ThruMapper:

Through-Wall Building Tomography with a Single Mapping Robot

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Change the world

Indoor Positioning & Mapping

- Evolving technology
  - Radio waves
  - Magnetic fields
  - Acoustic signals
  - Other sensors

- Facilitating indoor navigation applications
  - Museums
  - Shopping malls
  - Office buildings
  - Transport hubs

King's Cross Station, London

Navigation path from a train platform to a shop

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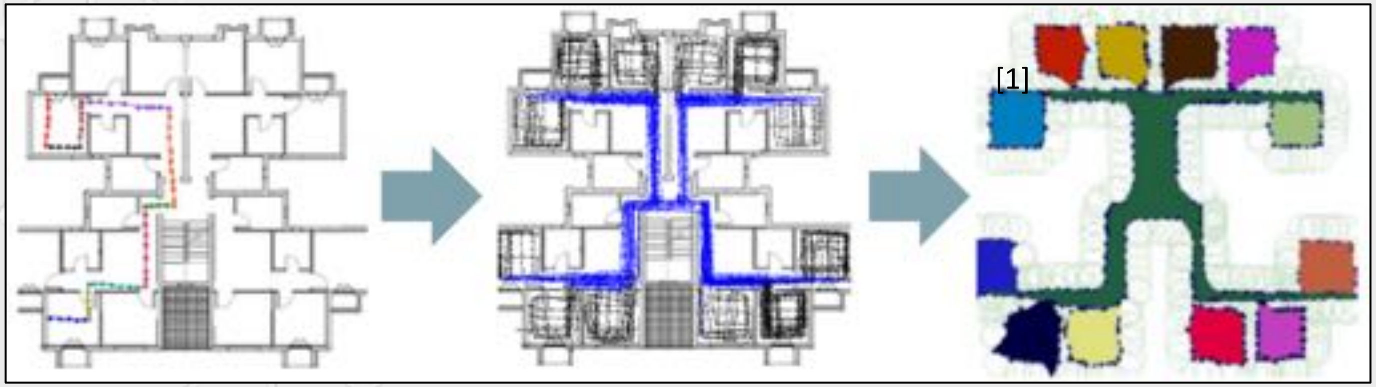
- What use is a navigation path without a map?

King's Cross Station, London

Navigation path from a train platform to a shop

Current Indoor Mapping Techniques

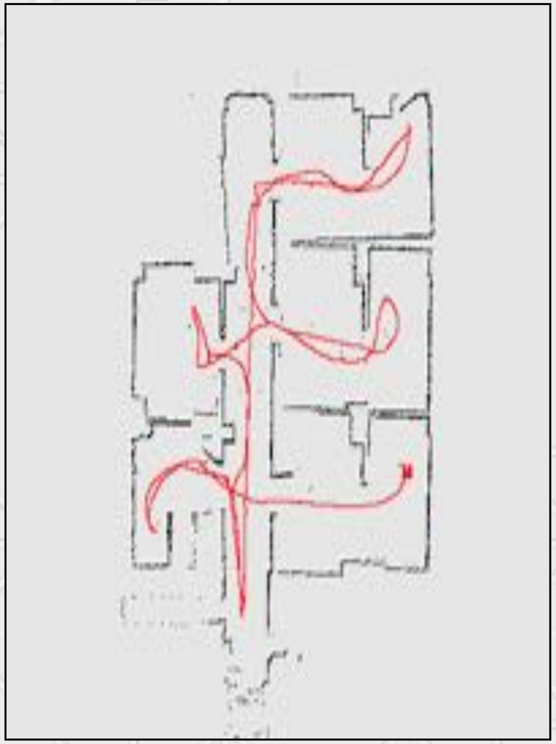
- Digital maps & floor plans
  - Detailed and up-to-date but only available for new buildings
- Crowdsourcing Information
  - Aggregating movement trajectories from mobile sensors
  - Requires high user density

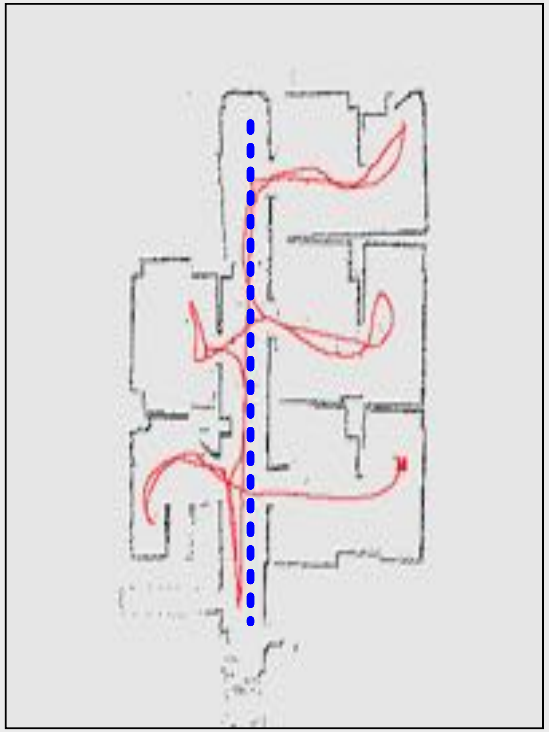


[1] M. Alzantot and M. Youssef. Crowdinside: Automatic construction of indoor floorplans. Advances in Geographic Information Systems, 2012

Current Indoor Mapping Techniques

- LiDAR, Camera SLAM
  - High resolution map generation
  - Requires access to every room/location to be mapped



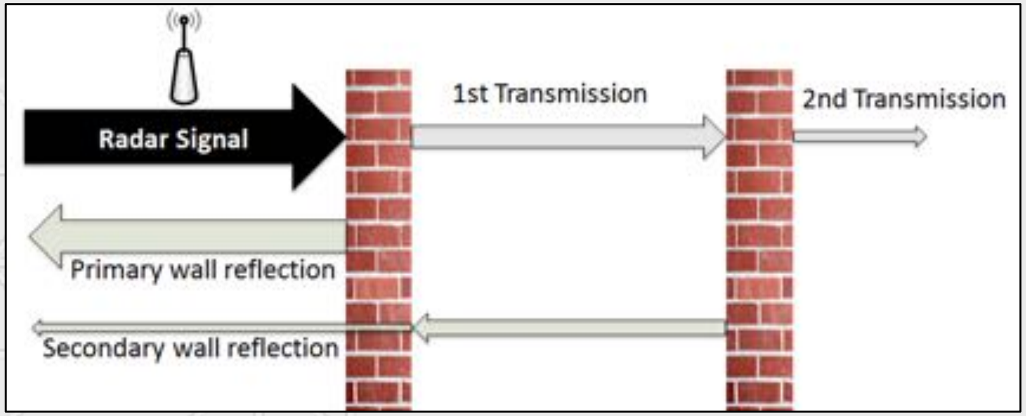


Making a map without traversal of all rooms ?

