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TEXAS
The University of Texas at Austin

Side-information-aided Non-coherent Beam Alignment Design for Millimeter Wave Systems

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Outline

Introduction

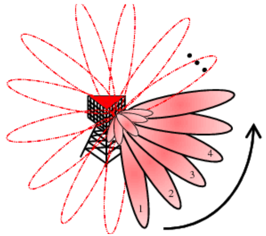
- Motivation
- Contribution
- Experimental Setup

Motivation and Challenges

Benefits of mmWave: large available spectrum and large compact antenna arrays

1. Directional beams

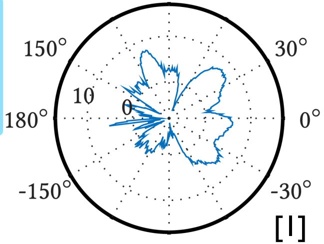
Large beam training overhead



2. Low-cost phased arrays

Beam pattern irregularities

Non-coherent measurements

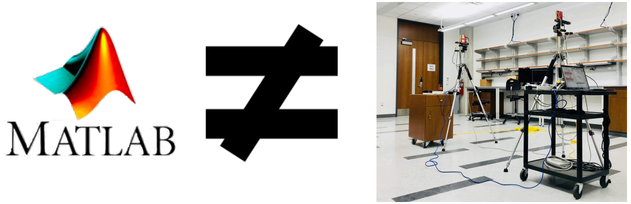


[1]

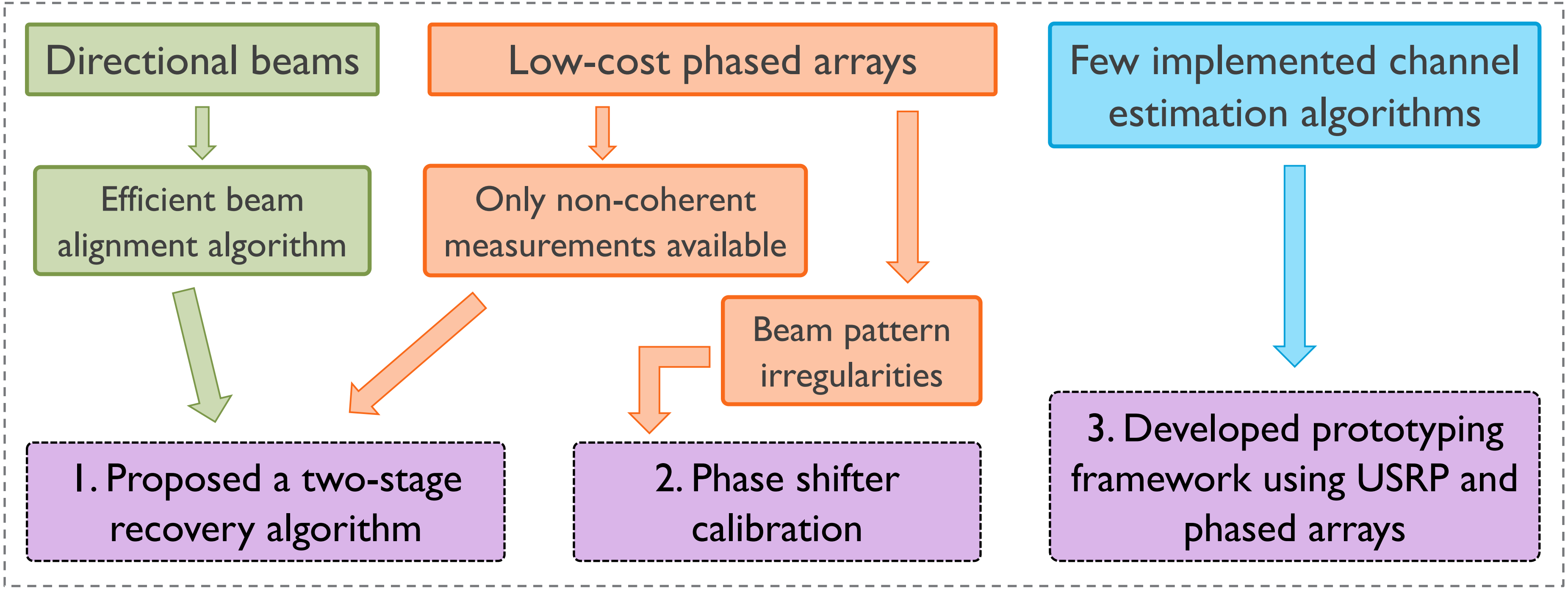
[1] Image Courtesy: [Steinmetzer et.al.:CoNEXT:2017]

