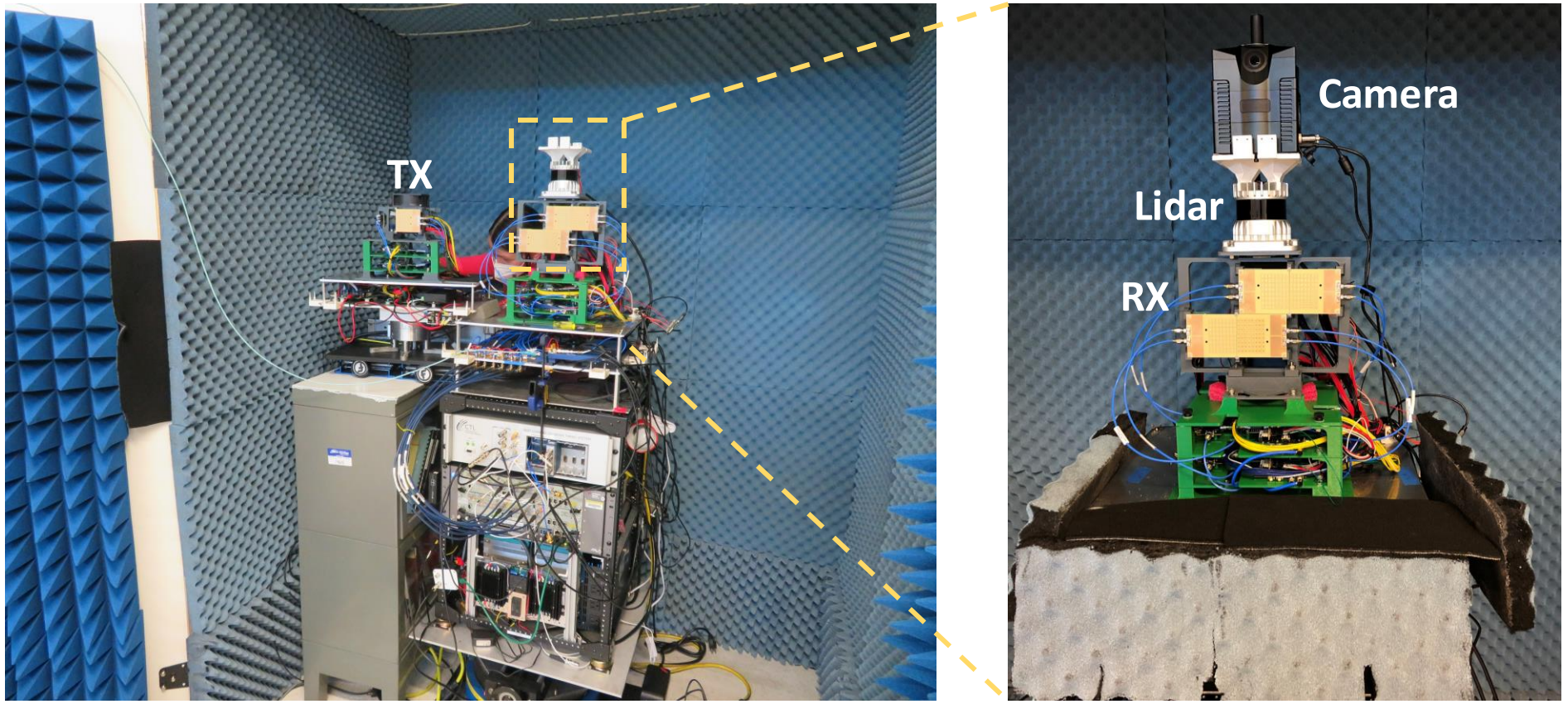
Human Sensing at mmWave and Sub-THz: NIST Channel Measurement and Modeling Methodologies

Radio Access and Propagation Metrology Group

National Institute of Standards and Technology (NIST), USA

28 GHz Context-Aware Channel Sounder

Tri-System

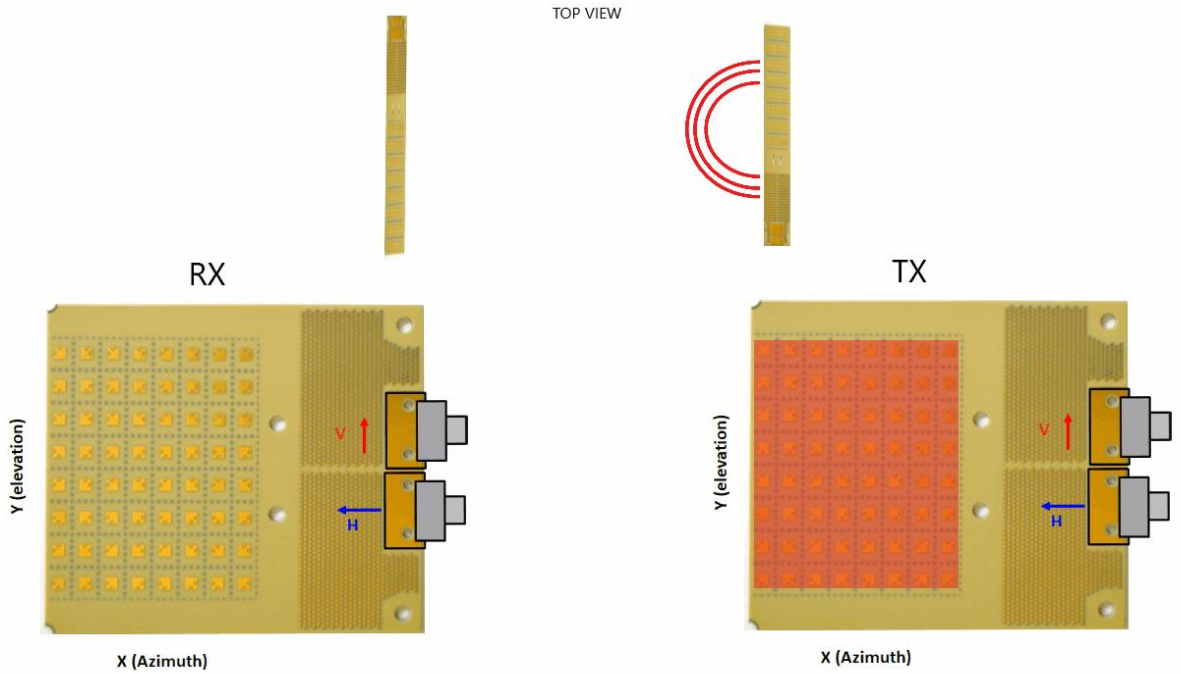


Monostatic configuration

RF
- 1 dual-polarized TX phase-array antenna board (64 microstrip antennas), synthesized into quasi-omnidirectional V and H patterns
- 4 dual-polarized RX phased-array antenna boards (256 microstrip antennas) – “Tetris” configuration – have 5.2° EL and 3.7° AZ beamwidths
- Optical cable use for phase synchronization between TX and RX
- 2 GHz bandwidth

- 360° (AZ) camera
- 360° (AZ) lidar

Switched Beamforming



Analog beamforming:

- 6-bit phase precision per antenna: coarse beams, limited tapering, cannot compensate for hardware non-idealities
- Takes 3.5 µs to write to each antenna register to change phase
- Takes 3.5 µs x 64 antennas ≈ 0.23 ms to form a single beam
- Takes 4 s to sweep 1800 beams (finest angular precision)

