Near-Field Measurement System for the Upper Mid-Band

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Asilomar Conference on Signals, Systems, and Computers

30 October 2024

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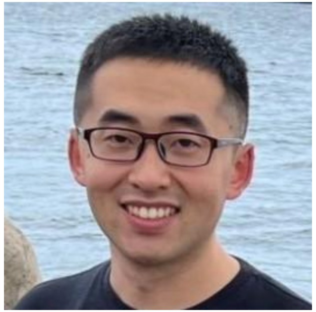

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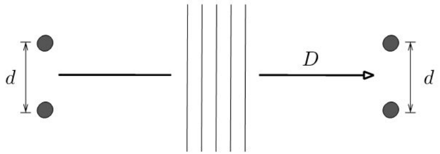
Outline

- ❑ Near-field modeling
- ❑ Experimental set-up
- ❑ Preliminary results
- ❑ Future work

Line-of-Sight (LOS) Multiple Input Multiple Output (MIMO)

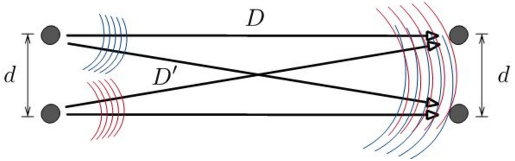
Plane Wave Model: Single rank only

$D \geq D_R$



Spherical Wave Model: High rank possible

$D \leq D_R$



Channel is (roughly) high-rank when:

$$D \leq D_R = \frac{2d^2}{\lambda} = \text{Rayleigh Distance}$$

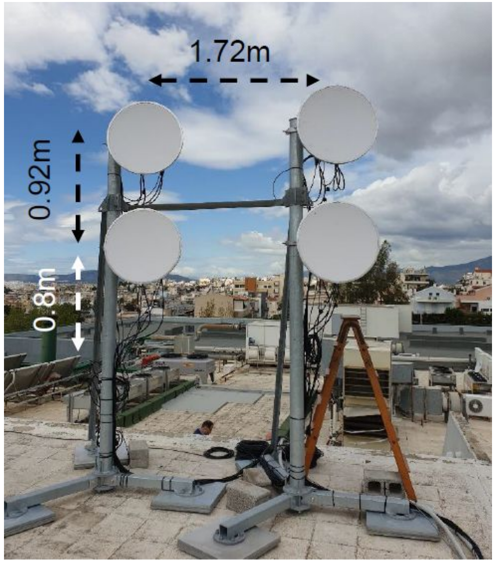
d = Array aperture, D = Distance

Enables spatial multiplexing in LOS!

Lozano, “Harnessing the Radio Wavefront Curvature with Line-of-Sight MIMO”, 2021

Ericsson LOS MIMO Demo

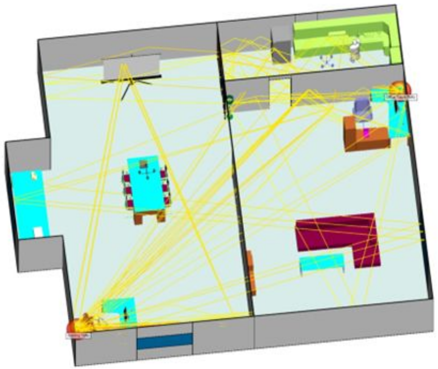
- Specifications:
  - 73 GHz carrier, 2.5 GHz bandwidth
  - 8 streams (4 spatial x 2 polarization)
  - At 5 bps/Hz: 2.5 x 8 x 5 = 100 Gbps!
- Demonstrated at 1.5 km



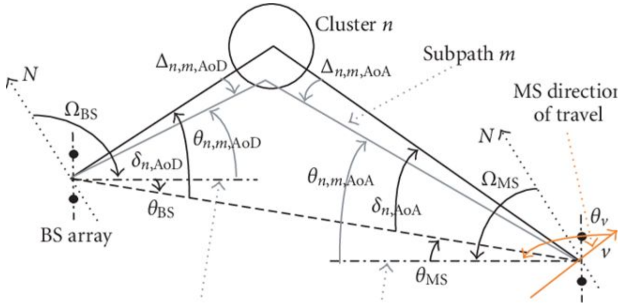
Source: Yinggang Li et al, High-capacity mmW point-to-point radio links for 5G and beyond, 2019.

Traditional Spatial Cluster Model

- Spatial cluster model
  - Widely-used (e.g., 3GPP 38.901)
  - Describes propagation by discrete paths



- Each path cluster is described by:
  - Angle of arrival (AoA)
  - Angle of departure (AoD)
  - Relative delay
  - Path gain

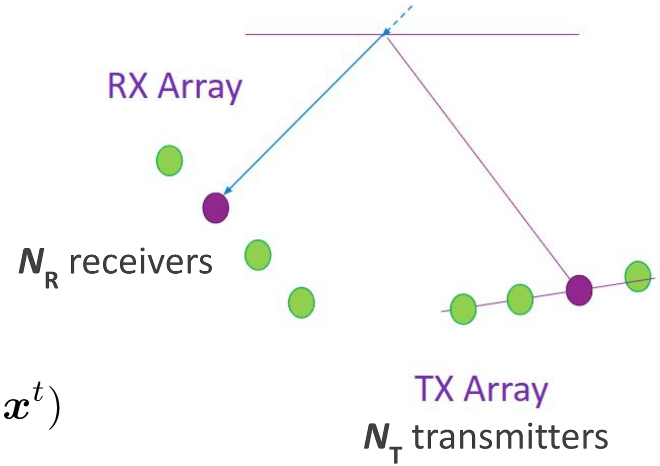


- Enables prediction of arbitrary array response
- But assumes planar waves

MIMO Channel Response via PWA

- MIMO response typically computed via a Plane Wave Approximation (PWA)

$$H_{mn}(f) = \sum_{\ell=1}^{L} g_\ell \exp\left(-\frac{j2\pi f}{c} d_\ell(\boldsymbol{x}_m^r, \boldsymbol{x}_n^t)\right)$$



