," in *INFOCOM*, 2015.

What might be similar?





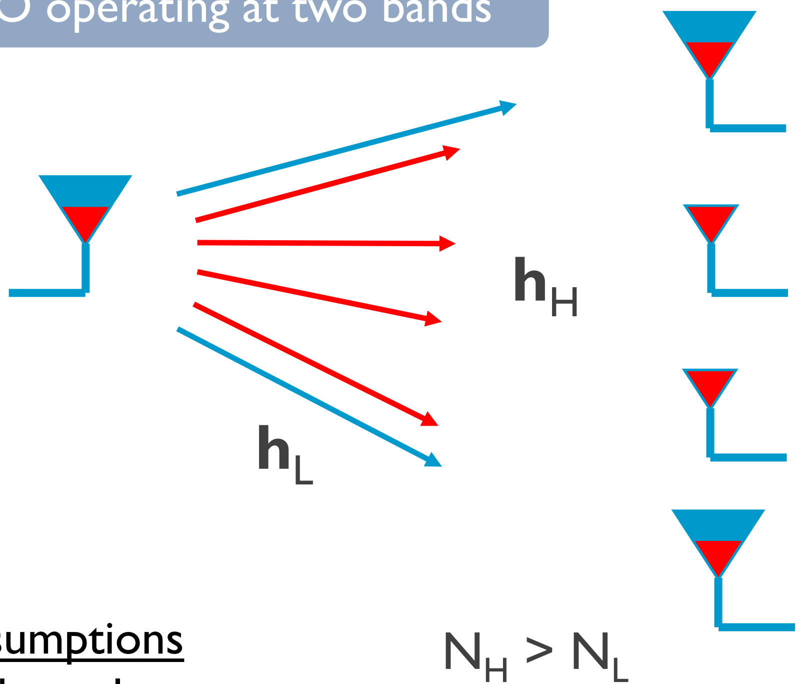
MmWave has higher spatial resolution (antennas) and temporal resolution (bandwidth)

Substantial spatial congruence though not complete

Of course the actual impulse response will not be the same

Problem setup

SIMO operating at two bands



Compute low frequency spatial correlation matrix

$$\mathbf{R}_{\mathrm{L}} = \mathbb{E}\left[\mathbf{h}_{\mathrm{L}}\mathbf{h}_{\mathrm{L}}^{*}\right]$$

Construct an estimate of the high frequency spatial correlation matrix

$$\hat{\mathbf{R}}_{\mathrm{H}} = f\left(\mathbf{R}_{\mathrm{L}}\right)$$

<u>Main assumptions</u>

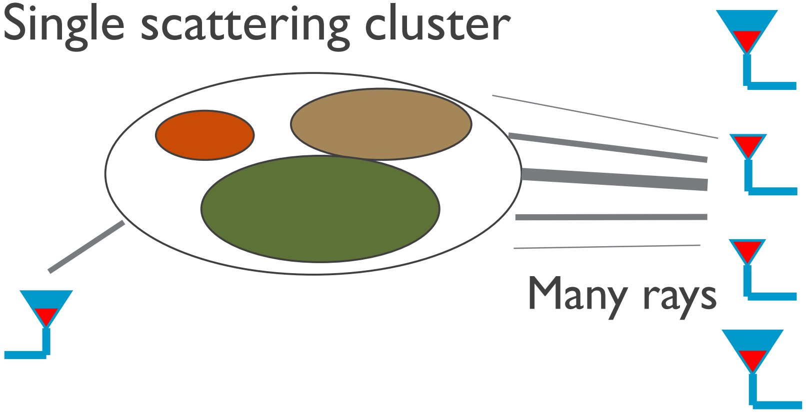
NLOS channels

Narrowband

Neglect hardware consraints

Modeling spatial correlation

Single scattering cluster



Assuming small angle spread, ULA

Wavelength dependence

$$[\mathbf{R}]_{i,j} = e^{\mathrm{j}(i-j)2\pi \frac{d}{\lambda}\sin(\bar{\theta})} B\left((i-j)2\pi\frac{d}{\lambda}\sin(\bar{\theta})\sigma_{\theta}\right)$$

Antenna element difference

Char. Fun. of normalized AoA distribution

Mean AoA $\bar{\theta}$
Angle spread σ_{θ} (varies w/ frequency)
Given AoA distribution

M. Bengtsson, B. Ottersten, "Low-complexity estimators for distributed sources," in IEEE Trans. Sig. Proc., vol.48, no.8, pp.2185-2194, Aug 2000.