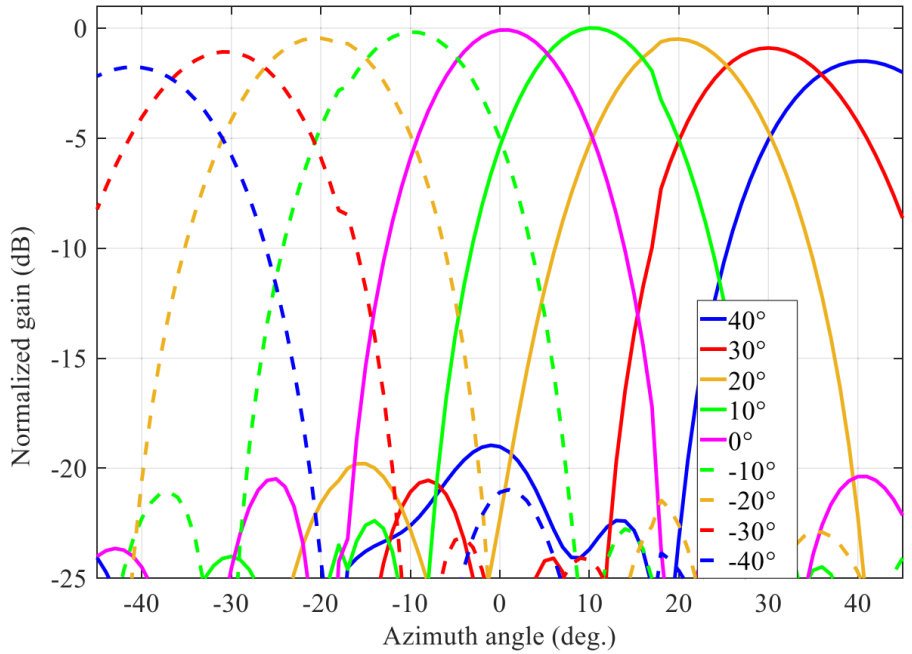
Switched beamforming[1]:

- Effectively infinite phase precision: ideal beams, Kaiser tapering, can compensate for hardware non-idealities
- Takes 3.5 µs to write to each antenna register to toggle on/off
- Takes 3.5 µs x 64 ≈ 0.23 ms to switch through all antennas
- Takes 0.23 m to sweep 1800 beams

[1] Caudill, Derek, et al. "Real-time mmWave channel sounding through switched beamforming with 3-D dual-polarized phased-array antennas." IEEE Transactions on Microwave Theory and Techniques 69.11 (2021): 5021-5032.

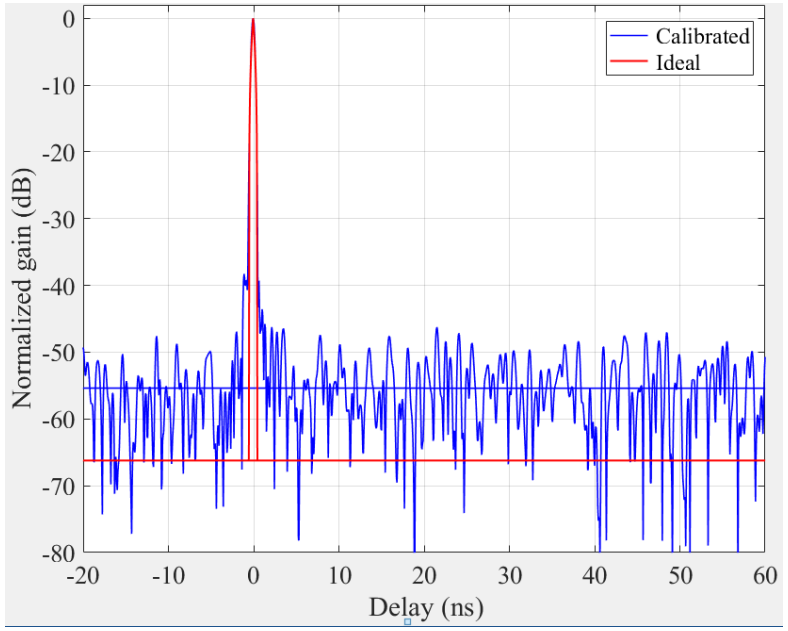
RF Measurement Error

Switched beamforming gives quasi-ideal beams and 18 dB sidelobe suppression in AZ and EL domains with Kaiser taper

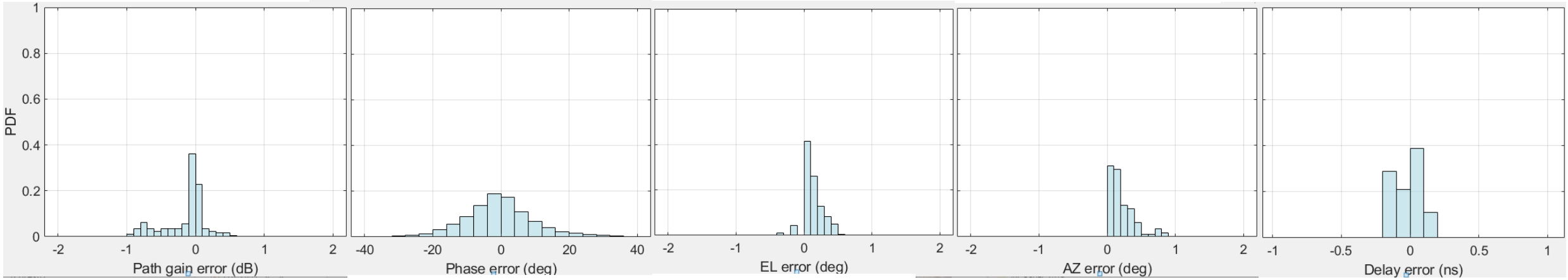


accuracy
resolvability

Pre-distortion filtering to de-embed RF fronts ends gives 47 dB sidelobe suppression in the delay domain



Domain error based on ground-truth LoS path:



Use Case: Gesture Recognition

Measurement Campaign

80 cases:

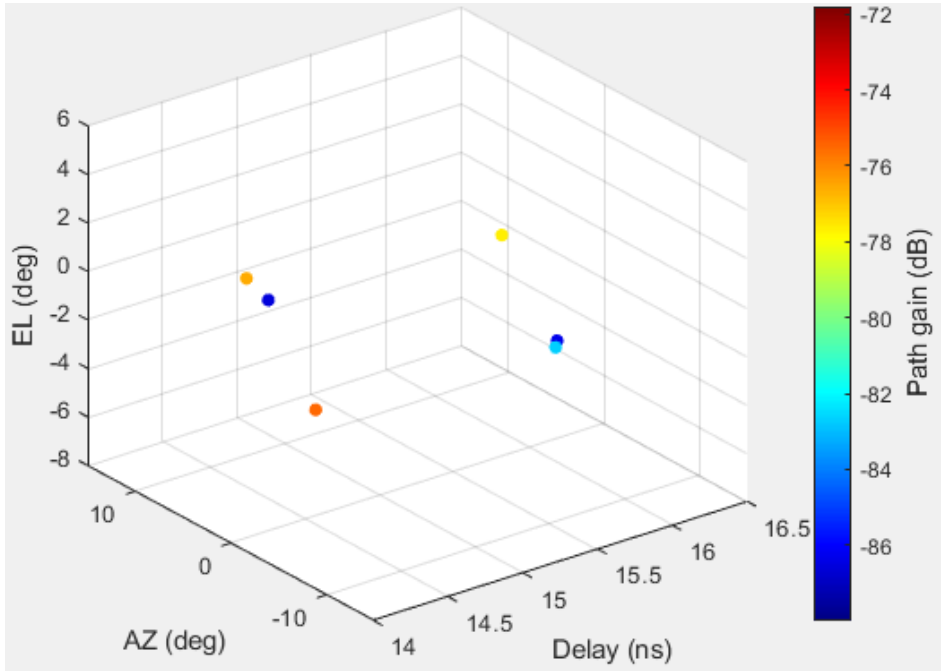
- 20 motions:
  - 16 hand gestures (while sitting):
    - 4 hand motions (up, down, left, right)
    - 2 hands moving simultaneously
  - 4 body motions:
    - Standing up
    - Sitting down
    - Standing still
    - Sitting still
- 4 human subjects
  - A: 168 cm, female
  - B: 160 cm, female
  - C: 169 cm, male
  - D: 179 cm, male