[1] M. Alzantot and M. Youssef. Crowdinside: Automatic construction of indoor floorplans. Advances in Geographic Information Systems, 2012

SAR Radar Based Solution

- Wall Penetration
  - Overcomes room access and line-of-sight obscuration issues
  - Signal suffers attenuation as signal traverses through a wall
- Distance measurement
  - Range resolution inversely proportional to signal bandwidth
  - Will need very wide bandwidth for a reasonable indoor applications

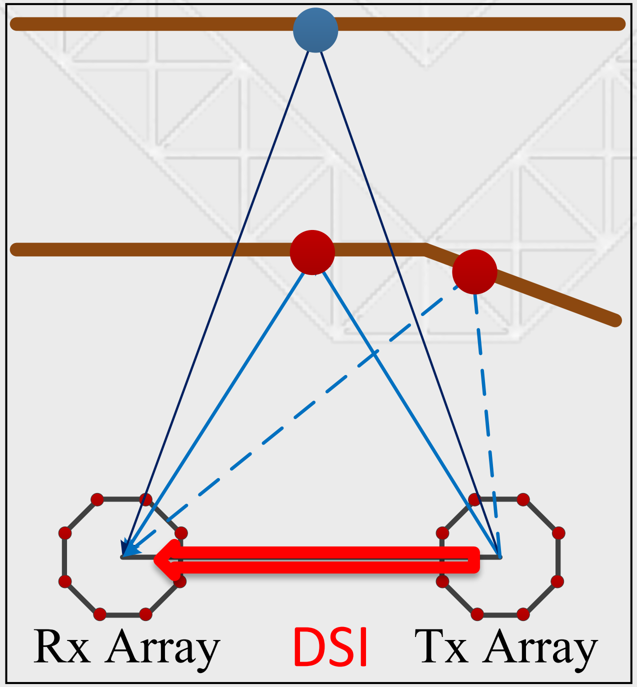


$$\Delta R = \frac{c}{2B}$$

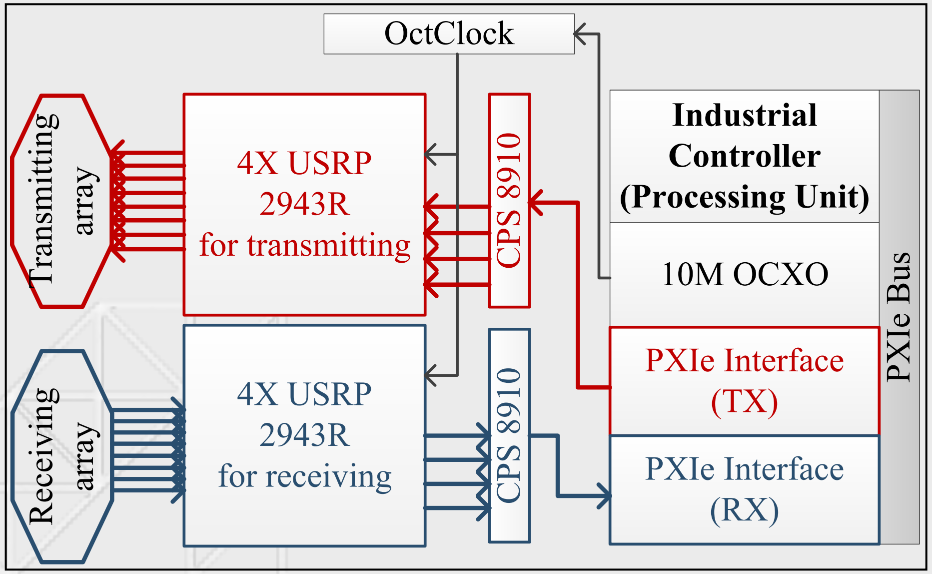
ThruMapper – Concept Radar

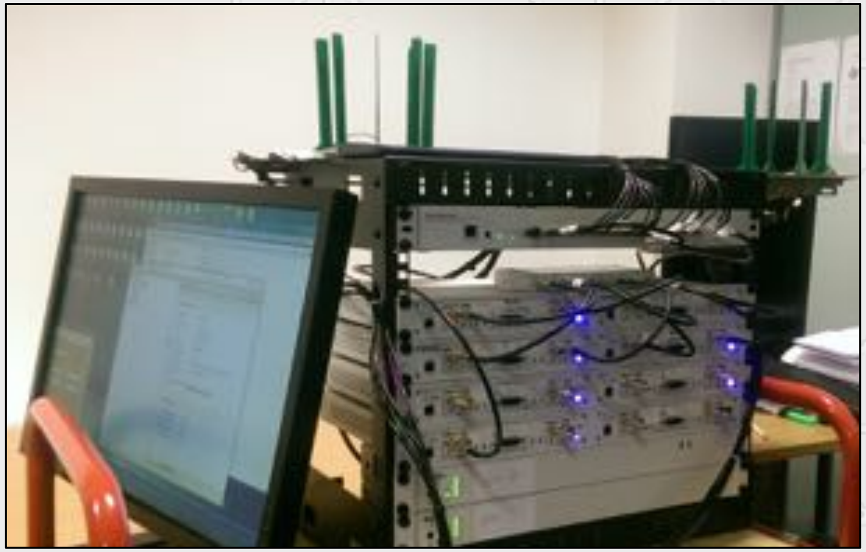
Phased Array Through-Wall Imaging Radar

- A Moving/Rotating Platform
  - Move through an area (e.g. corridor)
  - Identify signal reflections from LoS and NLoS walls
  - Including non-parallel walls
- Distance Measurement
  - High accuracy time delay estimation based wideband OFDM symbols
- Angle Measurement
  - Uniform circular phased array (UCA) antennas
  - **TX Array:** Probes walls from different angles through beam steering
  - **RX Array:** Identifies the position of every reflection point on the wall of interest
- Full-duplex (short distance)
  - No TX/RX switching
  - Subject to direct signal interference *[Major Issue]*