Correlation transform

Common approach used with FDD reciprocity w/ small H-L

$$\mathbf{T}^*\mathbf{R}_{\mathrm{L}}\mathbf{T} = \mathbf{R}_{\mathrm{H}}$$

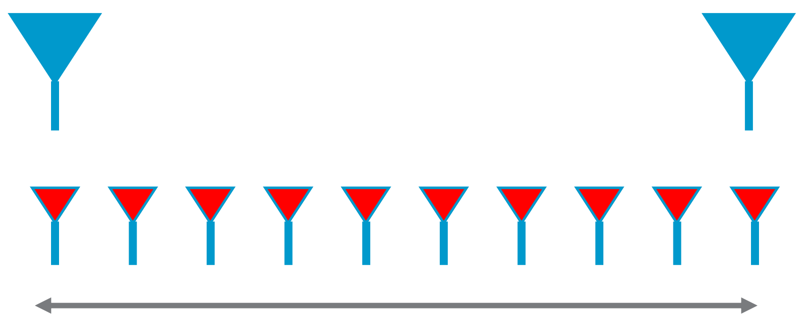
Square transformation matrix in conventional work

Different dimensions

Sample **larger portion** of the angle spread function

2 elements
Low freq.

10 elements
High freq.



Same physical space

$$\frac{d}{\lambda_{\mathrm{L}}} = \frac{1}{2}$$

$$\frac{d}{\lambda_{\mathrm{H}}} = \frac{1}{2} \qquad 9\frac{d}{\lambda_{\mathrm{H}}} = 9\frac{1}{2}$$

$$\max(i-j) = 9$$

See e.g. Aste98, Hugl99, Liang01, Hugl02, Chalise04, Jordan09

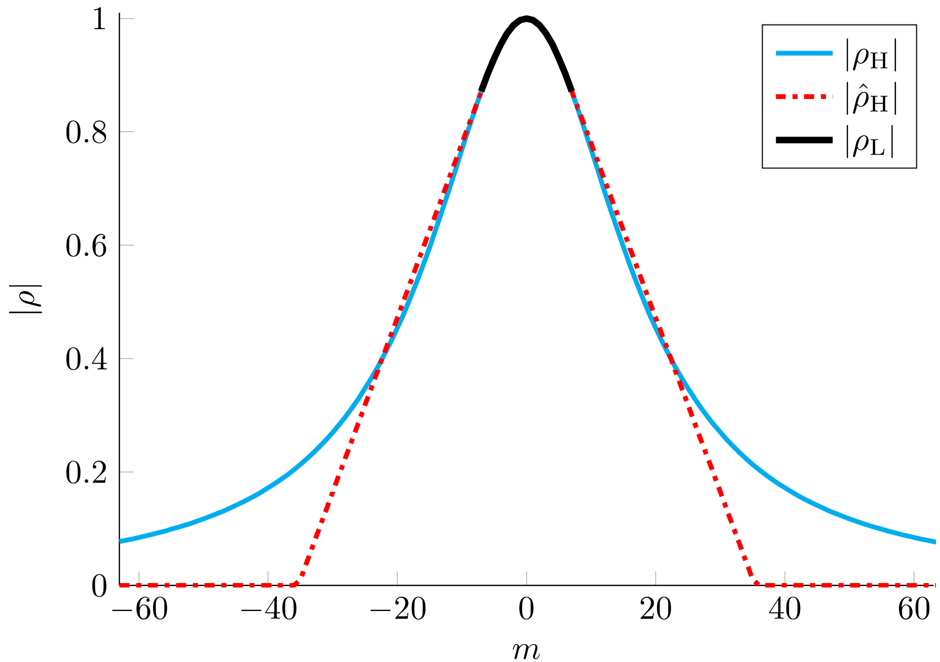
Proposed solutions

Approach #1

Interpolation and extrapolation of the transformed spatial correlation matrix (more general but less accurate)