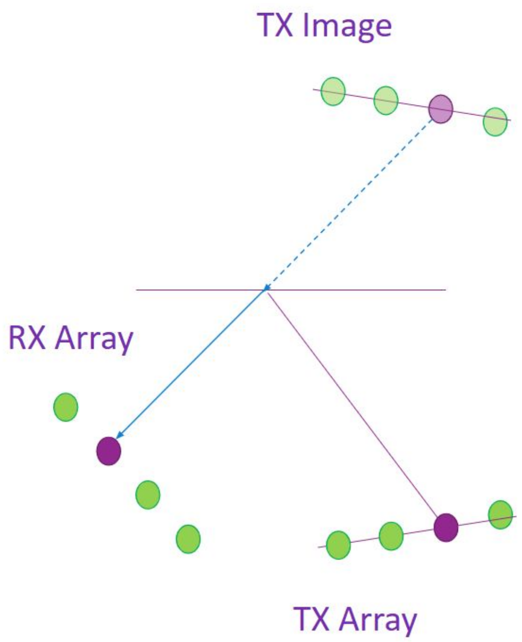
- d_ℓ = path distance function
- Path distance typically computed by PWA

$$\begin{aligned} d_\ell(\boldsymbol{x}^r, \boldsymbol{x}^t) &\approx \widehat{d}_\ell(\boldsymbol{x}^r, \boldsymbol{x}^t) \\ &= c\tau_\ell + (\boldsymbol{u}_\ell^r)^\intercal(\boldsymbol{x}_0^r - \boldsymbol{x}^r) + (\boldsymbol{u}_\ell^t)^\intercal(\boldsymbol{x}_0^t - \boldsymbol{x}^t) \end{aligned}$$

- $\boldsymbol{u}_\ell^r, \boldsymbol{u}_\ell^t$: Directions of AoA and AoD, corresponding to receiver (RX) and transmitter (TX), respectively

Reflection Model for Near-Field

- Reflection model
  - Each path described by its image
  - Path distance can be exactly computed
  - Captures spherical propagation for near-field
- Improves the model accuracy in near-field



Hu, Y., Yin, M., Rangan, S., & Mezzavilla, M. (2023). Parametrization and Estimation of High-Rank Line-of-Sight MIMO Channels with Reflected Paths. IEEE Transactions on Wireless Communications.

Parameters in 2D

- Plane wave model:

$$(g_\ell, \delta_\ell, \theta_\ell^t, \theta_\ell^r)$$

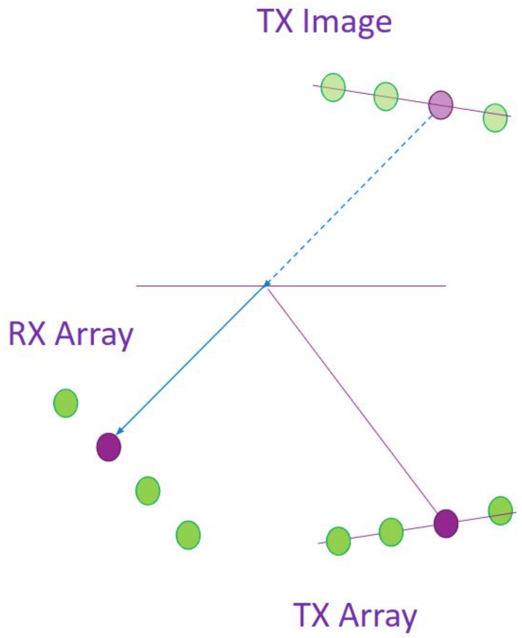
Relative delay

- Reflection model:

$$(g_\ell, \tau_\ell, \theta_\ell^t, \theta_\ell^r, s_\ell)$$

Absolute delay

Reflection parameter



Parameters in 3D

- Plane wave model:

$$(g_\ell, \delta_\ell, \theta_\ell^t, \phi_\ell^t, \theta_\ell^r, \phi_\ell^r)$$

Relative delay

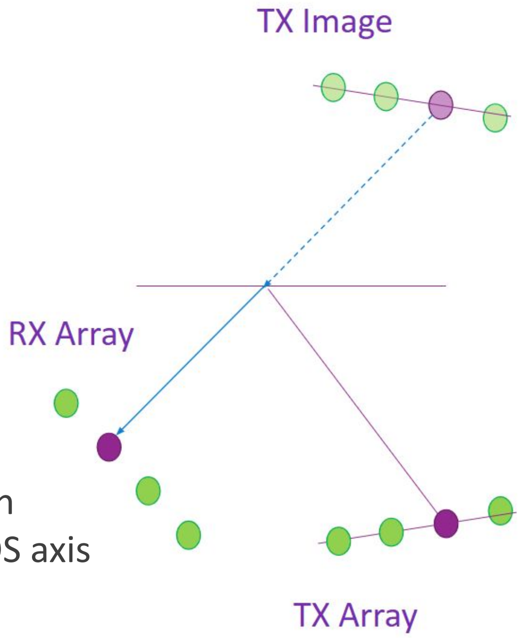
- Reflection model:

$$(g_\ell, \tau_\ell, \theta_\ell^t, \phi_\ell^t, \theta_\ell^r, \phi_\ell^r, s_\ell, \gamma_\ell)$$