ThruMapper Hardware





- Hardware: USRPs + PXI Architecture
- Software: Labview
- Technical Specs:
  - Operational Band: 2.4GHz ISM Band
  - Tx and Rx Uniform Circular Arrays: 8-element Phocus Array (x2)
  - Bandwidth: 120 MHz for all 16 channels

Enabling Strategies & Signal Processing Techniques

Joint Angle-Delay Estimation

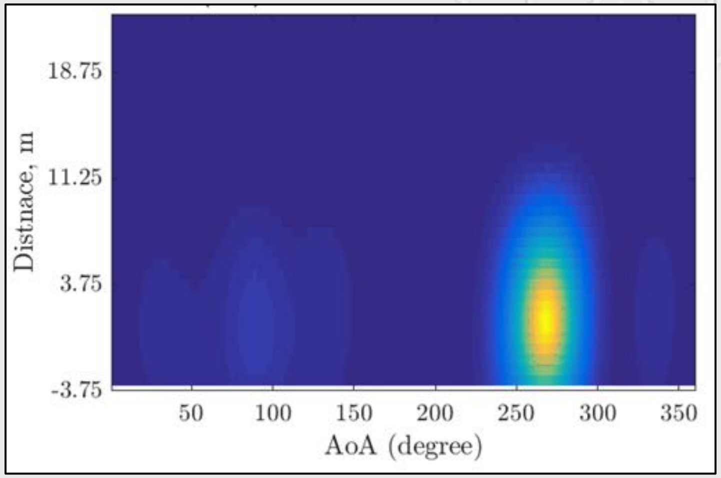
- JADE
  - Subspace technique for joint time delay and angle estimation
  - Extension of the well-known MUSIC algorithm
  - Angle-time manifold:

$$u(\theta,\tau) = a(\theta) \otimes g(\tau)$$

$\otimes$ is Kronecker product

$a(\theta)$ → Azimuth steering vector
$g(\tau)$ → Time delay manifold

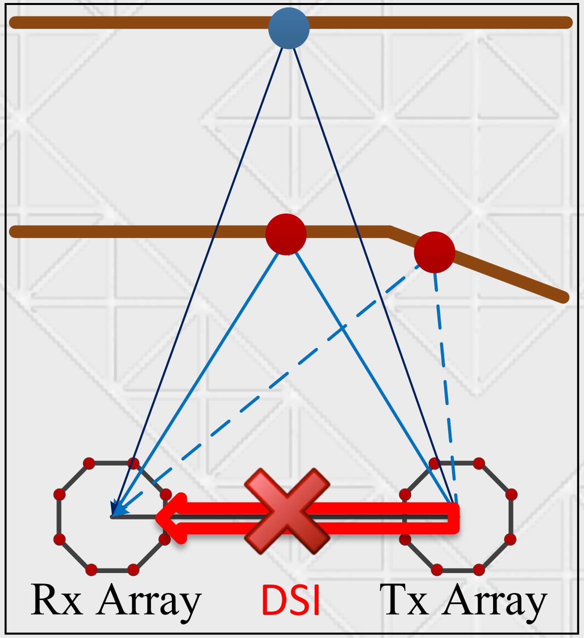
- Subspace Search
  - 2D search on the time and angle spans
  - $P(\theta,\tau) = \frac{u^*(\theta,\tau) \cdot u(\theta,\tau)}{u^*(\theta,\tau) \cdot E_N \cdot E_N^* \cdot u(\theta,\tau)}$
  - E_N is noise space



Angle-Delay (JADE) surface, $P(\theta,\tau)$

Direct Signal Interference (DSI)

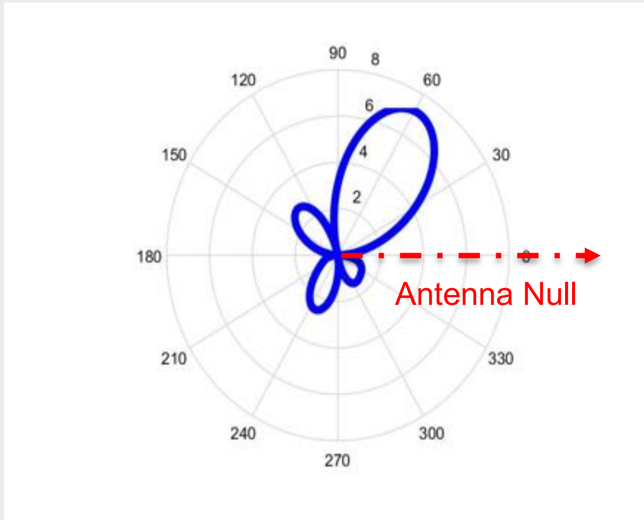
- Problematic
  - Mask the weak echoes from primary and secondary walls
  - Imposes a large dynamic range requirement on the receiver ADC
  - Saturate the receiver electronics



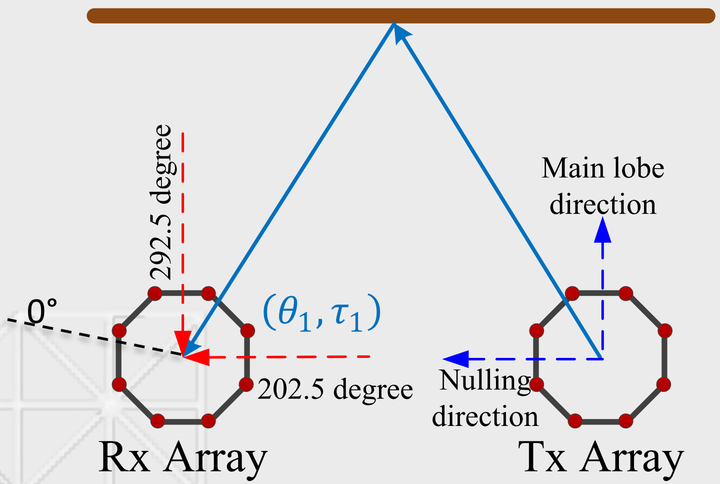
Interference Mitigation Strategy

- On Transmitting Array: ***Beam/Null Steering***
  - Antenna-null is steered to the receiver
  - Main lobe scans other directions
- On Receiving Array: ***Linear Projection***
  - Cancel signals from unwanted range and angle