3. Few implemented channel estimation algorithms

Unknown real performance

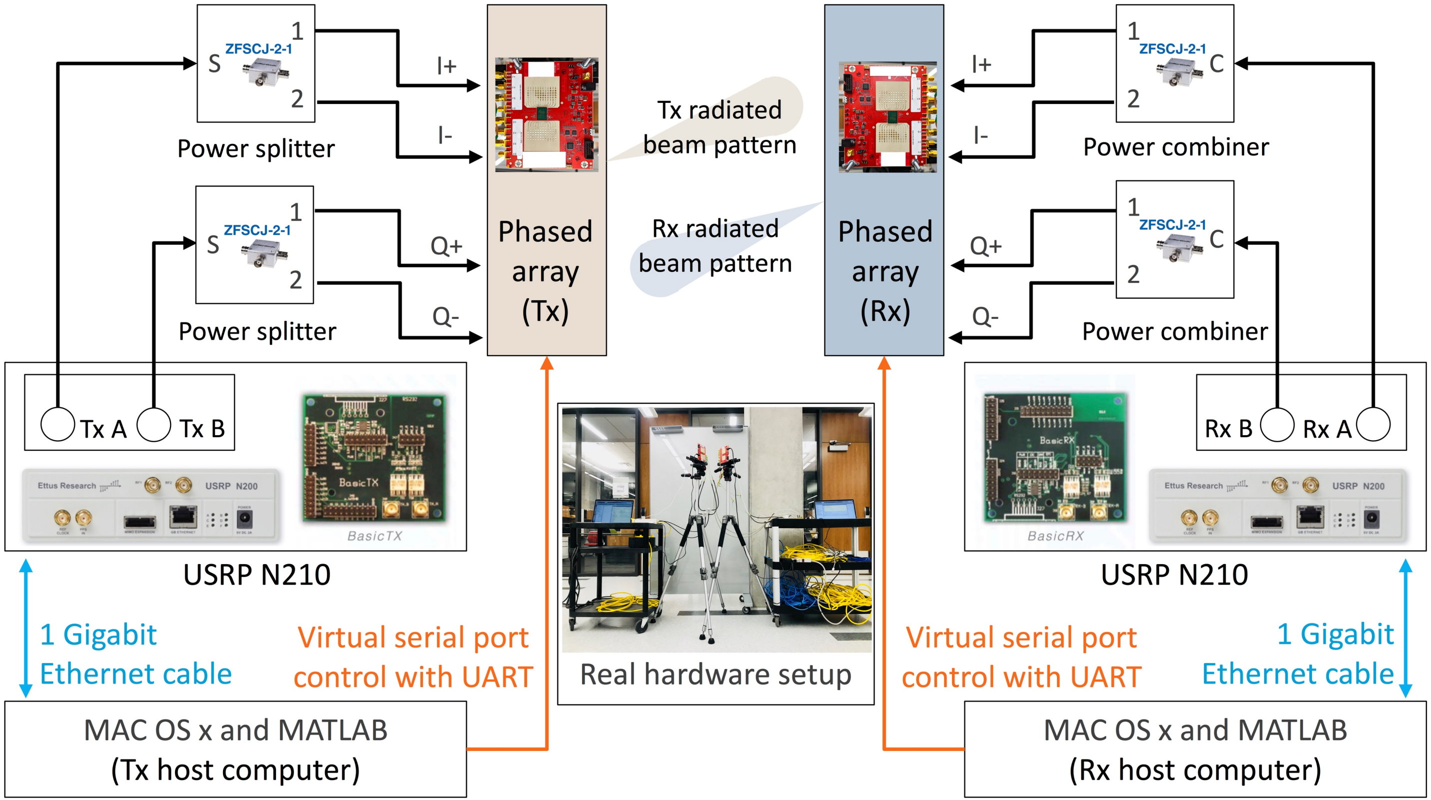


Contributions



Overall: validated proposed algorithm with calibrated prototype

Experimental Setup



Non-coherent beam alignment algorithm

- System model
- Algorithm overview

Two Beam Alignment Approaches

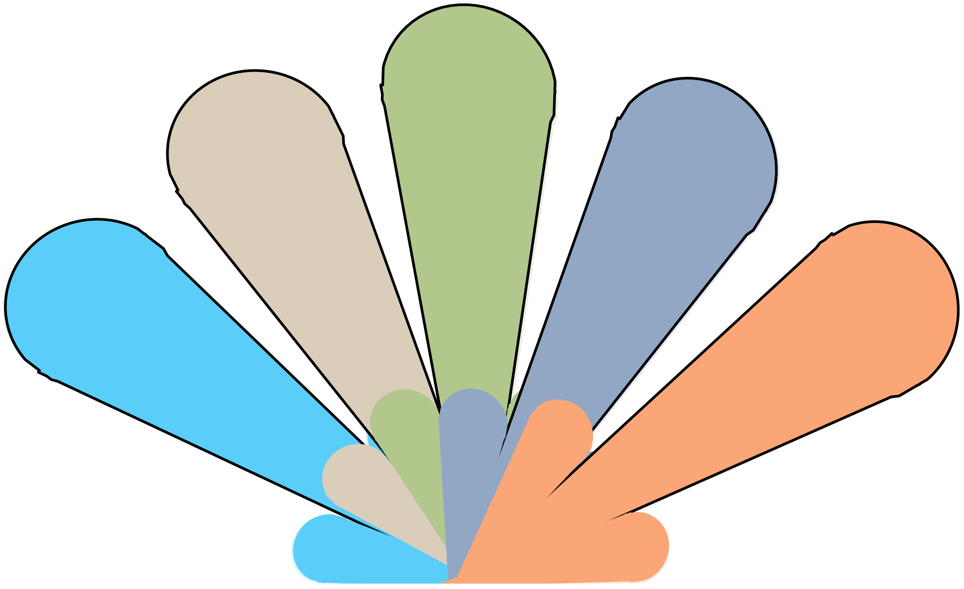


Illustration of beam alignment approaches

Beam Sweeping

- Try all beam patterns and select the one with maximum SNR

Compressive Channel Estimation (Super Resolution)

- Estimate the channel and align the beam in the estimated direction of the dominant path(s)

System Model

Signal model

$$\mathbf{Y} = \mathbf{W}^{H}_{[M_R \times N_{Rx}]}\mathbf{H}_{[N_{Rx}\times N_{Tx}]}\mathbf{F}_{[N_{Tx}\times M_T]} + \mathbf{Q}_{[M_R\times M_T]}$$