Absolute delay

Reflection parameter

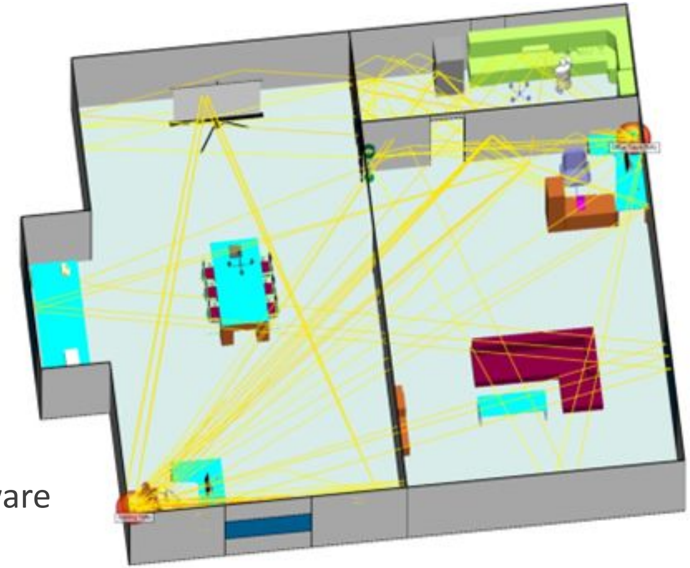
TX rotation around LOS axis



Today's Problem

- How do we measure the parameters for near-field
  - Must handle multi-path

$$H_{mn}(f) = \sum_{\ell=1}^{L} g_\ell \exp\left(-\frac{j2\pi f}{c} d_\ell(\boldsymbol{x}_m^r, \boldsymbol{x}_n^t)\right)$$



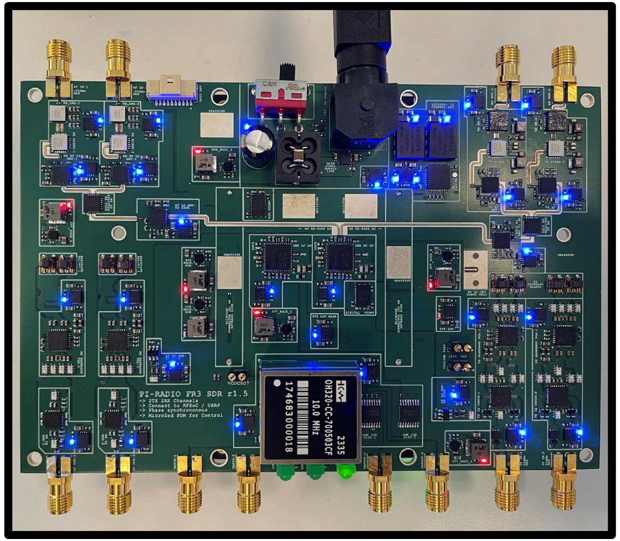
- Contribution of today's talk:
  - Near-field motivations and models
  - A measurement procedure with (relatively) low-cost hardware
  - Work is still in progress, initial results

Outline

- Near-field modeling
- Experimental set-up
- Preliminary results
- Future work

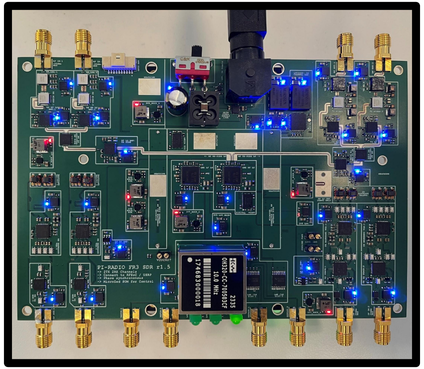
Frequency-range (FR)3 Transceiver (Pi-Radio)

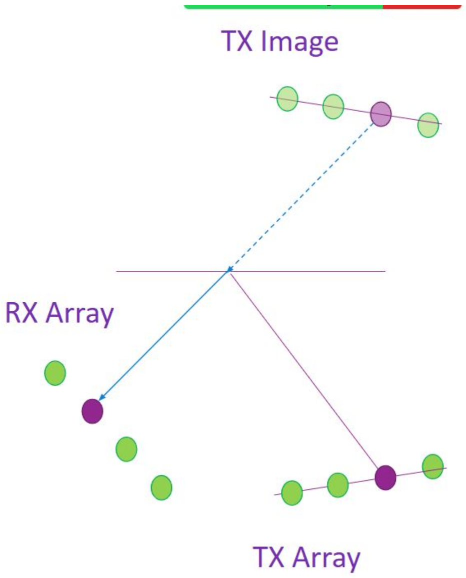
Parameter	Value
Frequency of operation	**6 to 22.6 GHz (goes up to 24 GHz with some trickery)**
Architecture	2-channel MIMO. Simultaneous TX/RX
Tile-able?	Yes. Multiple units can be tiled phase-coherently
IF Frequency of operation	1 to 6 GHz center frequency
Instantaneous Bandwidth	1 GHz
TX max power per channel	17 dBm
RX Noise Figure	**3 dB**
Control	MicroZed (stand-alone / Ethernet), and direct GPIO
Antennas	Stock Vivaldi. Has RF + Control interfaces for new antennas
Programmable Gain (TX/RX)	**53 dB of independently programmable gain, per channel**
Onboard Clock Stability	0.5 parts per billion (ppb). Ultra-high stability
LO Phase Noise	-236 dBc/Hz FoM and -134 dBc/Hz normalized 1/f noise



Challenges

- Challenge 1:
  - Current hardware is 2x2
  - Low spatial resolution

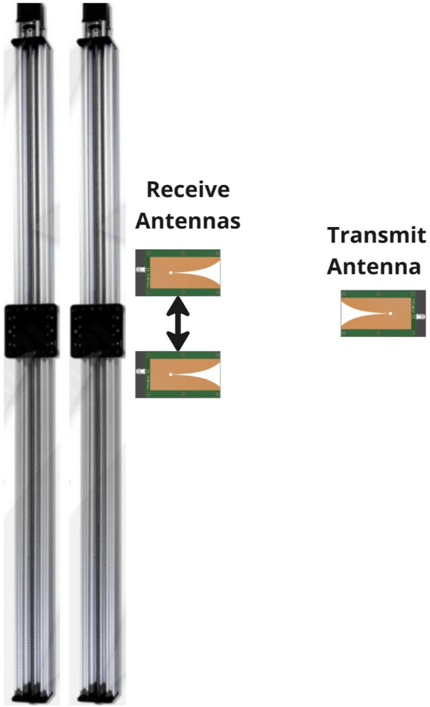




- Challenge 2:
  - Traditional channel sounding only gets AoA
  - Need absolute distance for each image point