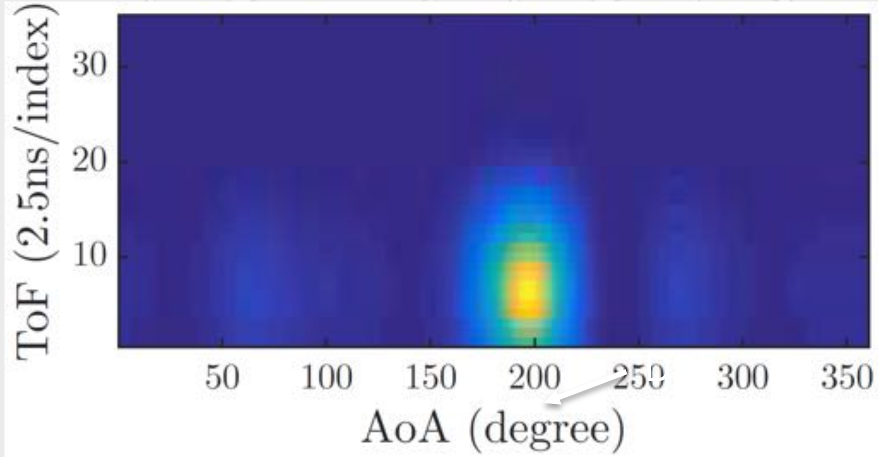
Transmit Array



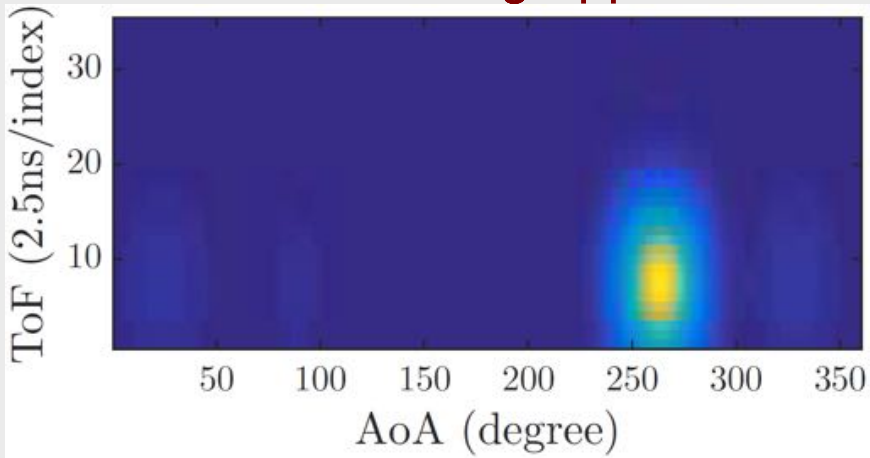
Transmit Nulling Experiment



No Transmit Nulling



Transmit Nulling Applied



DSI: Tx array is ~202^o bearing from Rx array

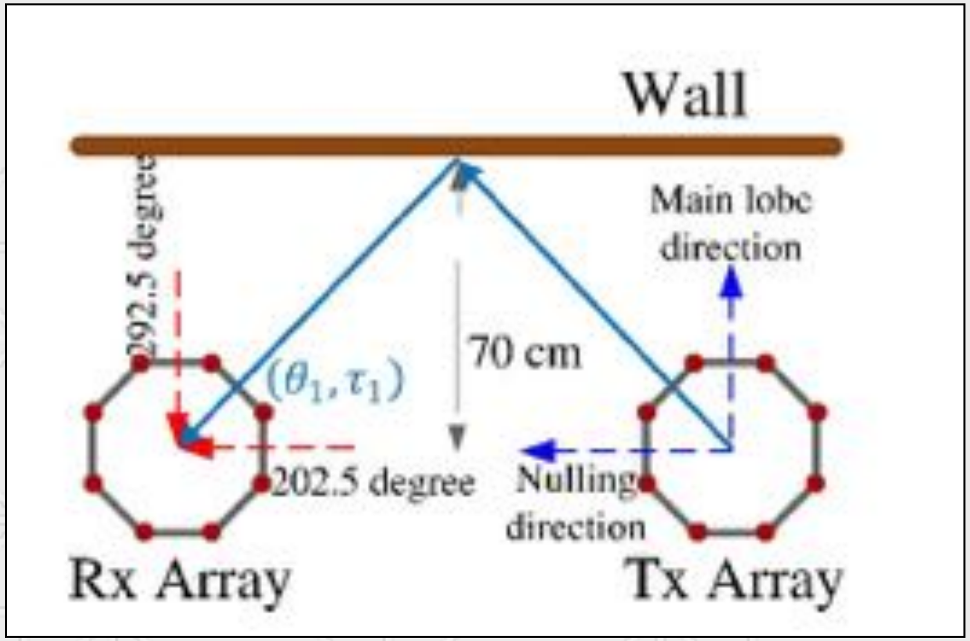
Wall Reflection: Strongest scattering point of wall is equidistant between the Tx and Rx array