Approach #2

Parametric estimation of the mean AoA and angle spread
(requires knowledge of distribution)



Antenna difference

M. Jordan, X. Gong, and G. Ascheid, "Conversion of the spatio-temporal correlation from uplink to downlink in FDD systems," in Proc. IEEE Wireless Commun. Netw. Conf. (WCNC), 2009, pp. 1–6.

Evaluating performance of a MMSE estimator

Assume that the estimated covariance is used for MMSE estimation

Theorem 1. *If the true correlation matrix,* $\mathbf{R}_{\mathrm{H}}$*, and the translated correlation matrix,* $\hat{\mathbf{R}}_{\mathrm{H}}$*, differ by an additive perturbation* $\boldsymbol{\Gamma}$ *(i.e.,* $\hat{\mathbf{R}}_{\mathrm{H}} = \mathbf{R}_{\mathrm{H}} + \boldsymbol{\Gamma}$*) that ensures positive definiteness of* $\hat{\mathbf{R}}_{\mathrm{H}}$*, then the* EMSE *of the estimator is*

$$\mathrm{EMSE} = \mathrm{tr}\left(\boldsymbol{\Upsilon}\mathbf{R}_{\tilde{\mathbf{y}},\mathrm{H}}\boldsymbol{\Upsilon}^*\right), \qquad (12)$$

where $\mathbf{R}_{\tilde{\mathbf{y}},\mathrm{H}} = \mathbb{E}[\tilde{\mathbf{y}}\tilde{\mathbf{y}}^*] = (\tilde{\mathbf{S}}\mathbf{R}_{\mathrm{H}}\tilde{\mathbf{S}}^* + \sigma_{\mathbf{v}}^2\mathbf{I}_{KM})$ *and*

$$\boldsymbol{\Upsilon} = \boldsymbol{\Gamma}\tilde{\mathbf{S}}^*(\mathbf{R}_{\tilde{\mathbf{y}},\mathrm{H}} + \tilde{\mathbf{S}}\boldsymbol{\Gamma}\tilde{\mathbf{S}}^*)^{-1} - \mathbf{R}_{\mathrm{H}}\tilde{\mathbf{S}}^*\mathbf{R}_{\tilde{\mathbf{y}},\mathrm{H}^{-1}}\tilde{\mathbf{S}}(\mathbf{I}_M + \boldsymbol{\Gamma}\tilde{\mathbf{S}}^*\mathbf{R}_{\tilde{\mathbf{y}},\mathrm{H}}^{-1}\tilde{\mathbf{S}})^{-1}\boldsymbol{\Gamma}\tilde{\mathbf{S}}^*\mathbf{R}_{\tilde{\mathbf{y}},\mathrm{H}}^{-1}. \qquad (13)$$

MSE from true cov.

$$\mathrm{MSE} = \mathrm{MMSE} + \mathrm{EMSE}$$

Excess mean squared error

I. Esnaola, A. M. Tulino, and H. V. Poor, "Mismatched MMSE estimation of multivariate Gaussian sources," in Proc. IEEE Int. Symp. Inf. Theory (ISIT), 2012, pp. 716–720.