- Tri-system sampled in time at 2.6 ms over 3.9 s (1500 time samples)

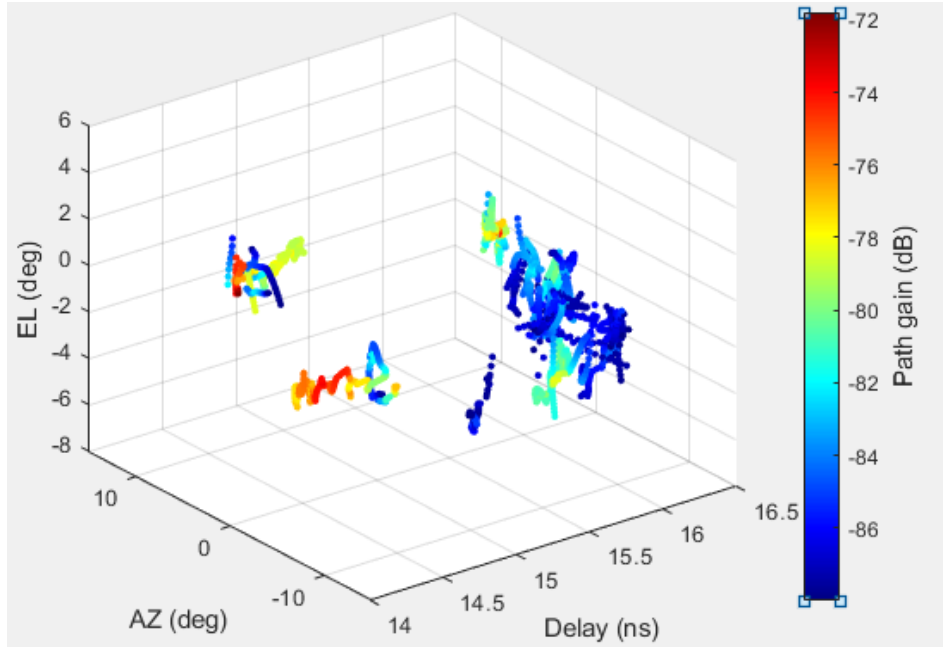
MPCs from RF

- One RF time sample consists of 256 phase-synchronized complex CIRs captured in 0.5 ms
- The 256 CIRs are synthesized through the SAGE super-resolution to extract discrete MPCs indexed in path gain, phase, delay, azimuth AoA, and elevation AoA
  - Super-resolution algorithms nominally provide 5x the resolution of inherent beamwidth/beamwidth
- SAGE also de-embeds the microstrip antenna/ beam gain patterns so that the MPC properties reflect the channel alone (not the channel + the hardware)