$$\theta_1 = 264^o$$

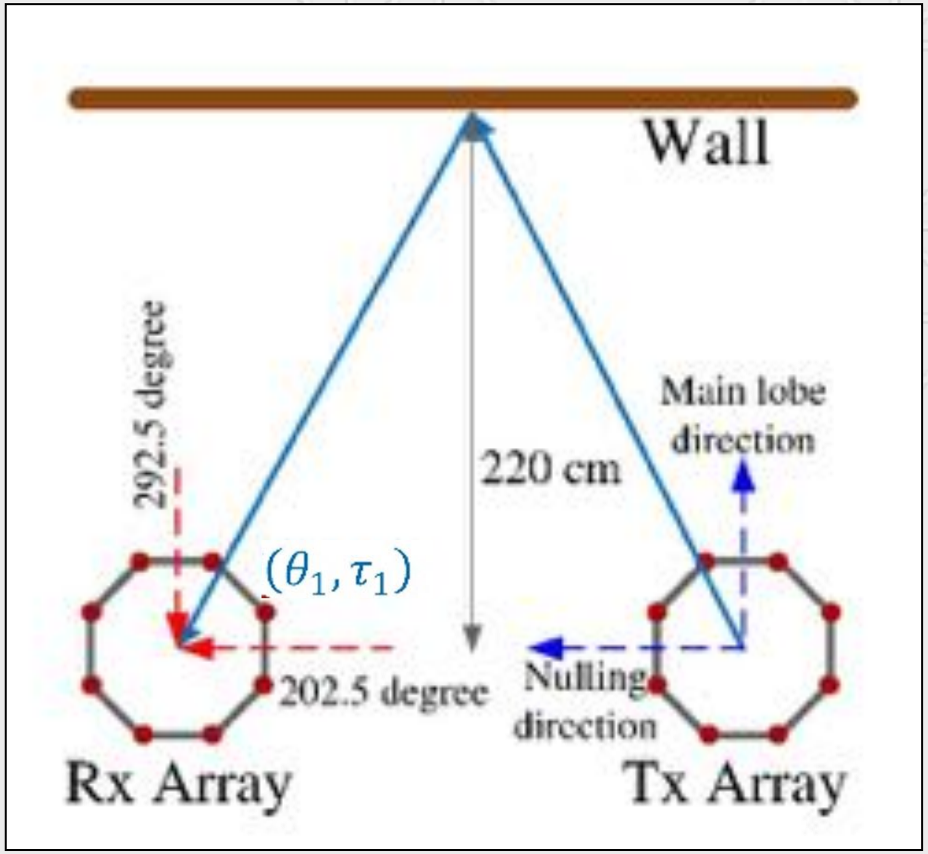
*ToF difference between DSI and wall reflection path is 2.5 ns ~ 75 cm

System Characterisation using LoS Wall

Close



Standoff



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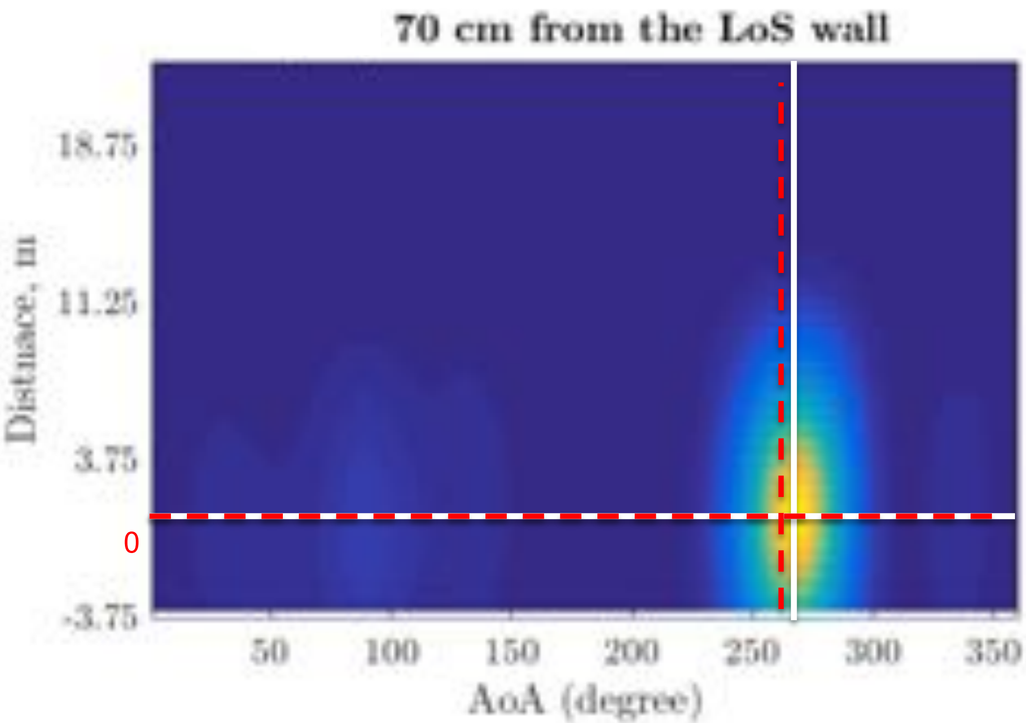