Key Idea: Synthetic Aperture

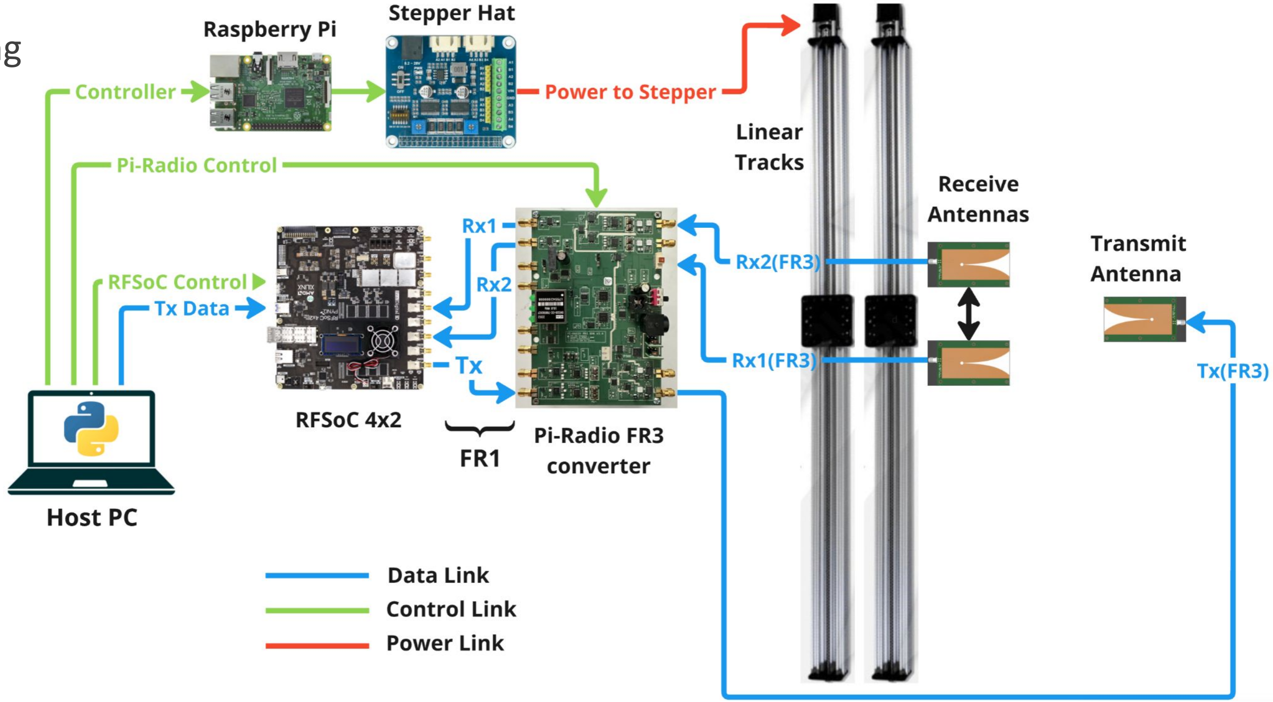
- Make multiple measurements
- Each measurement has only two RX antennas
- But, can vary:
  - Spacing between antennas
  - Centroid location of antennas
- Helps estimating the RM parameters



Hu, Y., Yin, M., Rangan, S., & Mezzavilla, M. (2023). Parametrization and Estimation of High-Rank Line-of-Sight MIMO Channels with Reflected Paths. IEEE Transactions on Wireless Communications.

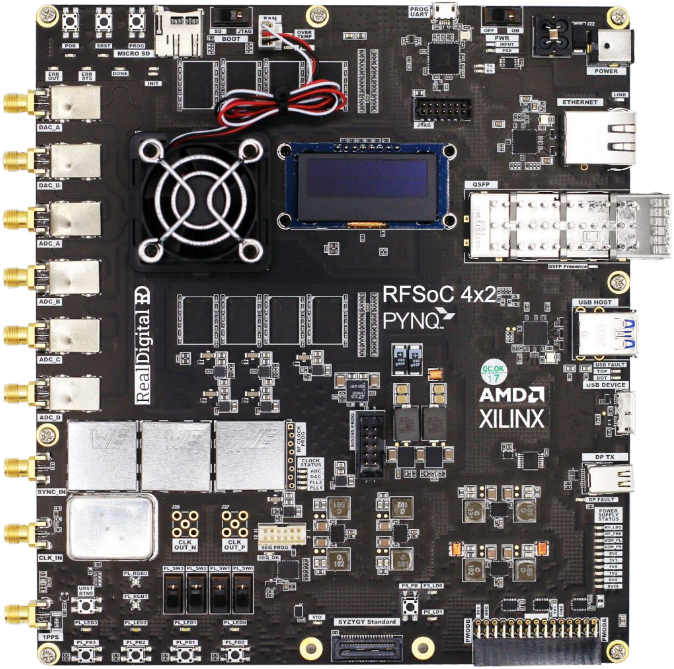
Proposed Measurement Setup

- Digital MIMO baseband system using Xilinx RFSoC 4x2
- Pi-Radio MIMO FR3 Transceiver
- Wideband Vivaldi Antennas
- 2x1.5m Linear tracks for a synthetic wide aperture 1x2 antenna
- Host computer for baseband processing and Visualization



Digital Baseband System

- Xilinx RFSoC 4x2
- Zynq Ultrascale+ RFSoC XCZU48DR-2FFVG1517E
- Baseband processing using Python/Pynq
- 2 x 14-bit 9.85 GSPS RF-DACs
- 4 x 14-bit 5 GSPS RF-ADCs

