General MIMO Framework for Multipath Exploitation in Through-the-Wall Radar Imaging

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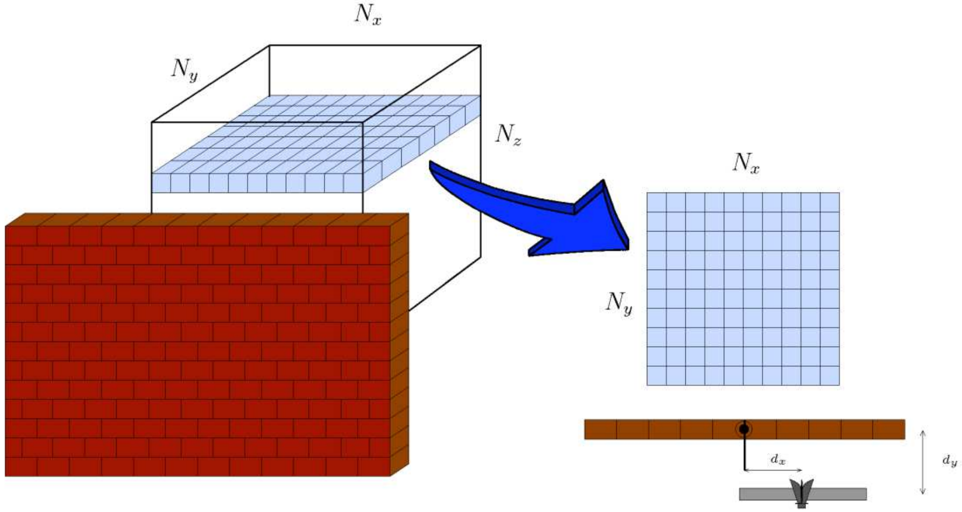
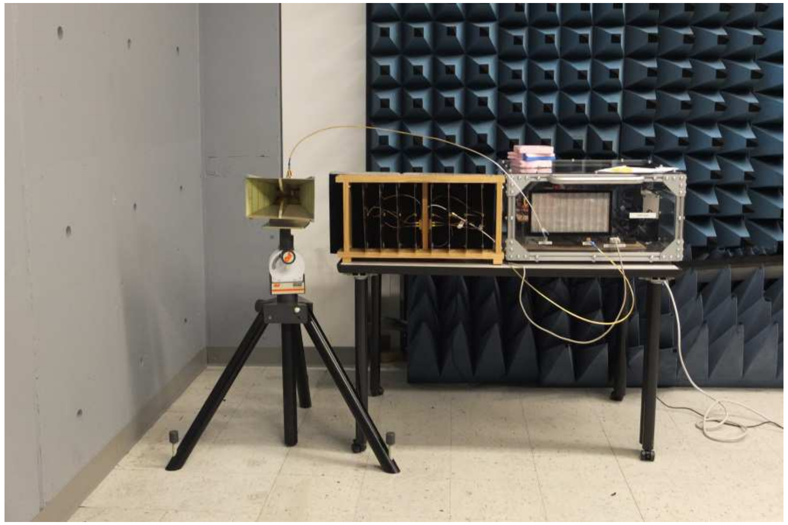
Motivation

Through-the-wall Radar Imaging is a technology, permitting seeing through visually opaque materials. Applications include

- Police and firefighter missions
- Search and rescue operations in natural disasters
- Military applications





Motivation II

Major Challenges in Imaging

- Multipath propagation of EM waves → ghost targets
- Imaging and velocity estimation of moving targets
- Fully utilize multistatic MIMO configuration
- Highly resolved images → huge amount of data

Our Approach:

- Jointly model multipath and direct returns
- Apply Compressive Sensing to reduce measurements
- Group sparse reconstruction of target location and velocity

Outline

- Signal Model
- Sparse Reconstruction Algorithm
- Results
- Conclusion

Linear Target Motion Model

- Translatory target motion with constant velocity
- Array of M transmitters sending K wideband pulses each
- Pulse repetition interval (PRI) is T_r
- The p-th target at pulse k is located at

$$x_p(k) = (x_p + v_{xp}kMT_r, y_p + v_{yp}kMT_r)$$

Direct Path Received Signal Model

- MIMO pulse radar system
- M transmit and N receive elements
- Carrier frequency of wideband pulse f_c
- Reflected signal of P targets is

$$z_{mnk}(t) = \sum_{p=0}^{P-1} \sigma_p s\left(t - kMT_r - mT_r - \tau_{pmn}(k)\right) \exp(-2j\pi f_c \left(kMT_r + mT_r + \tau_{pmn}(k)\right))$$