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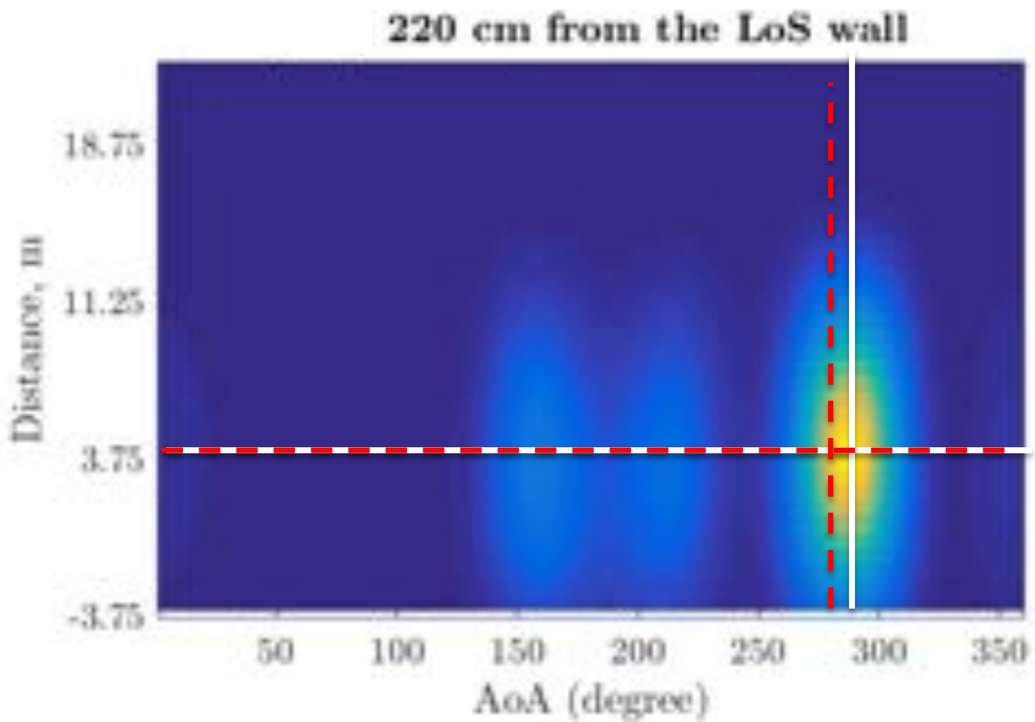
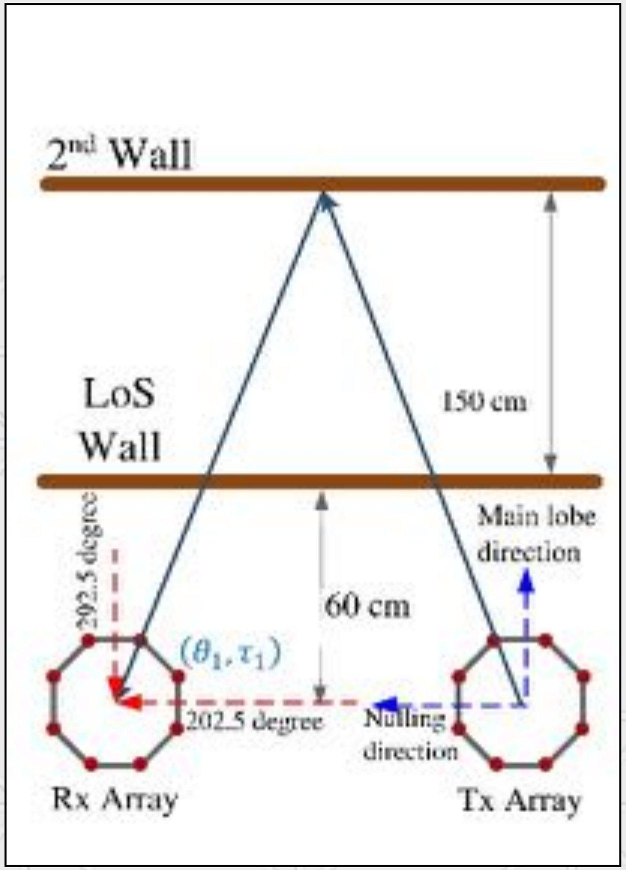
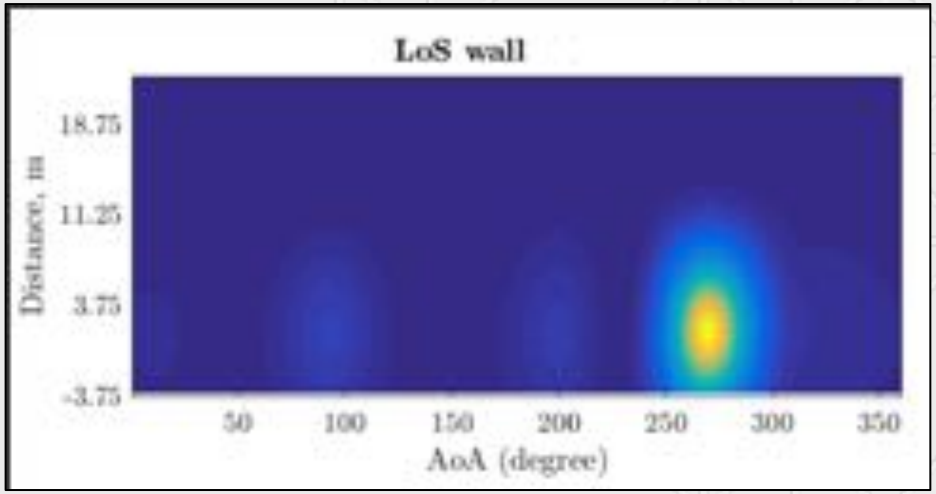