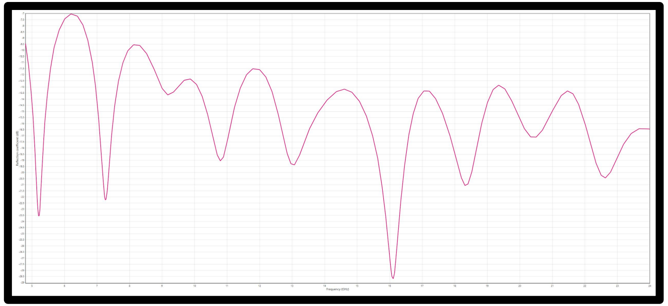


Wideband Vivaldi Antenna (Pi-Radio)

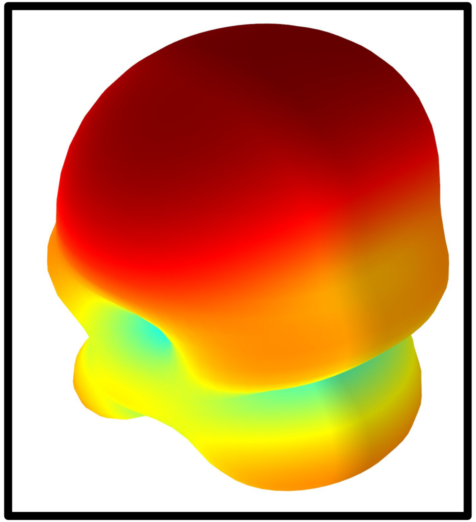
- Vivaldi End-Fire Antennas cover the whole range of 6-24 GHz

Model

S Parameters (S11)

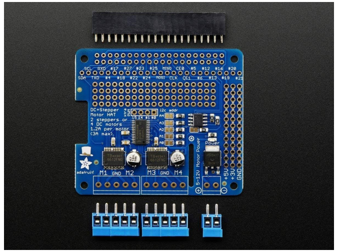


Farfield Radiation Pattern



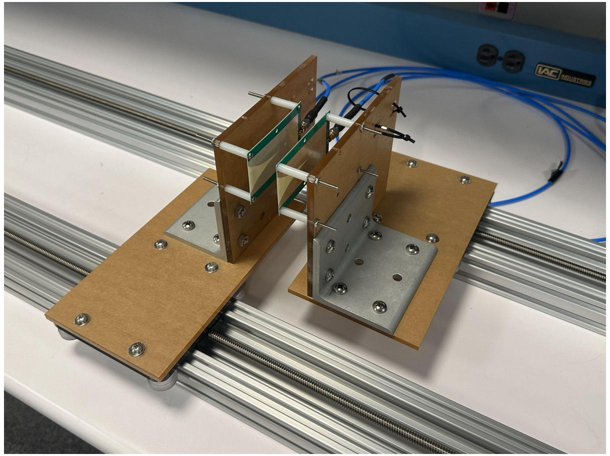
Synthetic Wide Aperture Antennas

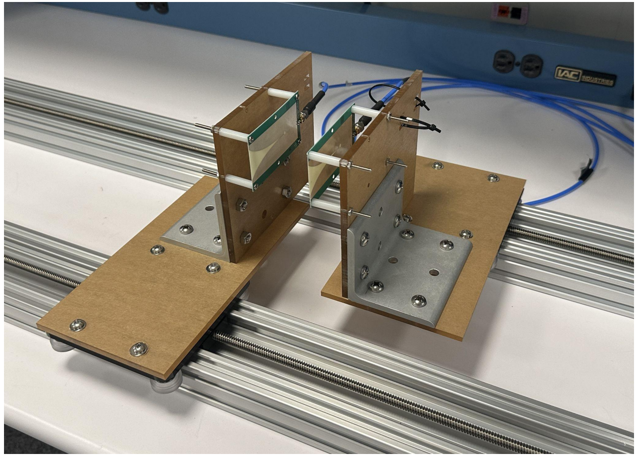
- Using 2x 1.5m linear tracks with some control circuitry to tune antenna aperture