Vectorization

- M_{R}: Number of Rx beam patterns trained
- M_{T}: Number of Tx beam patterns trained
- $M_{\mathrm{R}} \times M_{\mathrm{T}} \triangleq M$: Number of total trainings
- $\mathbf{W}$: Combining matrix $\mathbf{W} = [\mathbf{w}_1, \mathbf{w}_2, \dots, \mathbf{w}_{M_{\mathrm{R}}}]$
- $\mathbf{F}$: Beamforming matrix $\mathbf{F} = [\mathbf{f}_1, \mathbf{f}_2, \dots, \mathbf{f}_{M_{\mathrm{R}}}]$
- $\mathbf{Q}$: Noise matrix

Vector representation

$$y_v = \underbrace{(\mathbf{F}^T \otimes \mathbf{W})\,(A^*_{\mathrm{Tx}} \circ A_{\mathrm{Rx}})}_{\triangleq \mathbf{A}}\, z + \mathbf{n}_{\mathrm{Q}}$$

Two-stage phase retrieval algorithm

Non-coherent measurement

$$\boldsymbol{y} = |\mathbf{A}\boldsymbol{z} + \boldsymbol{n}|$$

Notations: $\boldsymbol{y} = |\boldsymbol{y}_v|$, $\mathbf{A} = (\mathbf{F}^T \otimes \mathbf{W})\mathbf{A}_\mathrm{D}$, $\mathbf{A} = \mathbf{PC}, \boldsymbol{n} = \mathrm{vec}(\mathbf{Q})$

Goal: design $\mathbf{A}$ and an algorithm to reproduce sparse vector $\boldsymbol{z}$

$\mathbf{A} = \mathbf{PC}$ → $\boldsymbol{y} = |\mathbf{P}(\mathbf{C}\boldsymbol{z}) + \boldsymbol{n}|$

Two sequential problem:

Problem 1: $\boldsymbol{y} = |\mathbf{P}\boldsymbol{y}_{\mathrm{cs}} + \boldsymbol{n}|$

Problem 2: $\boldsymbol{y}_{\mathrm{cs}} = \mathbf{C}\boldsymbol{z}$

Problem 1: Low-dimensional phase retrieval

Problem 2: Traditional compressive sensing

The two-stage sparse vector recovery

Procedure of solving the channel estimation problem

Step I: Design beamformer $\mathbf{F}$ and combiner $\mathbf{W}$ such that $\mathbf{A} = (\mathbf{F}^T \otimes \mathbf{W})\mathbf{A}_\mathrm{D}$

Step II: Using low rank approximation of $\mathbf{A}$, design $\mathbf{P}, \mathbf{C}$ such that $\mathbf{A} = \mathbf{PC}$

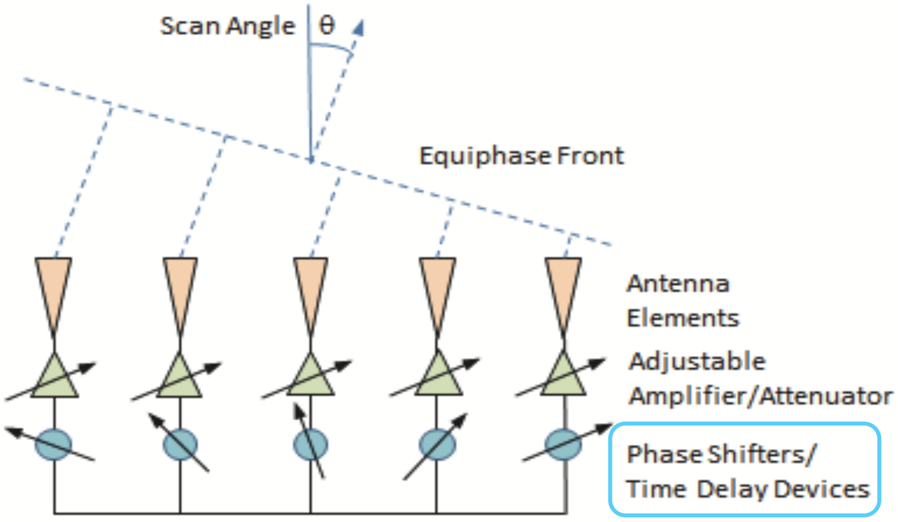
Step III: Solve problem 1, $\boldsymbol{y} = |\mathbf{P}\boldsymbol{y}_{\mathrm{cs}} + \boldsymbol{n}|$ with classical PhaseLift algorithm

Step IV: Solve problem 2, $\boldsymbol{y}_{\mathrm{cs}} = \mathbf{C}\boldsymbol{z}$ with classical OMP algorithm

Phase matching based calibration

- Introduction
- Element Gain Calibration
- Phase Error Calibration

Phase Shifter Calibration - Motivation



Phased array antenna architecture
Image Courtesy: [Hassett:EuCAP:2017]