Key:
- - - - - - Ground Truth
——— Measured Data

Detecting Secondary Walls





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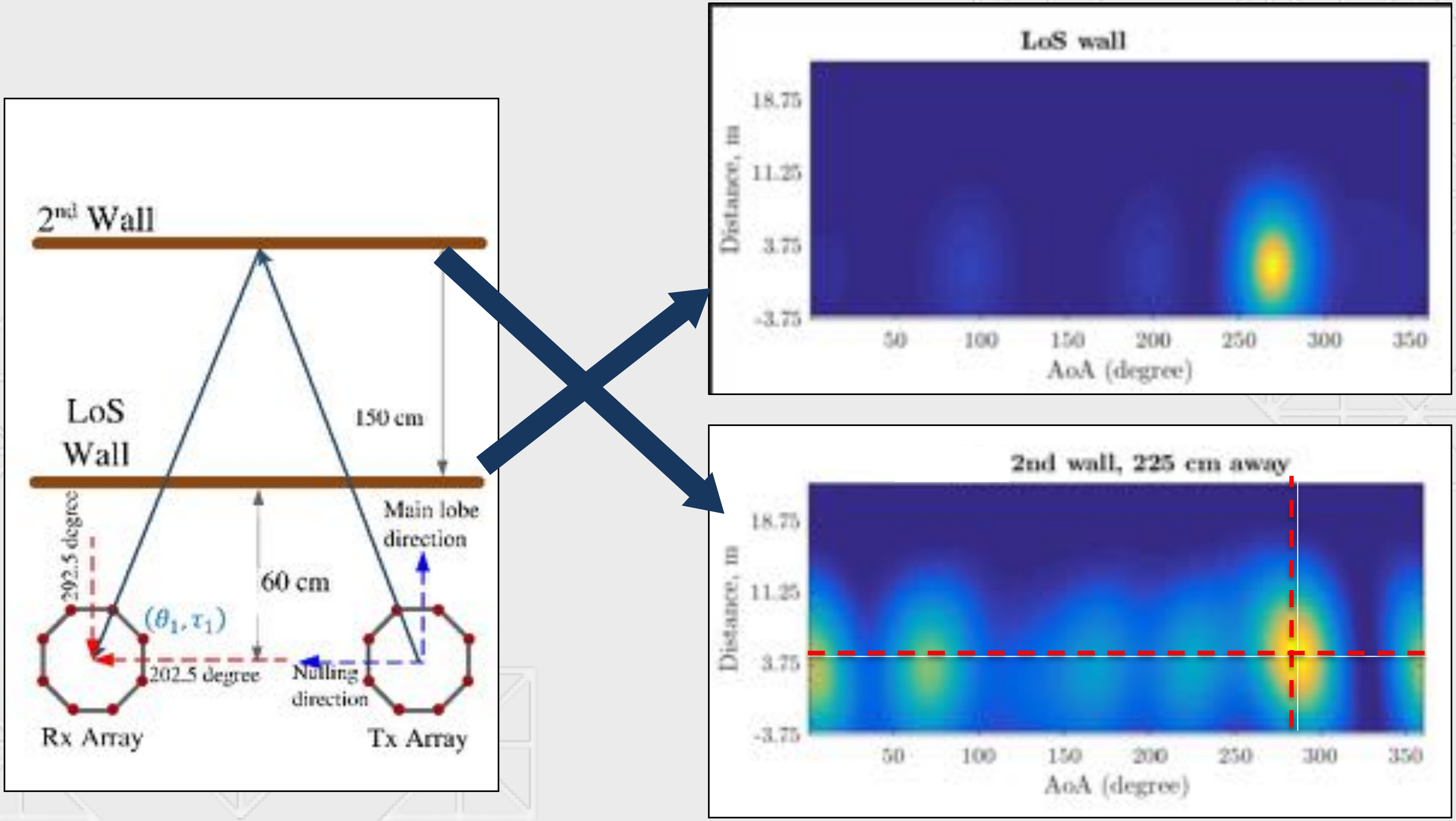
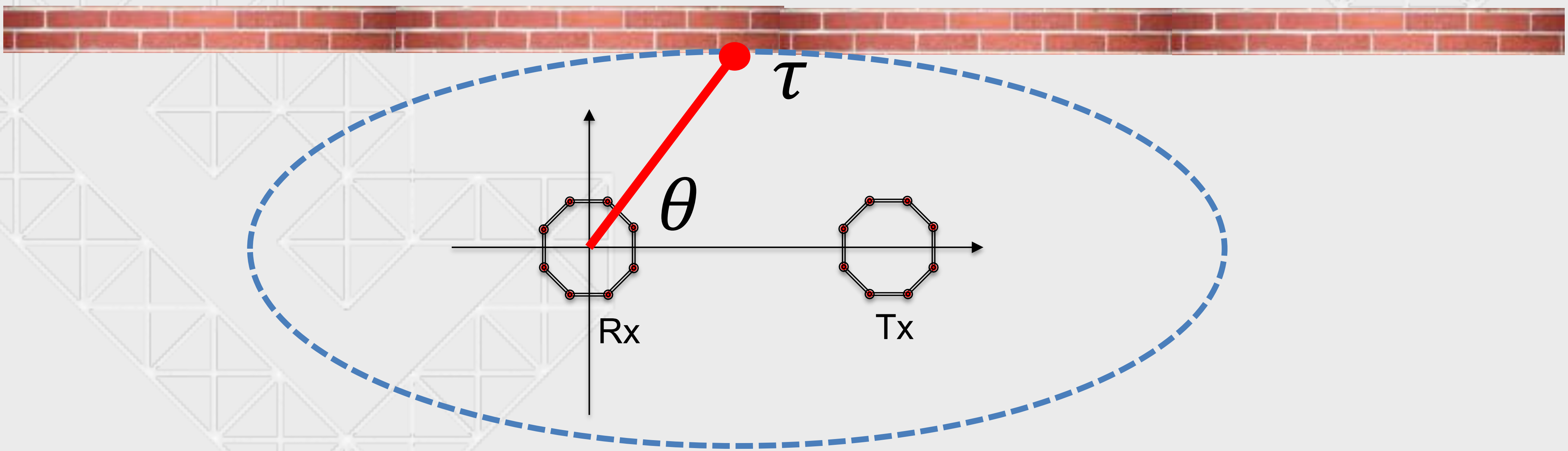
Detecting Secondary Walls



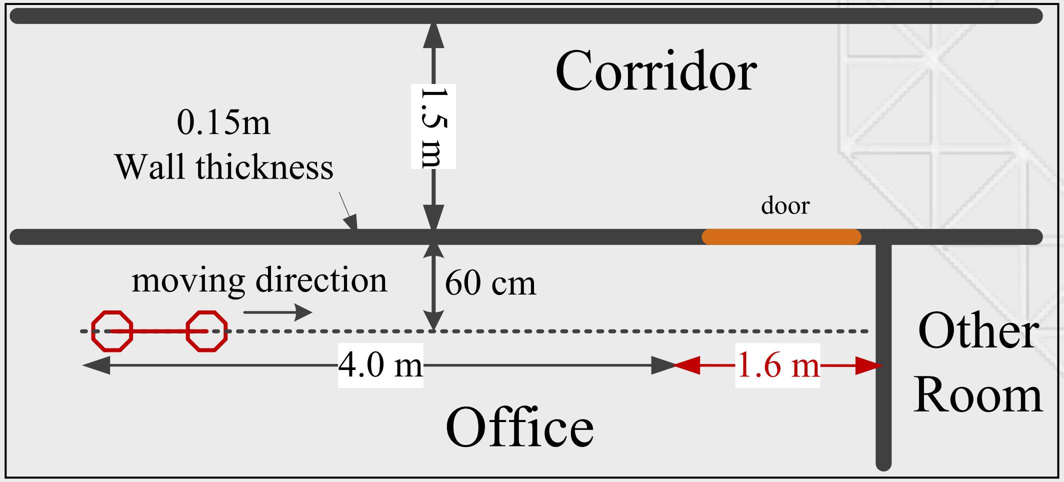
Key:
------ Ground Truth
——— Measured Data