MPCs extracted from one time

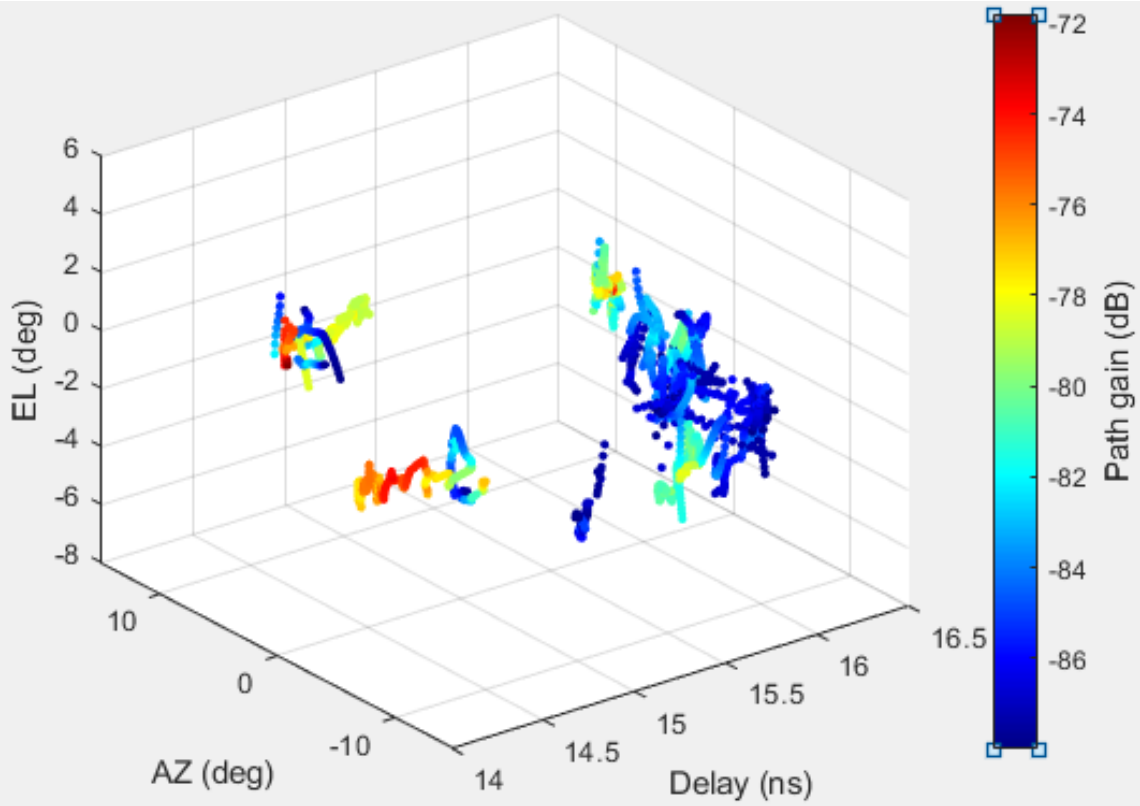


MPCs aggregated over time

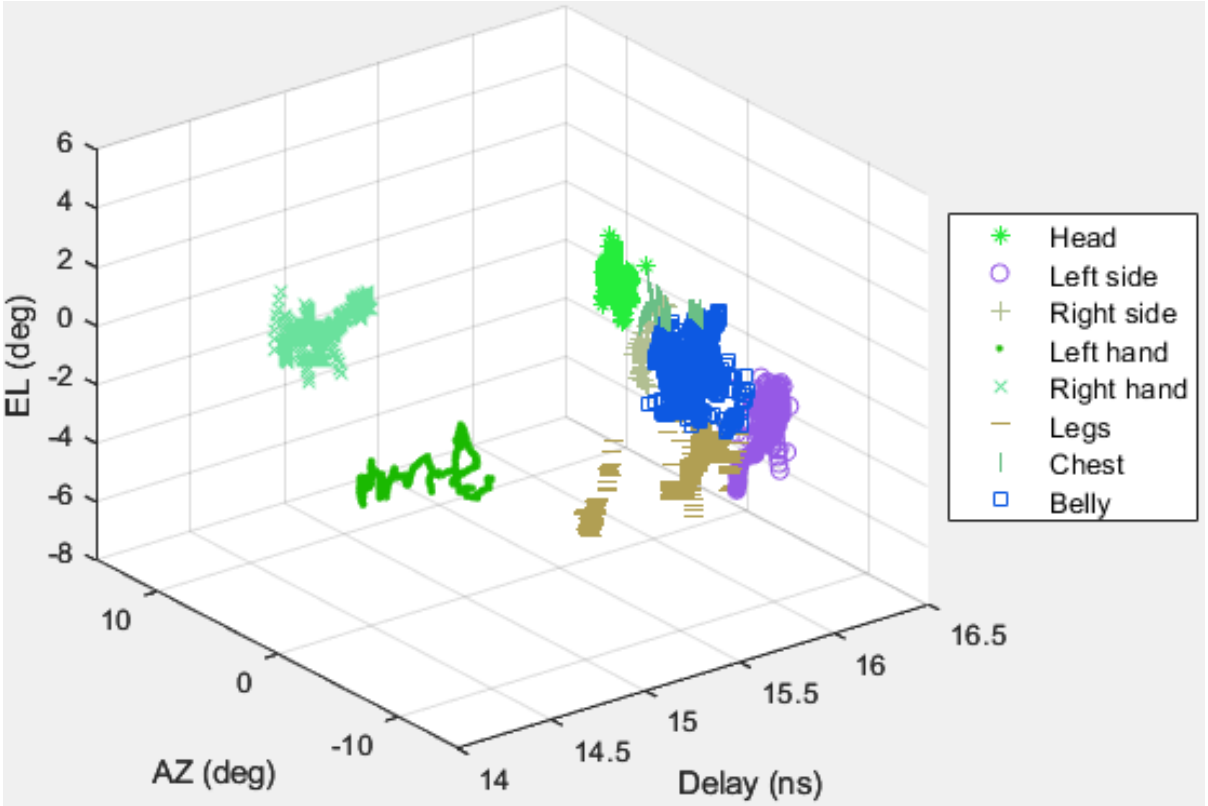


Time Clustering

MPCs aggregated over time



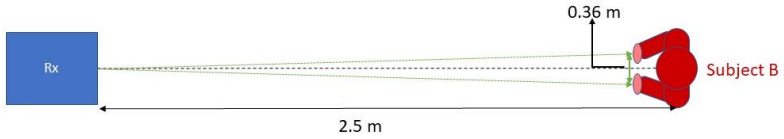
MPCs clustered over time



- MPCs are clustered jointly in the path gain, EL, AZ, delay, and time domains[2]
  - Clustering is conventionally processed just in the path gain, EL, AZ, and/or delay domains
  - Augmenting to the time domain not only increases resolvability and robustness, it also makes spatial/temporal consistency a byproduct of the clustering process
- Eight body parts can be consistently resolved over the 80 cases

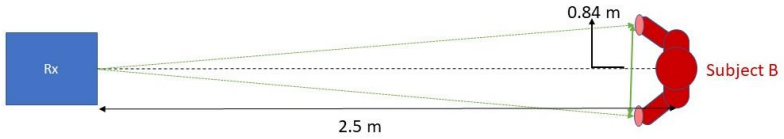
[2] Varshney, Neeraj, et al. "Quasi-deterministic channel propagation model for an urban environment at 28 GHz." *IEEE Antennas and Wireless Propagation Letters* 20.7 (2021): 1145-1149.

RF Signature



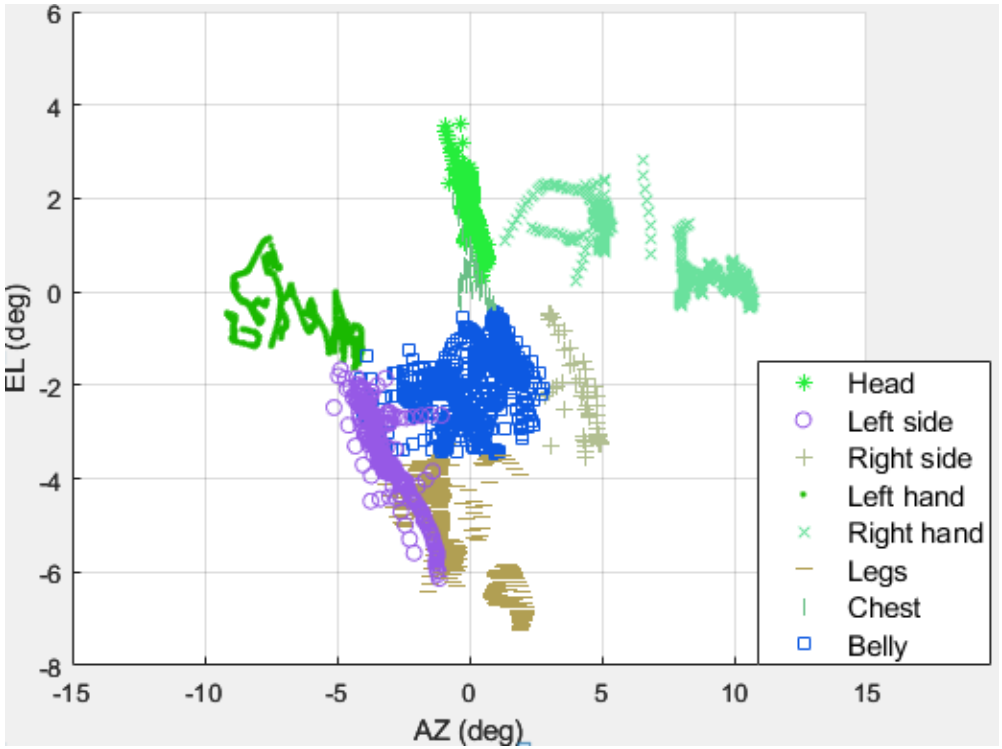
The black dotted line refers to the center of the head i.e. AOA = 0°
The distance between hands (center to center) is 0.36 m.

$\theta_{Left\_hand} = -4.1181°$
$\theta_{Right\_hand} = 4.1181°$

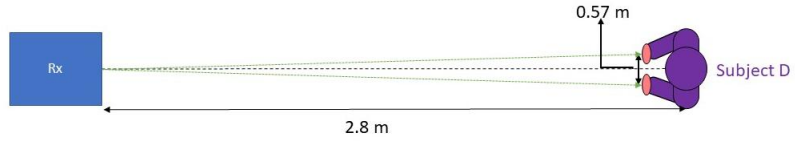


The distance between hands (center to center) is 0.84 m.

$\theta_{Left\_hand} = -9.5366°$
$\theta_{Right\_hand} = 9.5366°$

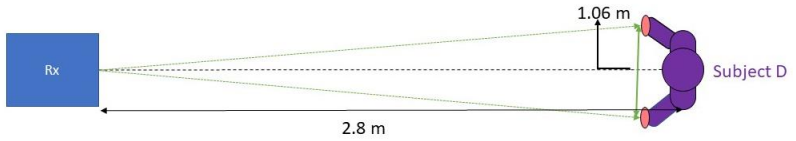


160 cm, female



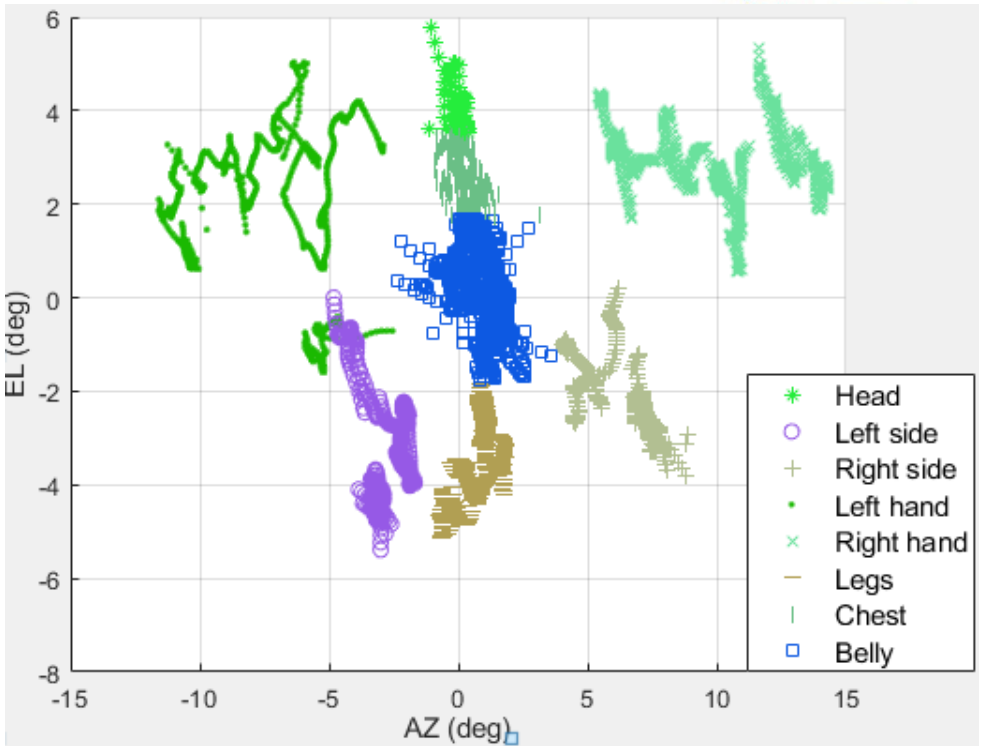
The black dotted line refers to the center of the head i.e. AOA = 0°
The distance between hands (center to center) is 0.57 m.