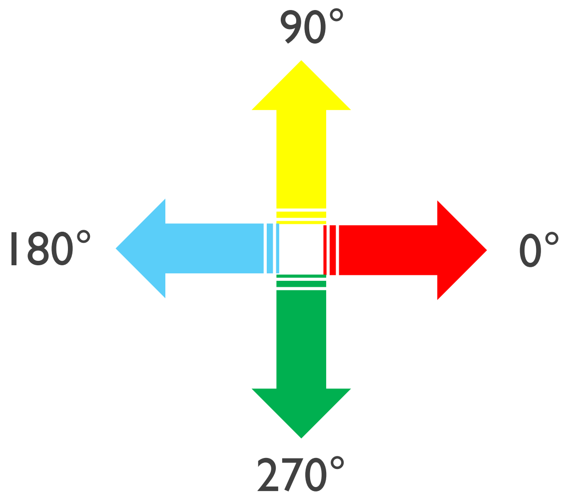
Phase Shifter Error

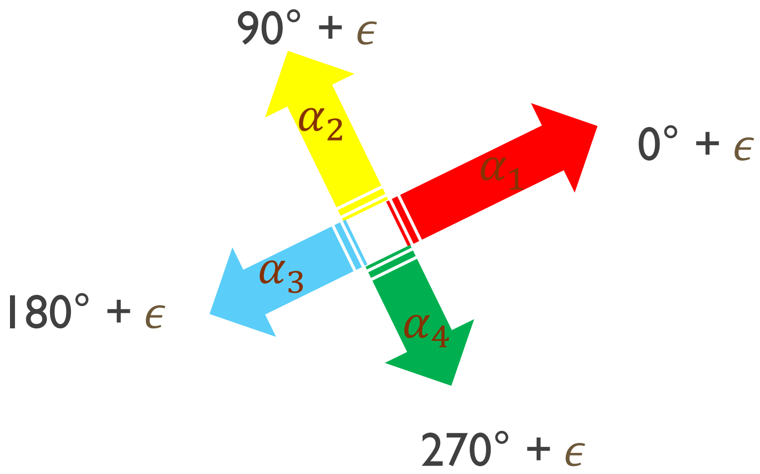
The error in default phase shifts introduces irregularities in the beam patterns

Phase Shifter Calibration

Measure the initial phase error of all elements and adjust it to generate the desired beam pattern

Phase Shifter Calibration - Introduction



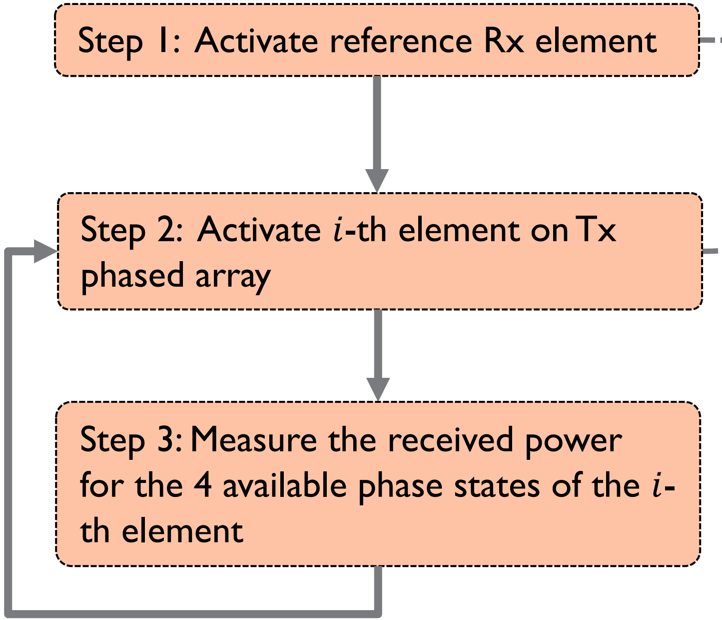


Perfect phase shifter without phase error or gain error

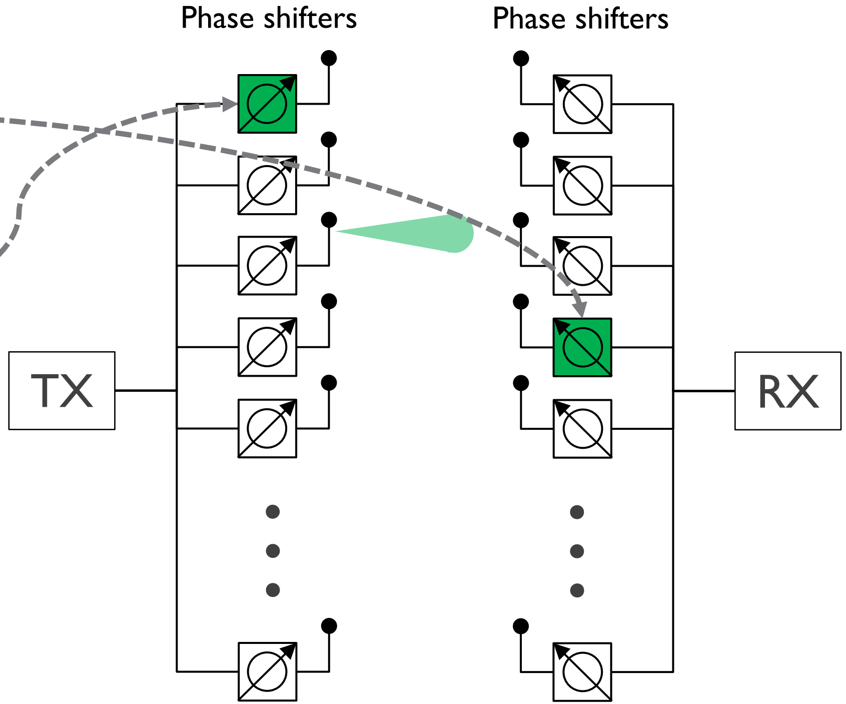
Real phase shifter with phase error and gain error