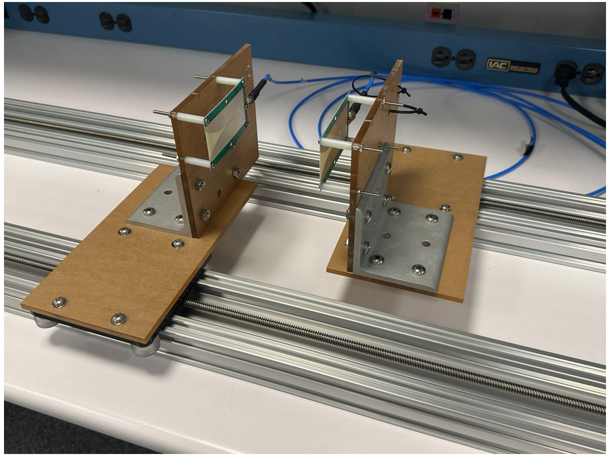


Synthetic Wide Aperture Antennas

- Using 2 x 1.5m linear tracks and stepper motors with 0.1mm accuracy

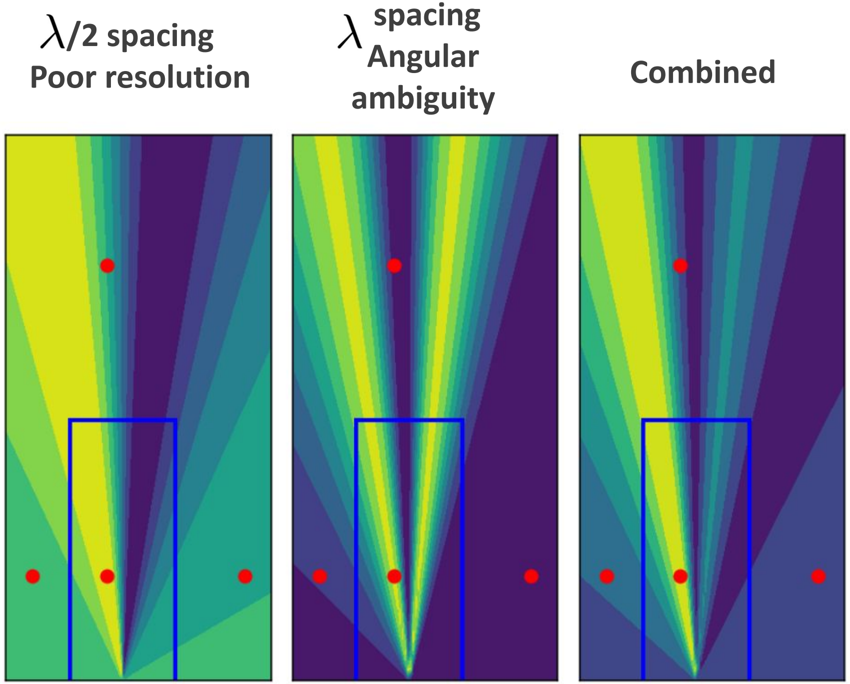






Combining Multiple Spacings

- Solves challenge 1 (low spatial resolution)
- Trade-off between the resolution and ambiguity for different spacings
- Can combine both configs and improve the estimation



Algorithm of TX Distance Estimation

Algorithm 1 Multi-measurement Triangulation

Require: M measurements with different antenna spacings and locations

```
Perform standard sparse channel decomposition for each measurement
Extract paths and spatial signature for each path from the sparse channels
for each detected path do
    for each candidate location x do
        Calculate the expected phase rotation if TX is at x
        Compute the correlation of the expected phase rotation and the actual detected phase rotation
        of the path for all measurements and RX antennas.
    end for
    Find the x location with maximum correlation {This is the TX location for that path}
end for
```

$$\rho_i(x, y) = \Sigma_m |\Sigma_r e^{-j\theta_{imr}} e^{j\bar{\theta}_{imrxy}}|^2$$

$$(X, Y)_i = argmax_{(x,y)} \; \rho_i(x, y)$$

Measurement ‘m’, receiver antenna ‘r’, and path ‘i’

Outline

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- ➡ ❑ Preliminary results
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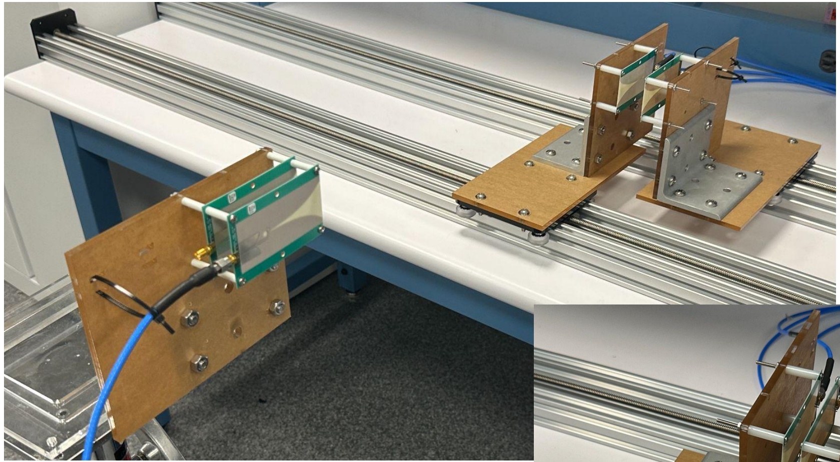
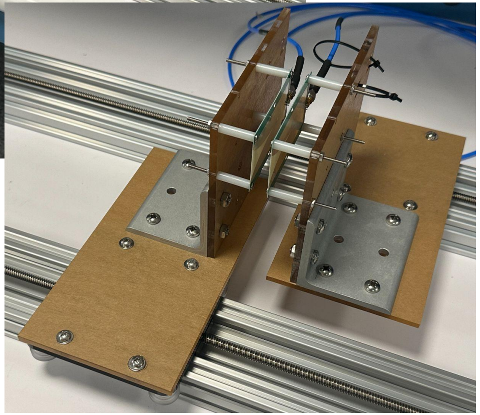
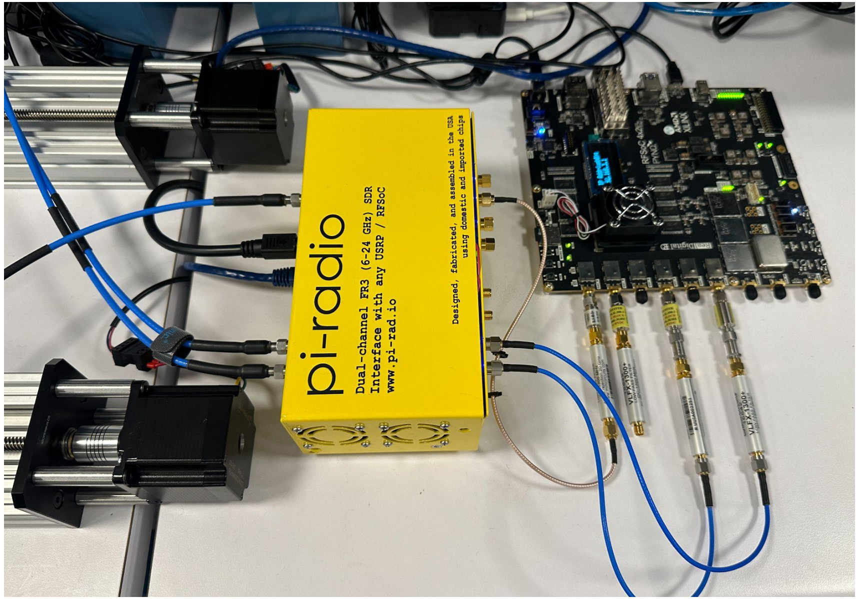
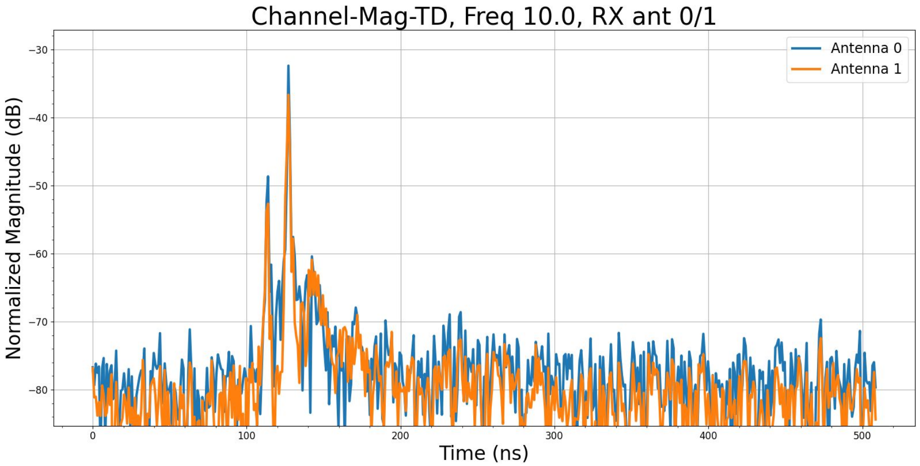
Physical Measurement Setup