$\theta_{Left\_hand} = -5.8118°$
$\theta_{Right\_hand} = 5.8118°$



The distance between hands (center to center) is 1.06 m

$\theta_{Left\_hand} = -10.7184°$
$\theta_{Right\_hand} = 10.7184°$



179 cm, male

Keypoints from Camera/Lidar

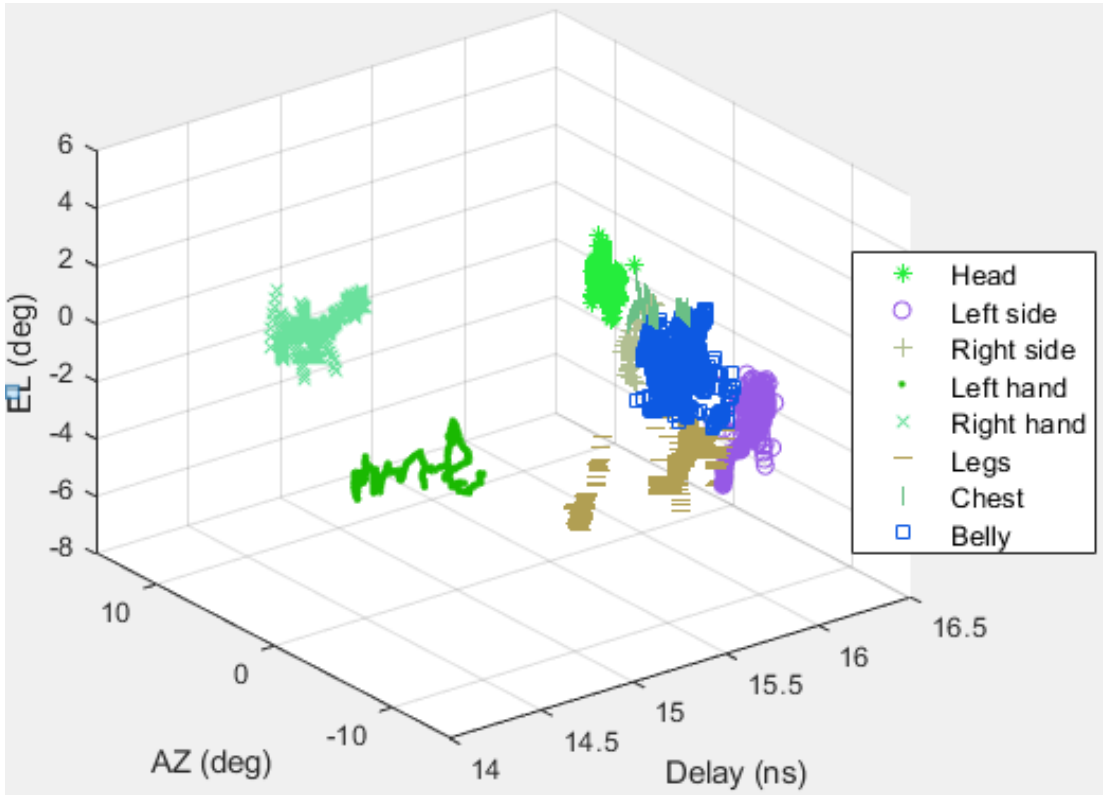
Camera time sample

Lidar time sample

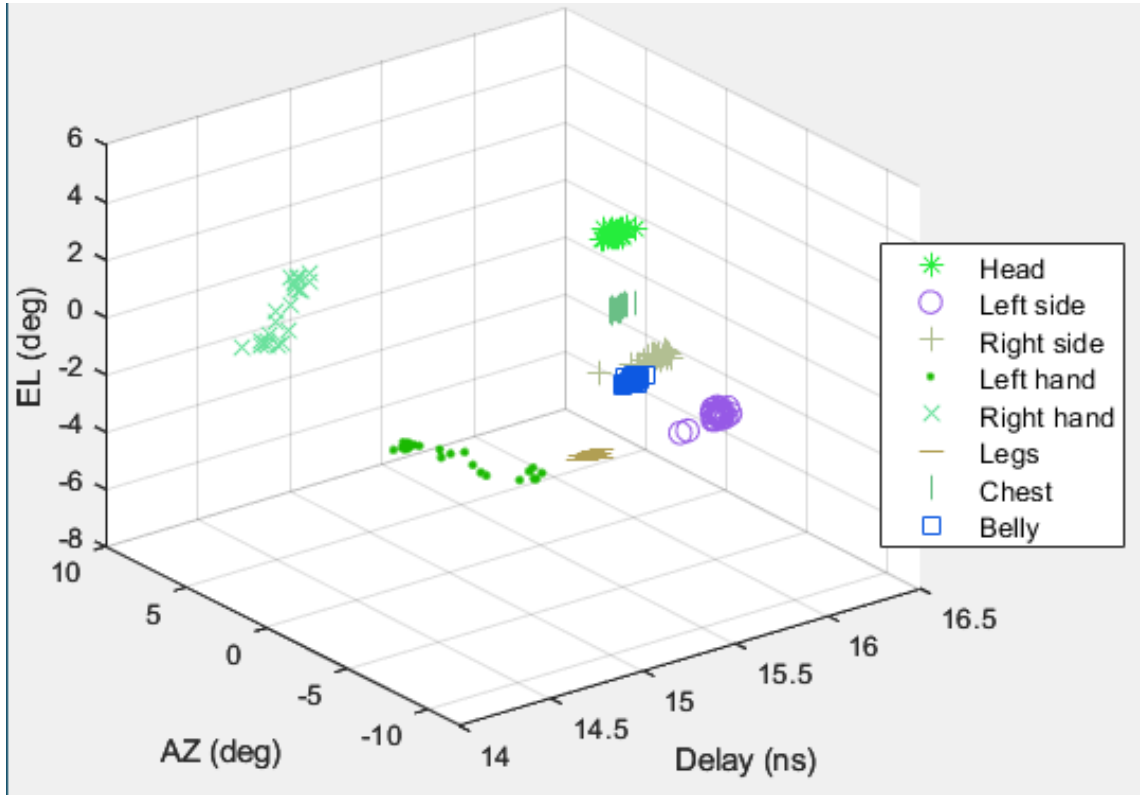
- 2D keypoints (EL, AZ) are extracted from camera samples
  - 17 keypoints based on salient body features (hands, knees, shoulders, etc.)
  - Machine-learning based algorithm
- Camera and lidar images are combined to convert 2D keypoints to 3D keypoints (EL, AZ, delay)