Objective: Find phase error ϵ and gain error α_i for all antenna elements

Element Gain Calibration Procedure



Procedure for element gain calibration



Example: phase shifter calibration for 4-th element

Green shifter: activated

Transparent shifter: deactivated

Phase Error Calibration Procedure

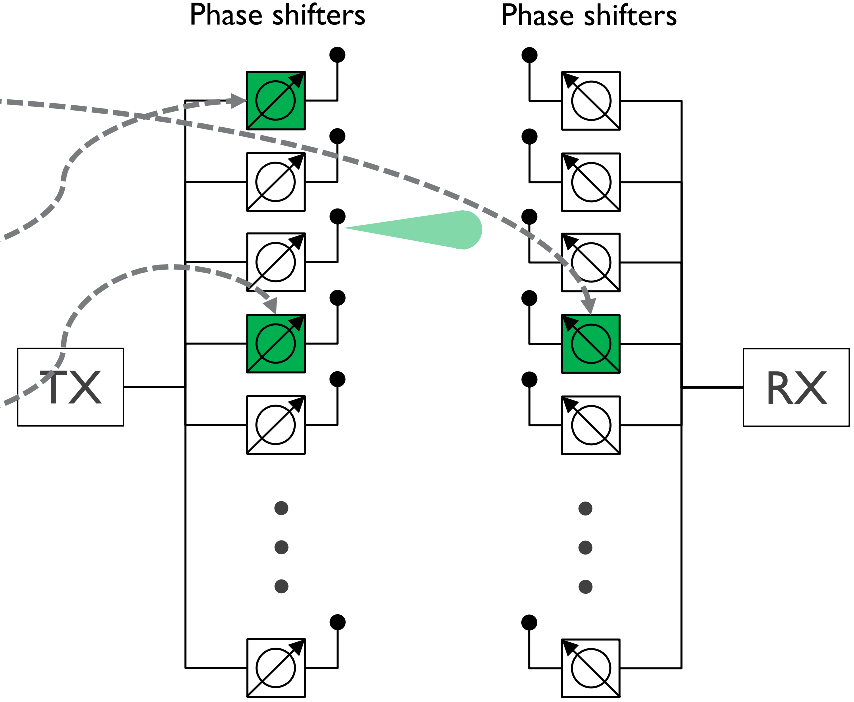
Step 1: Activate one element of Rx phased array (omnidirectional antenna)

Step 2: Activate the first element of Tx phased array (serving as a reference)

Step 3: Activate *i*-th element of Tx phased array (keeping other elements deactivated)

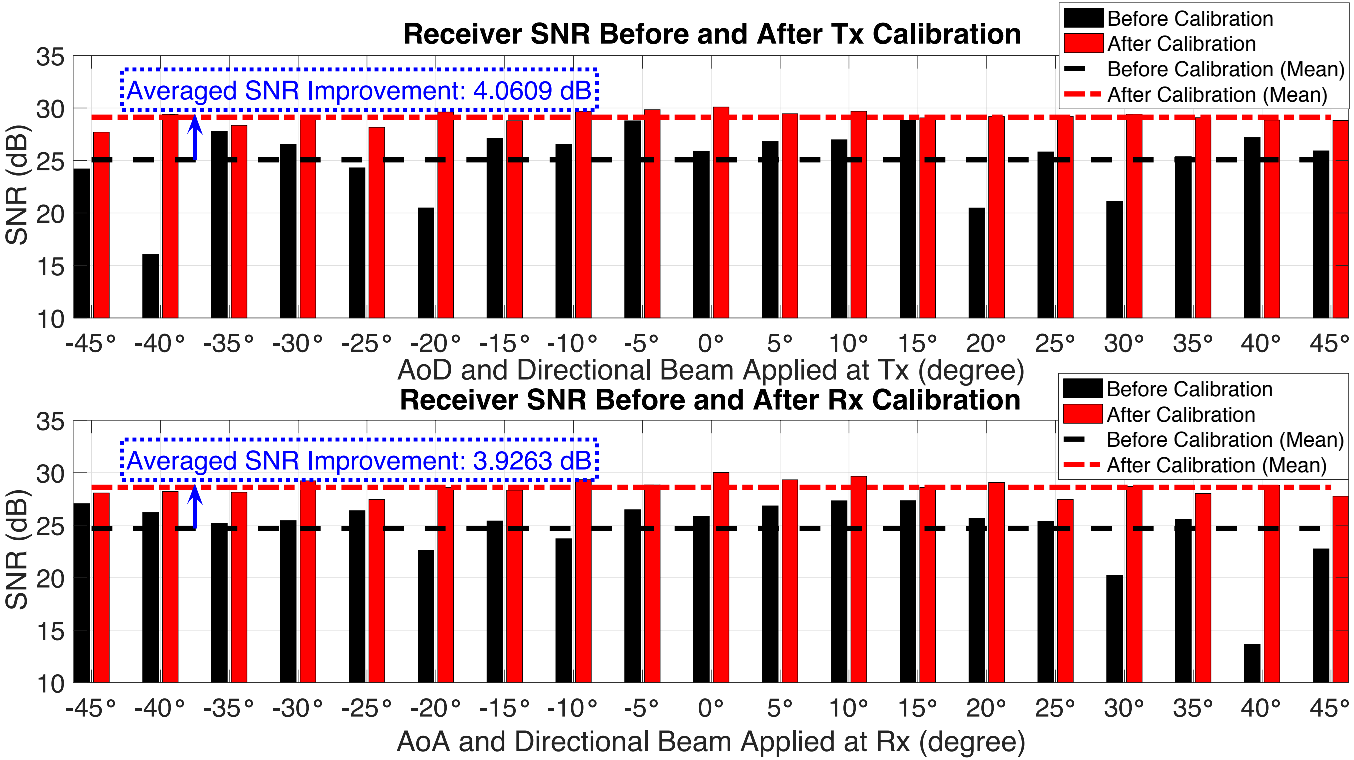
Step 4: Measure the received power for the 4 available phase shift states of the *i*-th element

Procedure for phase shifter calibration



Example: phase shifter calibration for 4-th element
Green shifter: activated
Transparent shifter: deactivated