Simulation setup

Low frequency system

$\bar{\theta} = 45^\circ$ $\sigma_\theta = 15^\circ$ Truncated Laplacian AoA

900 MHz with 4 antennas

High frequency system

Keep $\frac{d}{\lambda}$ constant, vary the number of antennas

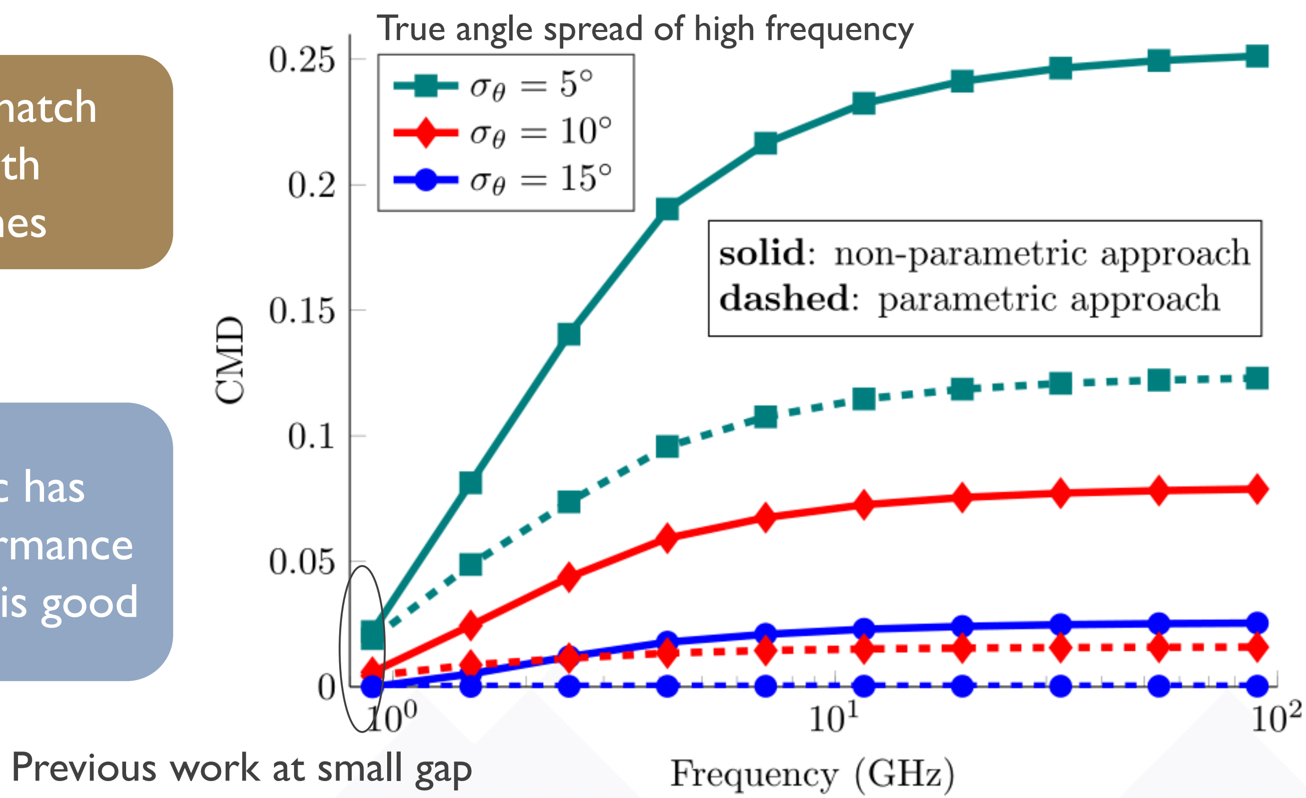
Vary true angle spread (model mismatch)

Correlation distance

$$d_{\mathrm{corr}}(\mathbf{R}_{\mathrm{H}}, \hat{\mathbf{R}}_{\mathrm{H}}) = 1 - \frac{\mathrm{tr}(\mathbf{R}_{\mathrm{H}}\hat{\mathbf{R}}_{\mathrm{H}})}{\|\mathbf{R}_{\mathrm{H}}\|_{\mathrm{F}}\|\hat{\mathbf{R}}_{\mathrm{H}}\|_{\mathrm{F}}} \in (0, 1]$$