MPCs vs. Keypoints

MPCs clustered over time



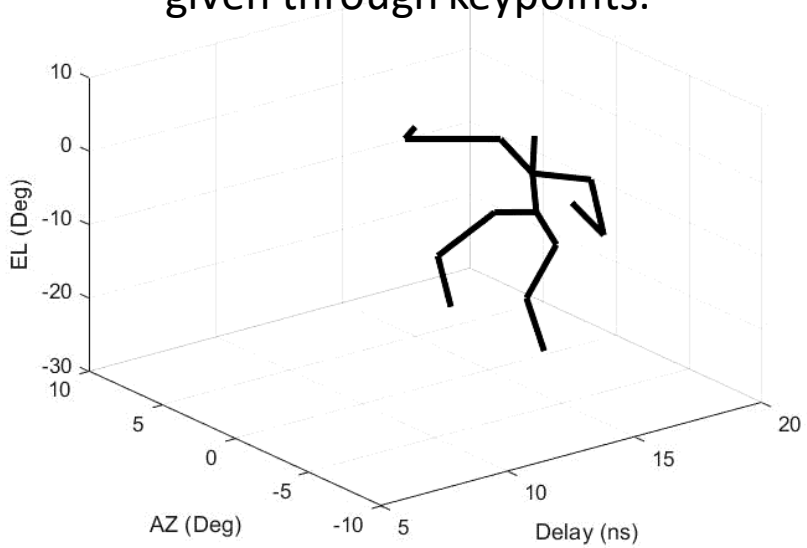
Keypoints clustered over time



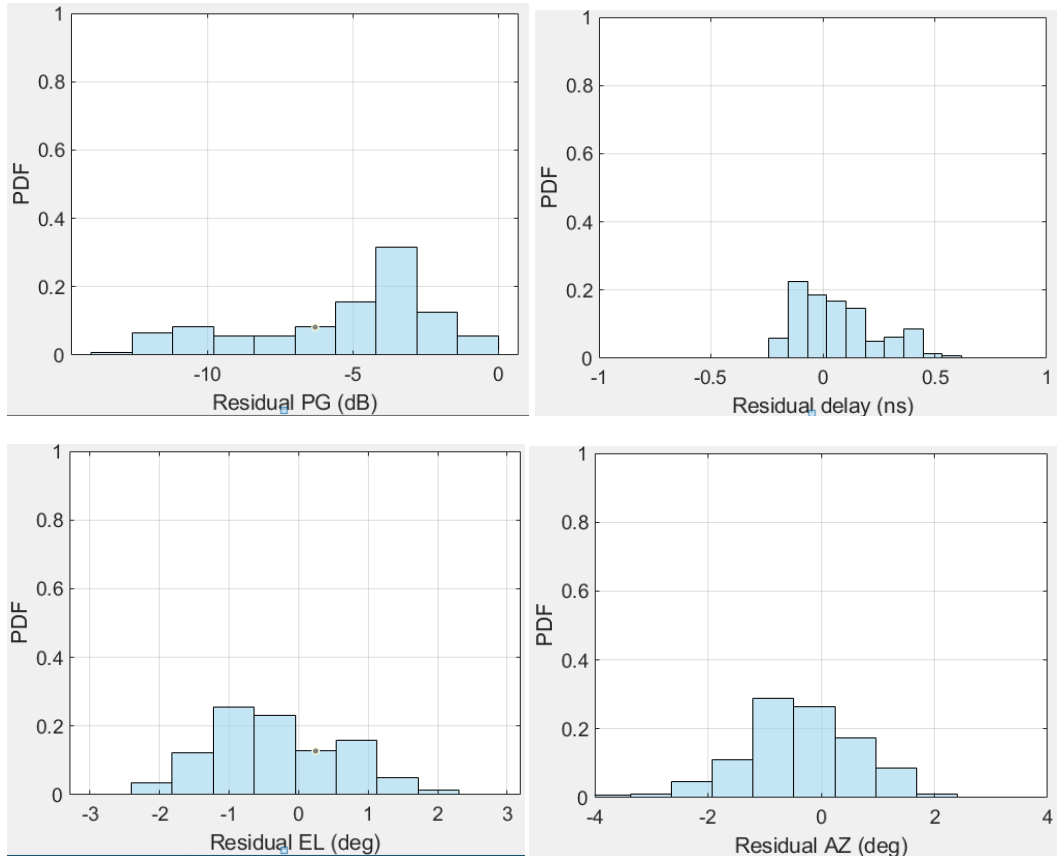
Temporal and spatial (EL, AZ, delay) calibration in tri-system paramount!

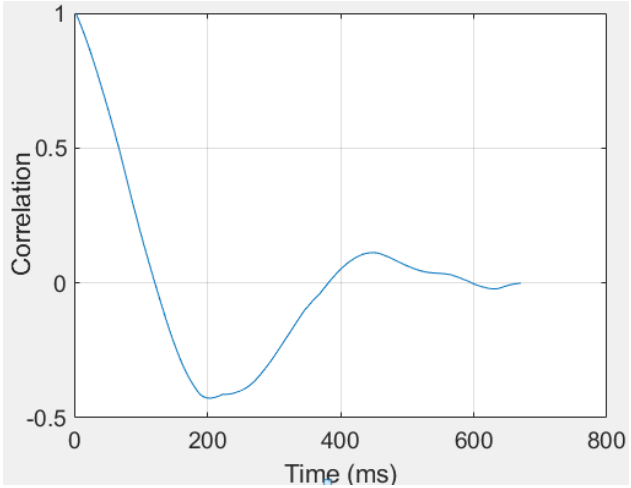
Quasi-Deterministic Channel Model

Deterministic component given through keypoints:



Stochastic component given through residual between cluster centroid per and keypoint (per time):





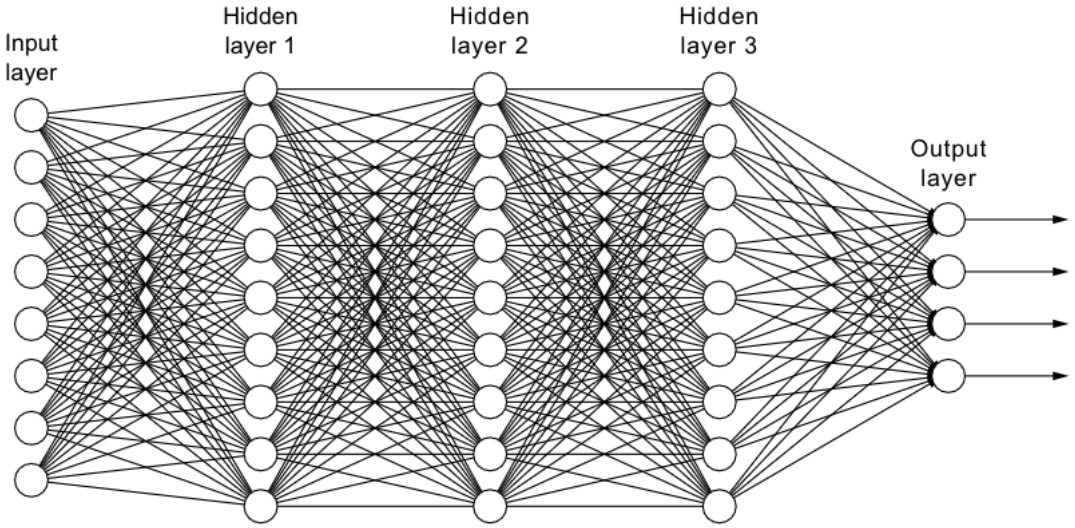
Spatial/temporal consistency given as a Sum-of-Sinusoid (SoS) process:

Stochastic component and spatial/temporal consistency parameters can be body-part and/or human-subject specific (or simply aggregate)

Machine-Learning Based Applications

Channel modeling:

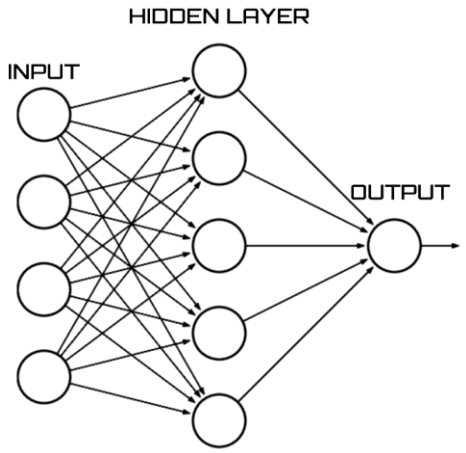
keypoints



MPCs

Classification:

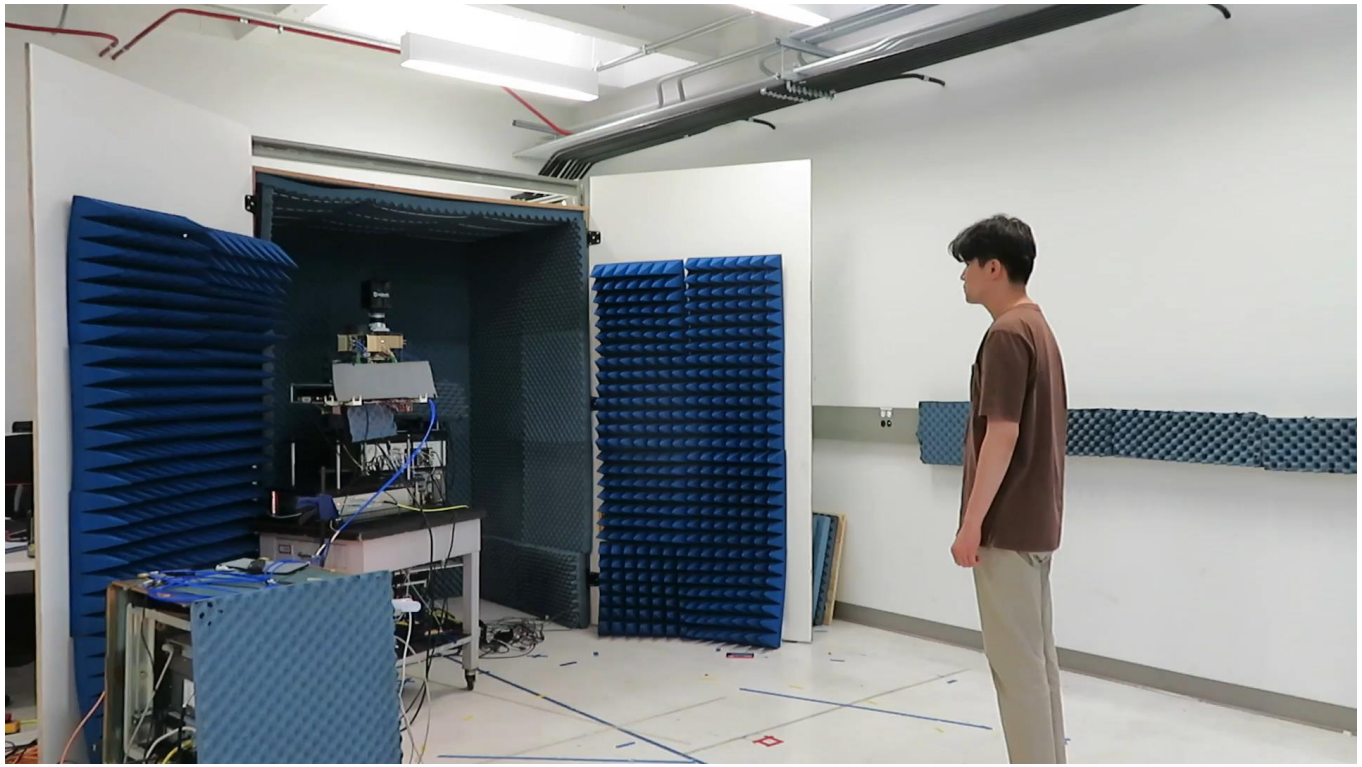
MPCs aggregated over time



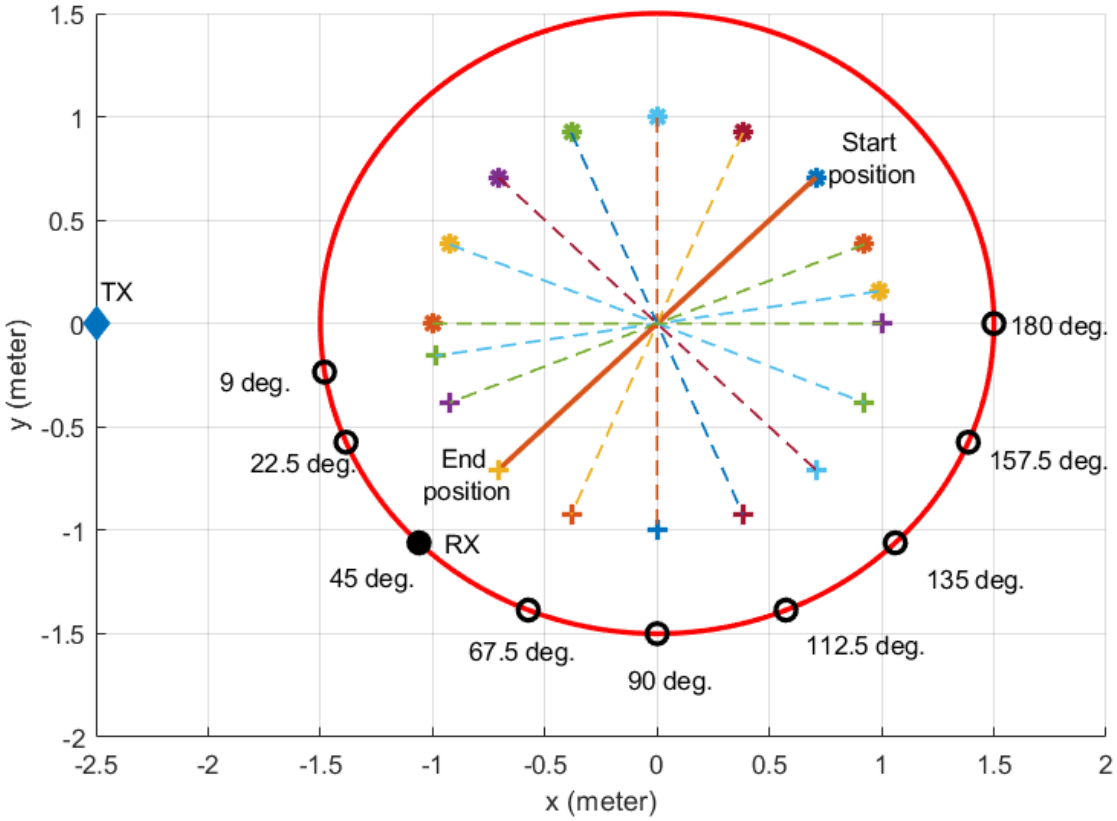
motion class

Use Case: Gait Recognition

Measurement Campaign

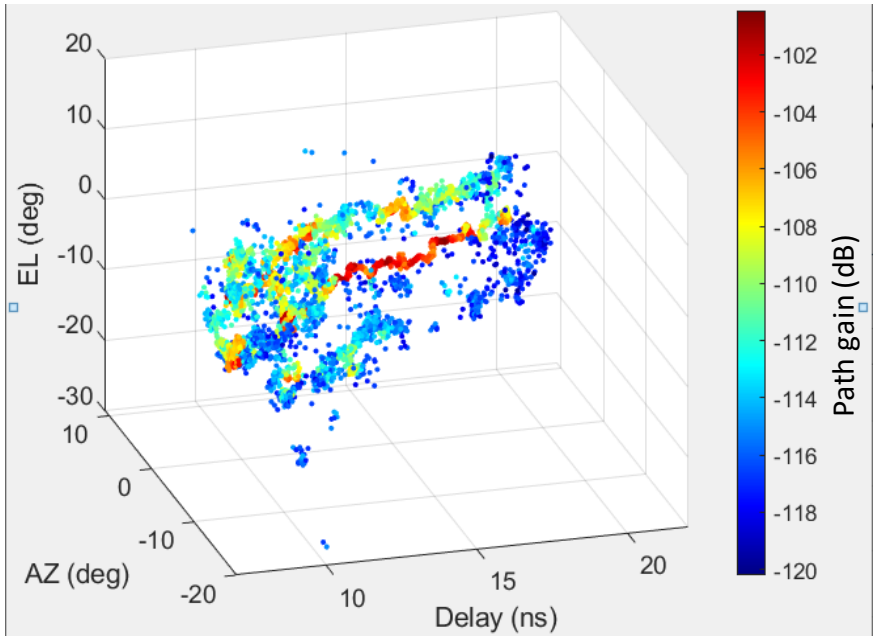


Bistatic configuration



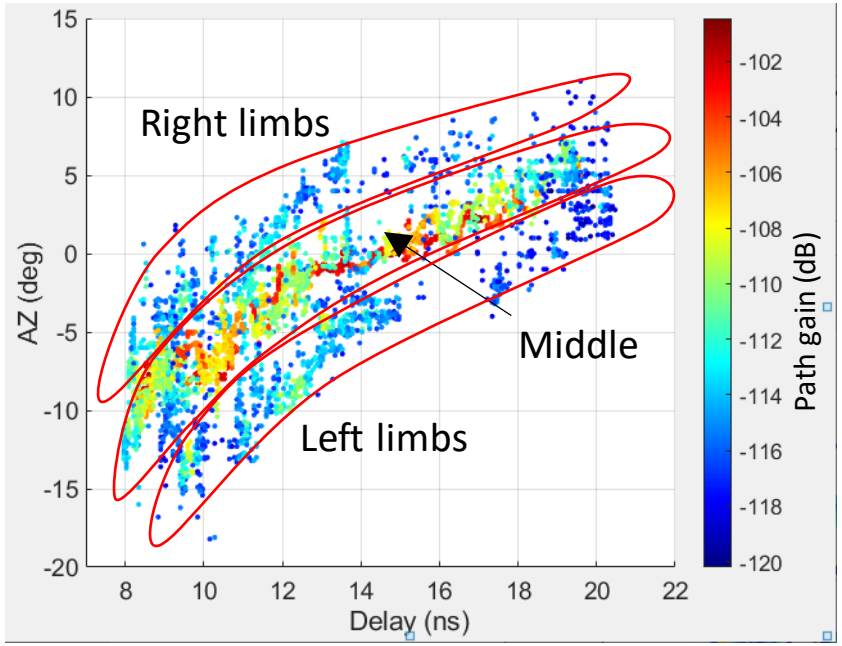
9 cases (bistatic angles) by moving TX

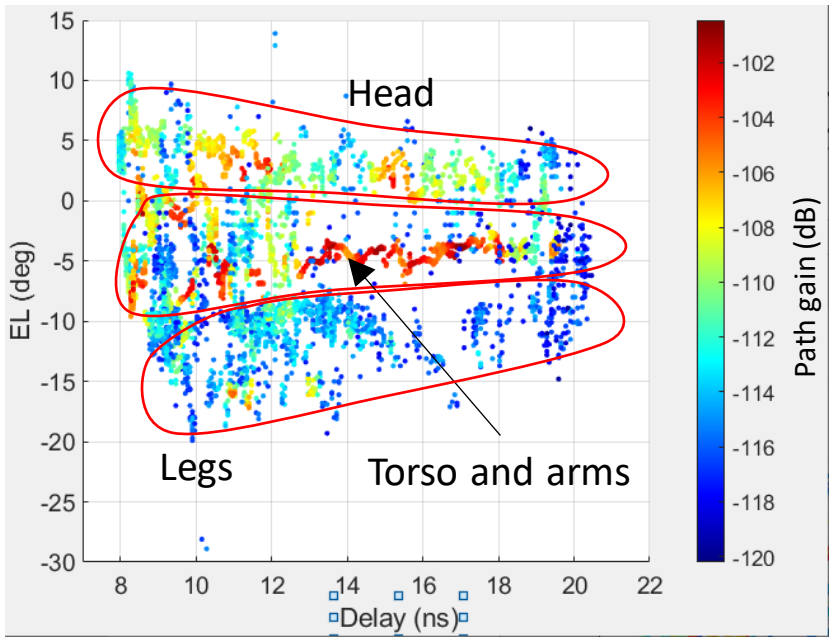
MPC Properties