Impact of Phase Shifters Calibration

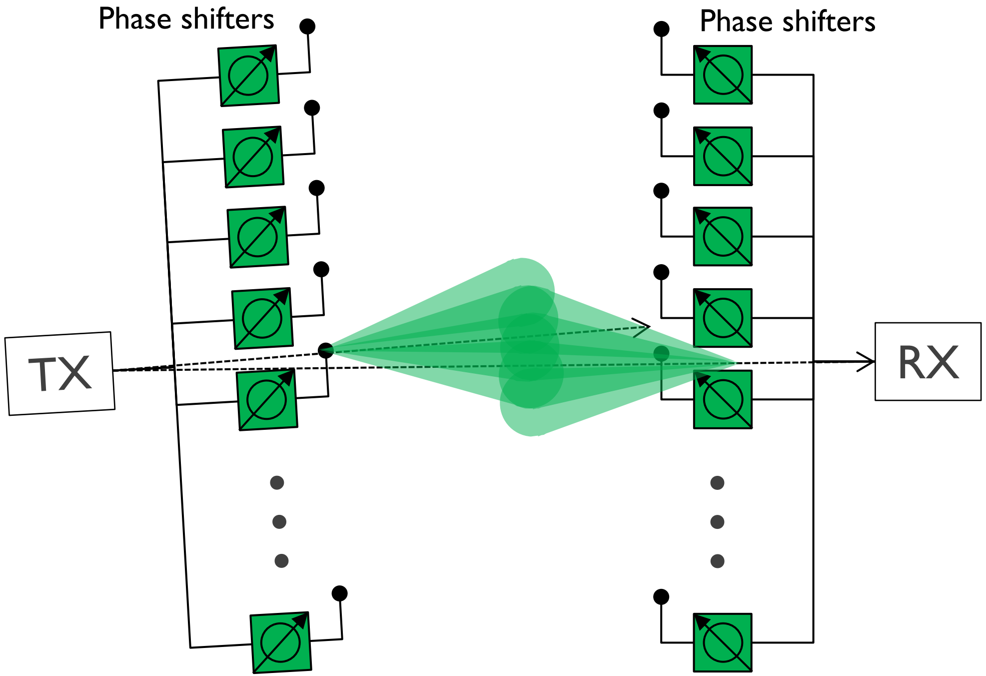


Up to 4 dB improvement with phase shifters calibration

Experimental procedure

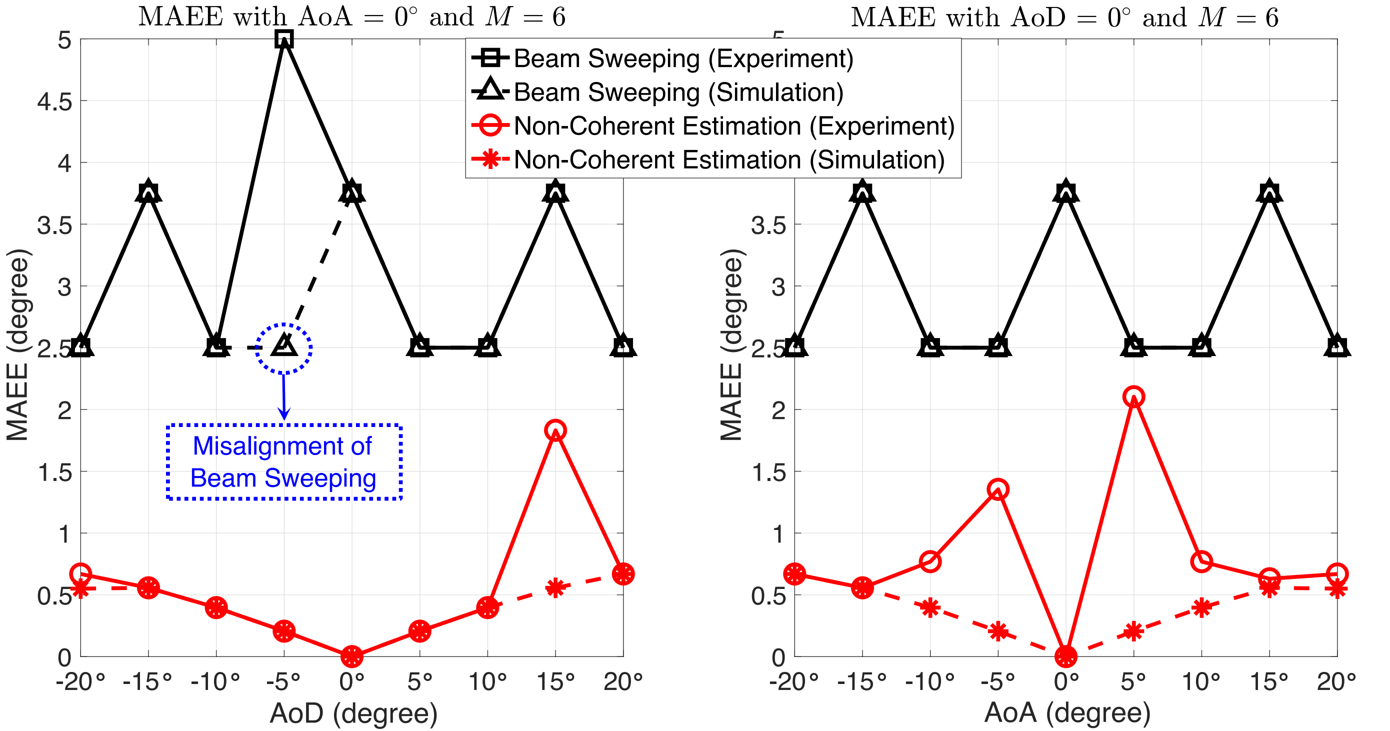
Experimental Procedure

Experimental environment



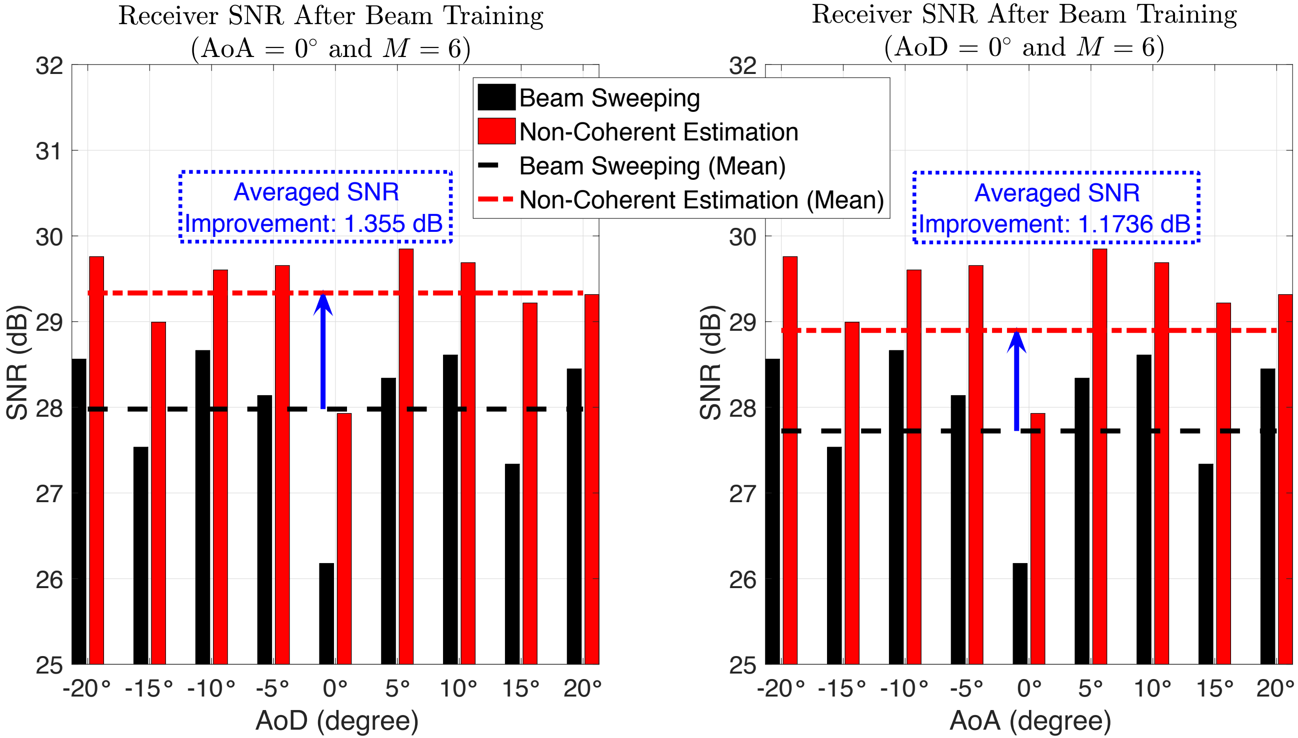
Schematic diagram of the experiment

Experiment Results



MAEE comparison between beam sweeping and proposed algorithm for simulations and experiments

Experiment Results



Receiver SNR comparison between beam sweeping and proposed algorithm

Conclusions

Conclusions

Non-coherent estimation improves beam alignment

- Proposed a two-stage recovery algorithm for sparse phase retrieval problem

Phase shifters calibration is important for configurable phase arrays

- Proposed a calibration method and enabled directional beams