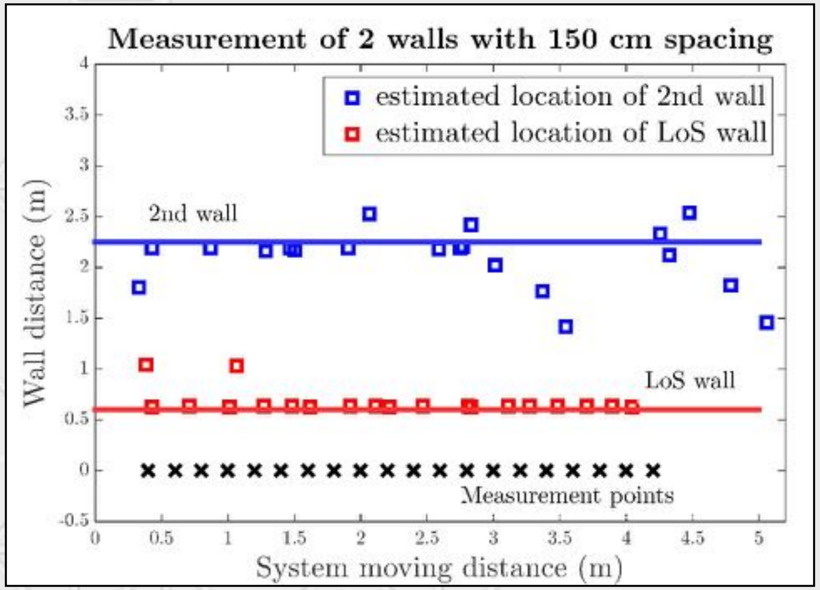
Mapping Space-Time Information

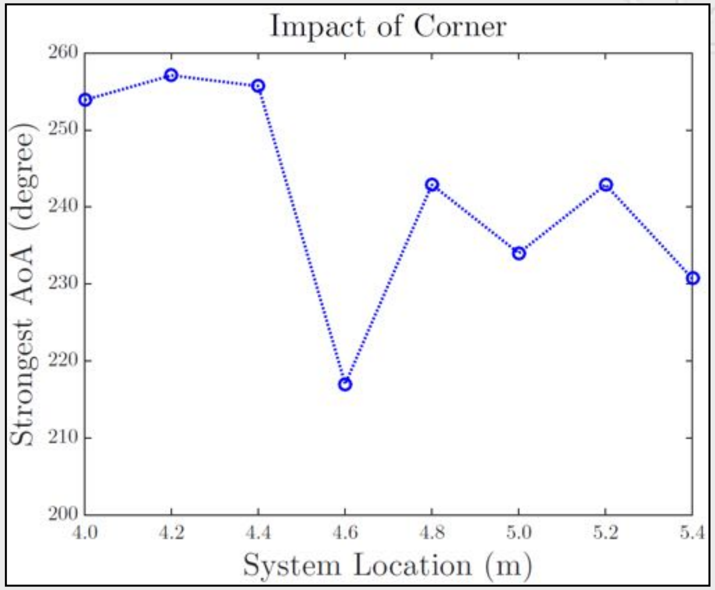
- Combine range & angle measurement into a single point in x and y
  - Orientation and position of the robotic platform (trolley) known
- Time delay leads to an iso-range contour
  - Ellipse with the Tx and Rx antenna arrays as focal points
- Integrate angle information to identify reflection point



Moving Trolley Wall Scan







Summary & Future Work

- ThruMapper
  - A single robot built around a 16 channel high-bandwidth full-duplex phased array radar
  - Enabled by Tx and Rx nulling interference cancellation
  - Joint angle-delay estimation
  - Demonstrated the potential to produce through-wall tomographic maps of room interiors
    - Issues with dihedral backscatter (corners reflections)

- Sensitivity
  - Increase SNR, Reduce SIR
  - Detection tertiary walls
- Reduce Signal Processing Time
  - Transitioning processing code to on-board FPGA
  - Move towards a real-time systems

Thank You!

Q&A

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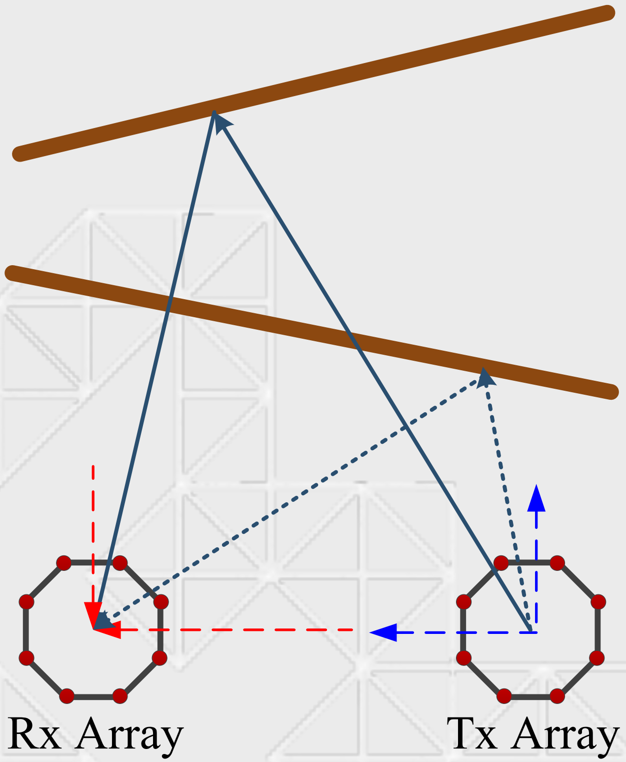
Non-Parallel Wall Layout



- Transmit sweeps in all outgoing bearings to the Tx array
- Consider obstacle with arbitrary orientation
- When Angle of incidence = Angle of reflection, return will arrive at Rx array → Detection

Progress with Imaging