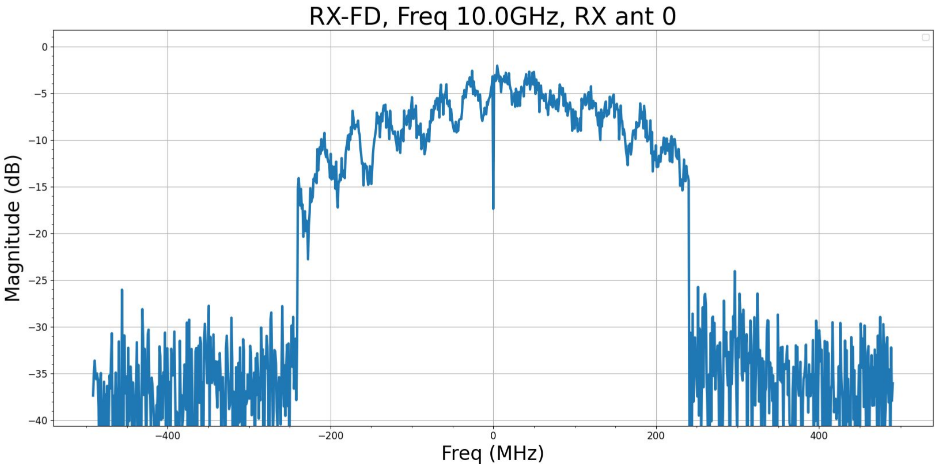




Measurements: 500 MHz Signal @ 10 GHz

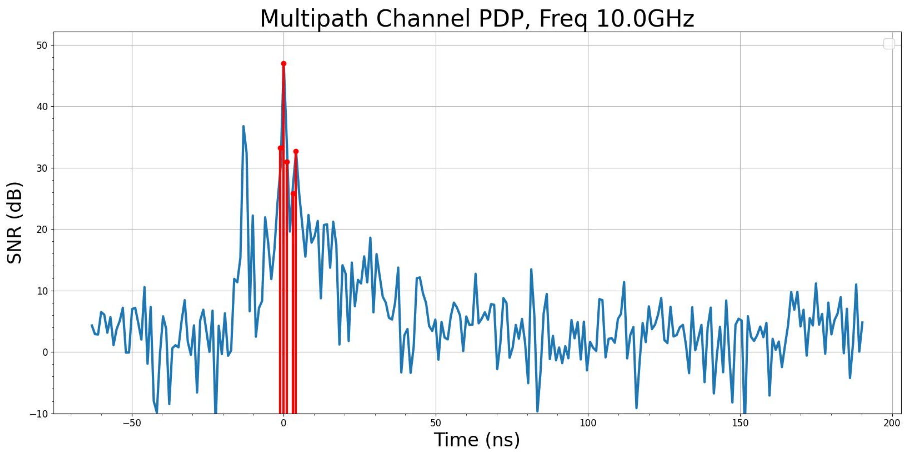


Time domain channel response



Frequency domain received signal

Demo of Triangulation



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Ongoing Works and Plans

- Estimating the TX reflection images in the environment
- Estimating the reflection model parameters
- Using analog switches to estimate the parameters in a 3D environment
- Extending the system to more than 2x2

Summary

- Discussed LOS MIMO models
- Reviewed PWA model vs Reflection Model (RM)
- Proposed a new measurement system for RM parameter estimation
- Demonstrated preliminary results from the proposed system

References

- Hu, Y., Yin, M., Rangan, S., & Mezzavilla, M. (2023). Parametrization and Estimation of High-Rank Line-of-Sight MIMO Channels with Reflected Paths. IEEE Transactions on Wireless Communications.
- 3GPP Technical Report 38.901, “Study on channel model for frequencies from 0.5 to 100 GHz (Release 16),” Dec. 2019.
- Efficient ray-tracing simulation for near-field spatial non-stationary mmWave massive MIMO channel and its experimental validation
- “AMD RFSoC 4x2,” https://www.amd.com/en/corporate/university-program/aup-boards/rfsoc4x2.html

Thank You!
Happy to discuss further!