Experimental validation of non-coherent beam alignment

- Developed a framework for prototyping beam alignment protocols
- Code published on GitHub for reference [3]

References

[1] D. Steinmetzer, D. Wegemer, M. Schulz, J. Widmer, and M. Hollick. 2017. Compressive Millimeter-Wave Sector Selection in Off-the-Shelf IEEE 802.11ad Devices. *In Proceedings of the 13th International Conference on Emerging Networking EXperiments and Technologies (CoNEXT '17).* ACM

[2] K. Hassett, Phased Array Antenna Calibration Measurement Techniques and Methods, *European Conference Antennas Propagation (EuCAP)*, Davos, 2016.

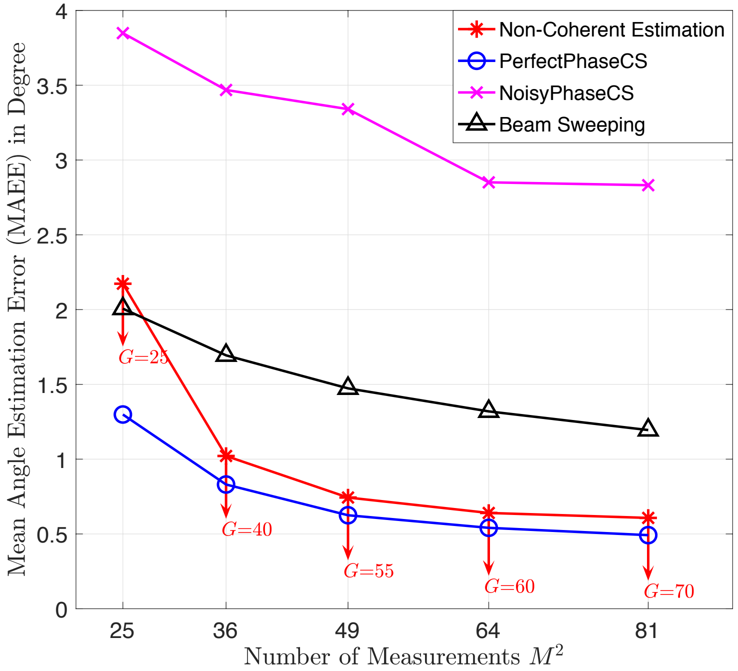
[3] Side-information-Aided Non-coherent Beam Alignment (SANBA) for MmWave Systems, https://github.com/yzhang417/SANBA-mmWave-SDR, Accessed on June 06, 2019