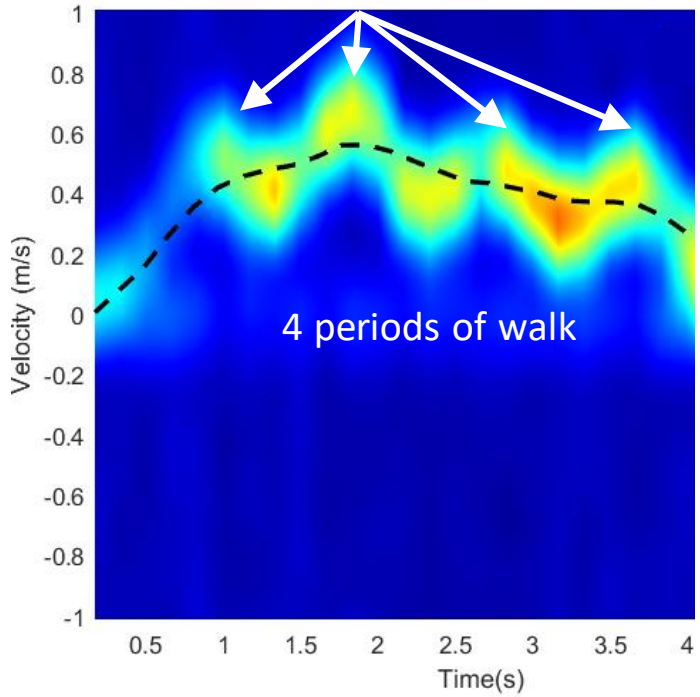
3D view

2D (top) view





2D (side) view

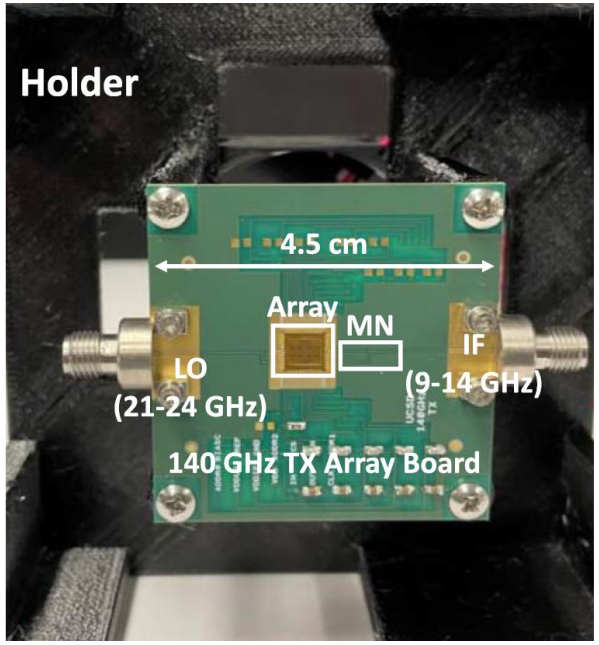


Doppler spectrum

140 GHz Channel Sounder

- 28 GHz: 2 GHz bandwidth
  -> 140 GHz: 20 GHz bandwidth
- 28 GHz: 3.7 AZ beamwidth
  -> 0.74 AZ beamwidth
- Sign language recognition

140 GHz phased-array antennas
(Rebeiz @ UCSD)



Keysight M8199A AWG

Keysight UXR0404AP digitizer