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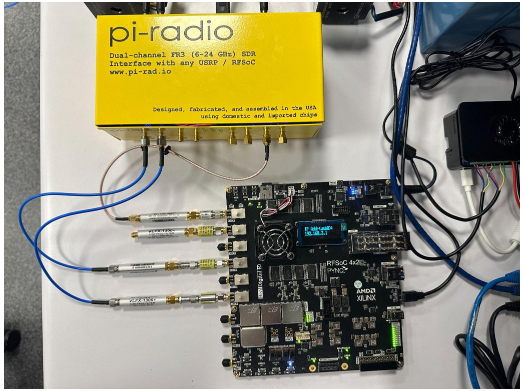

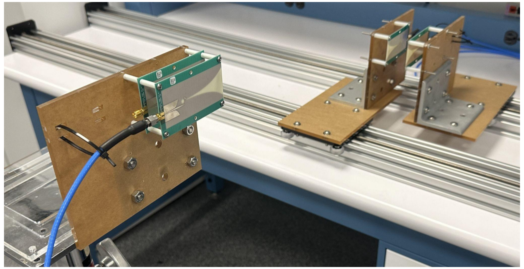

Accuracy of PWA Model

$$d_\ell(\boldsymbol{x}^r, \boldsymbol{x}^t) \approx \widehat{d}_\ell(\boldsymbol{x}^r, \boldsymbol{x}^t)$$
$$= c\tau_\ell + (\boldsymbol{u}_\ell^r)^\intercal(\boldsymbol{x}_0^r - \boldsymbol{x}^r) + (\boldsymbol{u}_\ell^t)^\intercal(\boldsymbol{x}_0^t - \boldsymbol{x}^t)$$

$$(\boldsymbol{u}^r)^\intercal = -\frac{\partial d_\ell(\boldsymbol{x}_0^r, \boldsymbol{x}_0^t)}{\partial \boldsymbol{x}^r}, \quad (\boldsymbol{u}^t)^\intercal = -\frac{\partial d_\ell(\boldsymbol{x}_0^r, \boldsymbol{x}_0^t)}{\partial \boldsymbol{x}^t}$$

$$\boldsymbol{u}_\ell^r = (\cos(\phi_\ell^r)\cos(\theta_\ell^r), \sin(\phi_\ell^r)\cos(\theta_\ell^r), \sin(\theta_\ell^r))$$
$$\boldsymbol{u}_\ell^t = (\cos(\phi_\ell^t)\cos(\theta_\ell^t), \sin(\phi_\ell^t)\cos(\theta_\ell^t), \sin(\theta_\ell^t)),$$

$$d_\ell(\boldsymbol{x}^r, \boldsymbol{x}^t) - \widehat{d}_\ell(\boldsymbol{x}^r, \boldsymbol{x}^t)$$
$$= O(\|\boldsymbol{x}_0^r - \boldsymbol{x}^r\|^2) + O(\|\boldsymbol{x}_0^t - \boldsymbol{x}^t\|^2)$$

Parameters of PWA Model

- Parameters we need to estimate for the PWA model:

$$(g_\ell, \tau_\ell, \phi_\ell^r, \theta_\ell^r, \phi_\ell^t, \theta_\ell^t), \quad \ell = 1, \ldots, L$$

- g_ℓ : Complex path gain
- τ_ℓ : Path delay
- $\phi_\ell^r, \theta_\ell^r$: Angle of Arrival of the path at the receiver
- $\phi_\ell^t, \theta_\ell^t$: Angle of Departure of the path at the transmitter

Path Distance Function for RM-NLoS

- The Reflection Model for Non-Line of Sight is suggested as follows:

$$d_\ell(\boldsymbol{x}_m^r, \boldsymbol{x}_n^t) = \left\| \boldsymbol{x}_m^r - \boldsymbol{U}_\ell \boldsymbol{x}_n^t - \boldsymbol{g}_\ell \right\|$$

- $\boldsymbol{U}_\ell$: Orthogonal Rotation Matrix
- $\boldsymbol{g}_\ell$: Translation Vector

Path Distance Function for RM-NLoS

$$\boldsymbol{R}_z(\phi) := \begin{bmatrix} \cos(\phi) & -\sin(\phi) & 0 \\ \sin(\phi) & \cos(\phi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\boldsymbol{R}_y(\theta) := \begin{bmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) \end{bmatrix}$$

$$\boldsymbol{R}_x(\gamma) := \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\gamma) & -\sin(\gamma) \\ 0 & \sin(\gamma) & \cos(\gamma) \end{bmatrix}$$

$$\boldsymbol{Q}_z(s) := \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & s \end{bmatrix}$$

$$d(\boldsymbol{x}^r, \boldsymbol{x}^t) = \Big\| c\tau \boldsymbol{e}_x + \boldsymbol{R}_y(\theta^r)\boldsymbol{R}_z(-\phi^r)(\boldsymbol{x}_0^r - \boldsymbol{x}^r) + \boldsymbol{Q}_z(s)\boldsymbol{R}_x(\gamma^t)\boldsymbol{R}_y(\theta^t)\boldsymbol{R}_z(-\phi^t)(\boldsymbol{x}_0^t - \boldsymbol{x}^t) \Big\|$$

Parameters of Reflection Model

- Parameters we need to estimate for the reflection model:

$$(g_\ell, \tau_\ell, \phi_\ell^r, \theta_\ell^r, \phi_\ell^t, \theta_\ell^t, \gamma_\ell^t, s_\ell), \quad \ell = 1, \ldots, L$$

- g_ℓ : Complex path gain
- τ_ℓ : Path delay
- $\phi_\ell^r, \theta_\ell^r$: Angle of Arrival of the path at the receiver
- $\phi_\ell^t, \theta_\ell^t$: Angle of Departure of the path at the transmitter
- γ_ℓ^t : Rotation Angle of the reflection around X axis
- s_ℓ : Parity of number of reflections along the path

Measurement Methodology

Calibration

Tools and softwares

FR3 Transceiver (Pi-Radio)

- 2-channel MIMO Transceiver
- 6-24 GHz RF
- 1-6 GHz IF