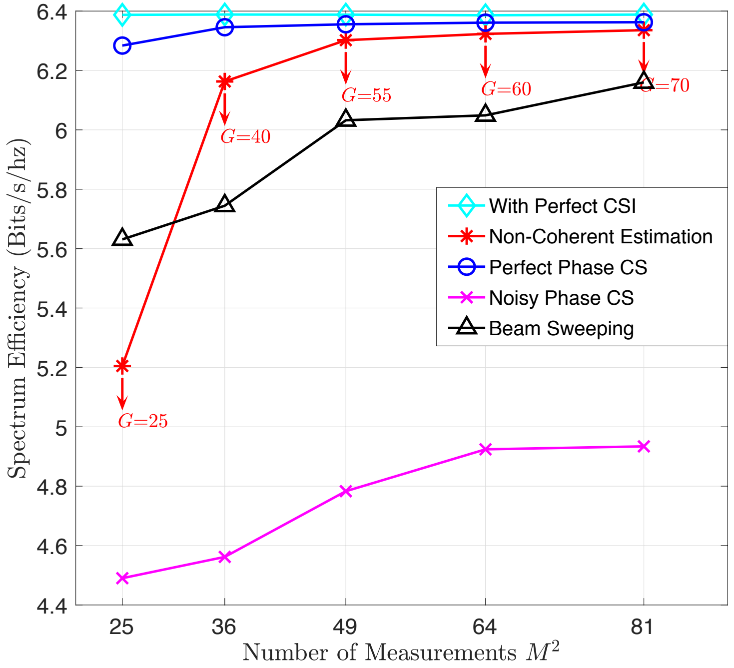
[4] M. E. Rasekh, Z. Marzi, Y. Zhu, U. Madhow, and H. Zheng, Non-coherent mmWave path tracking. *In Proceedings of the 18th International Workshop on Mobile Computing Systems and Applications.* ACM, 2017, pp. 13–18.

[5] R. W. Heath, N. Gonzalez-Prelcic, S. Rangan, W. Roh, and A. M. Sayeed. 2016. An overview of signal processing techniques for millimeter wave MIMO systems. *IEEE journal of selected topics in signal processing*, 10(3), 436-453.

Thank you!

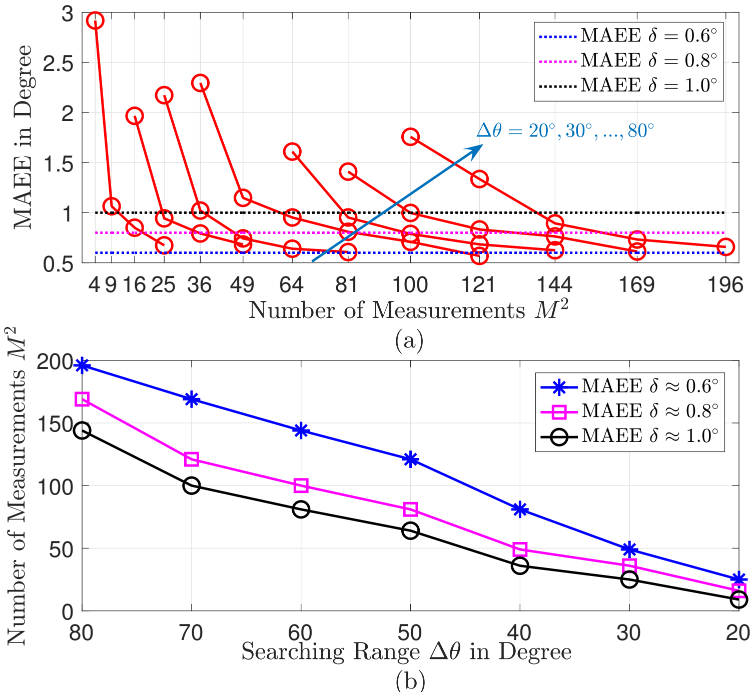
Simulation Results

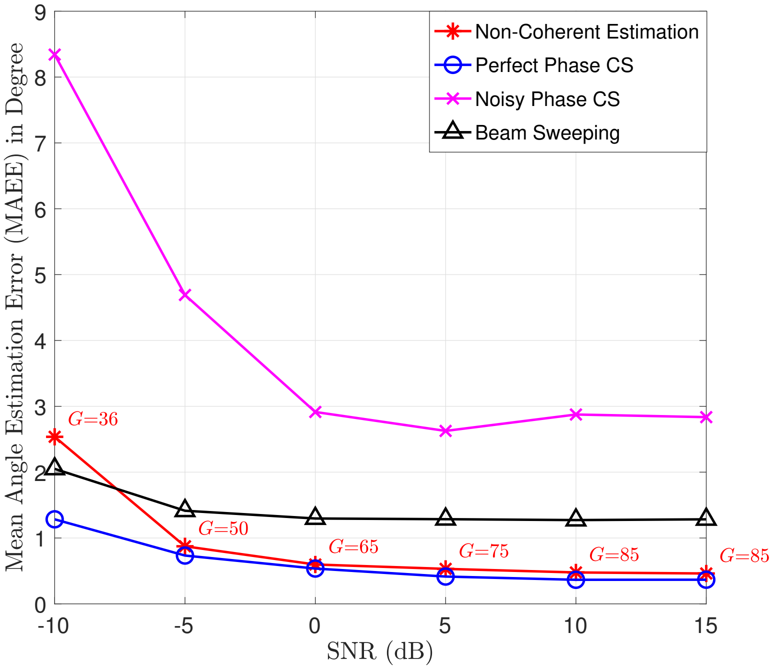




Observation: Better AoD and AoA estimation, improved spectrum efficiency

Simulation Results





Observation: MAEE estimation error with SNR, searching range