Model mismatch hurts both approaches

Parametric has better performance when model is good

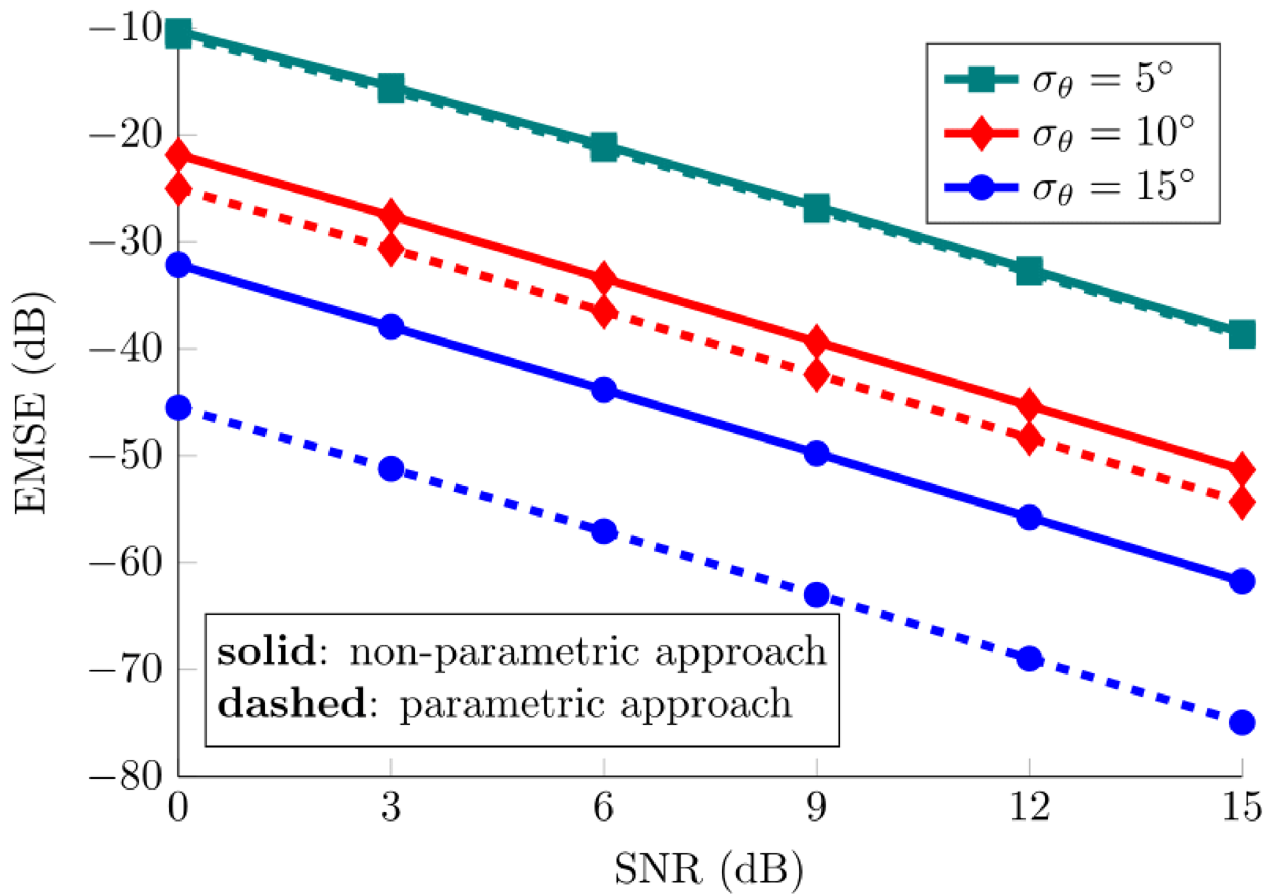


Excess MSE

-sub 6-GHz frequency 900 MHz -4 antennas -mmWave frequency 30 GHz – 32 antennas

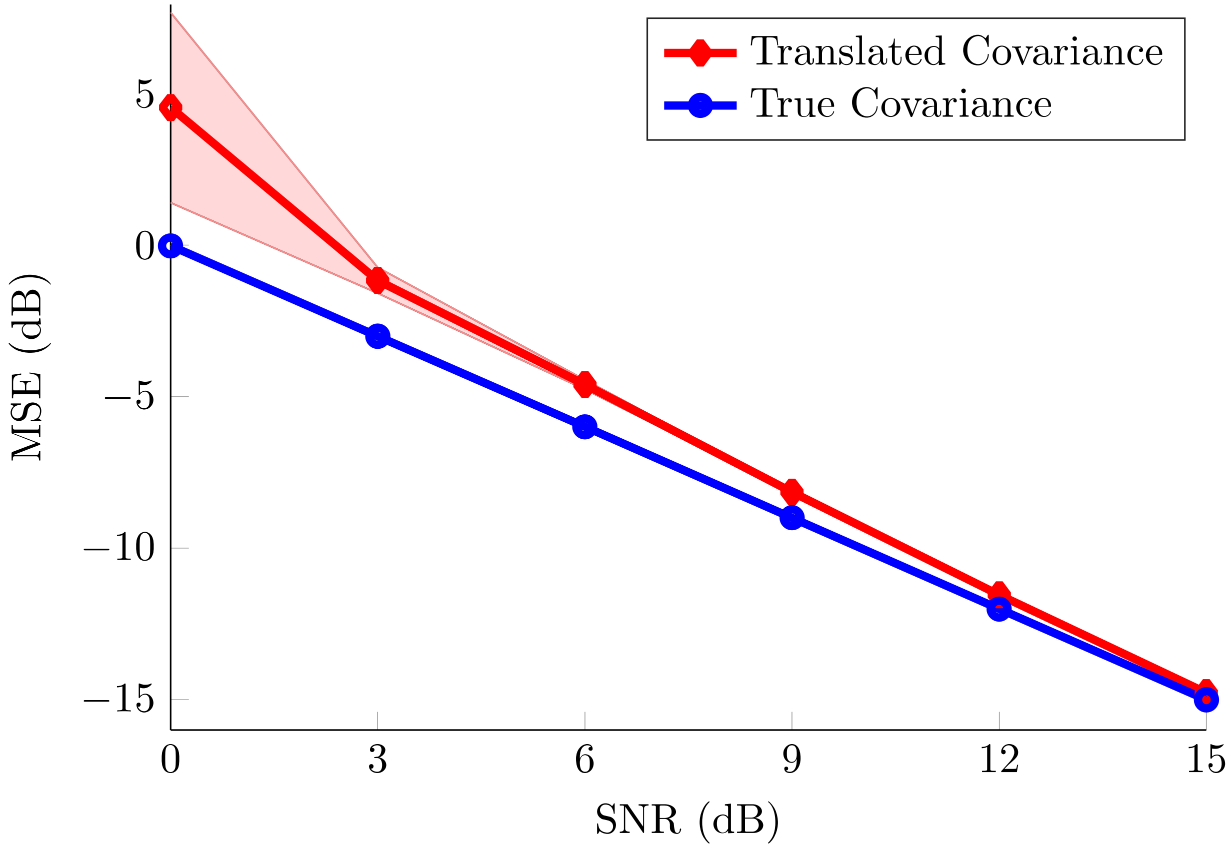
Error increases with angle spread mismatch

Decreases with SNR



Mean squared error comparison

Performance better at higher SNR, but low SNR is more important for mmWave



Conclusions

It may be possible to exploit some lower frequency channel information for higher frequencies channel estimation

Going beyond the simple setup: other array geometries, more complicated channels, channel mismatch, broadband channels, MIMO, hardware constraints

Making better use of the spatial correlation information: compressed channel estimation, compressive covariance estimation, initialization for beam training