- $\tau_{pmn}(k)$ is round-trip delay
- Discretize space, velocity, time and vectorize

$$\boldsymbol{z} = \boldsymbol{\Psi\sigma}, \qquad \mathbf{z} \in \mathbb{R}^{\mathrm{MNKT}}, \boldsymbol{\sigma} \in \mathbb{R}^{\mathrm{N_x N_y N_{vx} N_{vy}}}$$

Multipath Received Signal Model

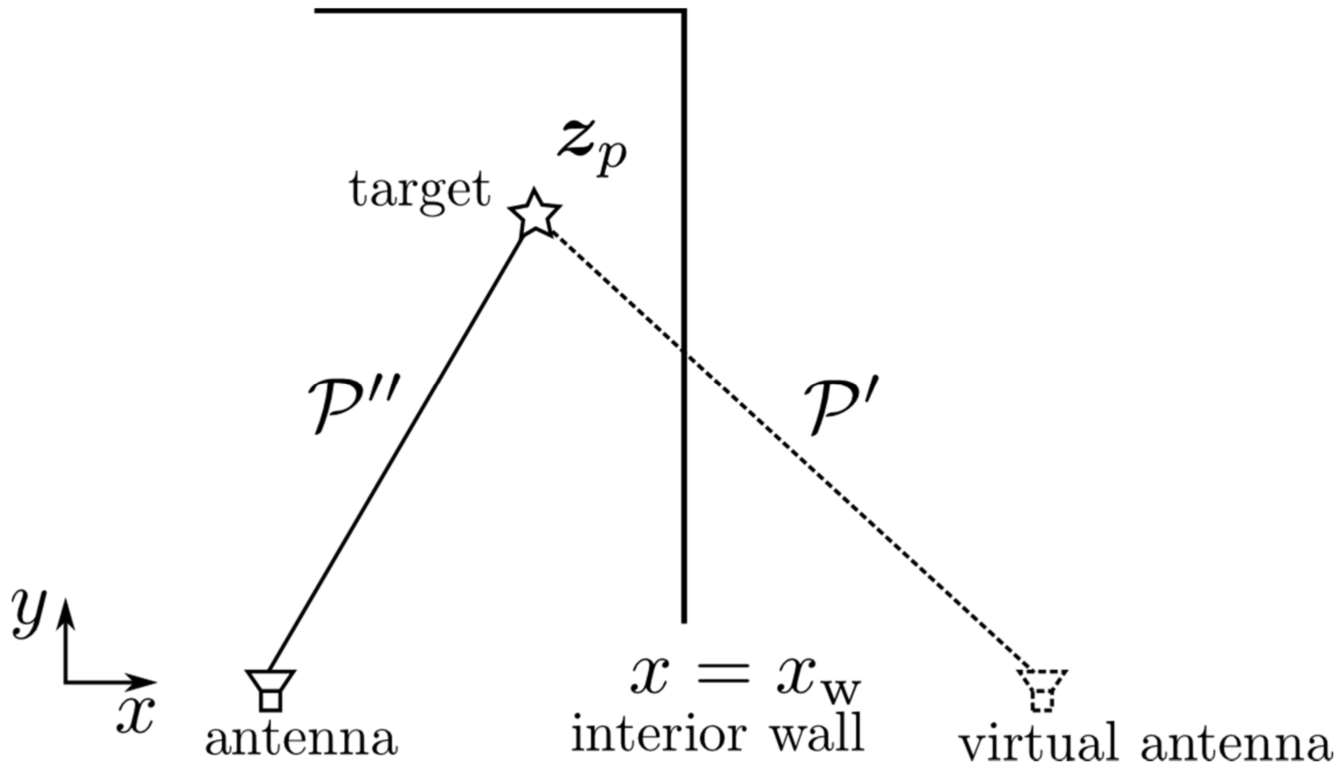
- Superposition of R multipath contributions received
- Multipath model

$$\boldsymbol{z} = \boldsymbol{\Psi}^{(0)}\boldsymbol{\sigma}^{(0)} + \boldsymbol{\Psi}^{(1)}\boldsymbol{\sigma}^{(1)} + \cdots + \boldsymbol{\Psi}^{(R-1)}\boldsymbol{\sigma}^{(R-1)}$$

- Path number 0 corresponds to direct path
- $\boldsymbol{\Psi}^{(\cdot)}$ represent the dictionaries associated with a certain propagation path
- $\boldsymbol{\sigma}^{(\cdot)}$ are the target state vectors associated with a path

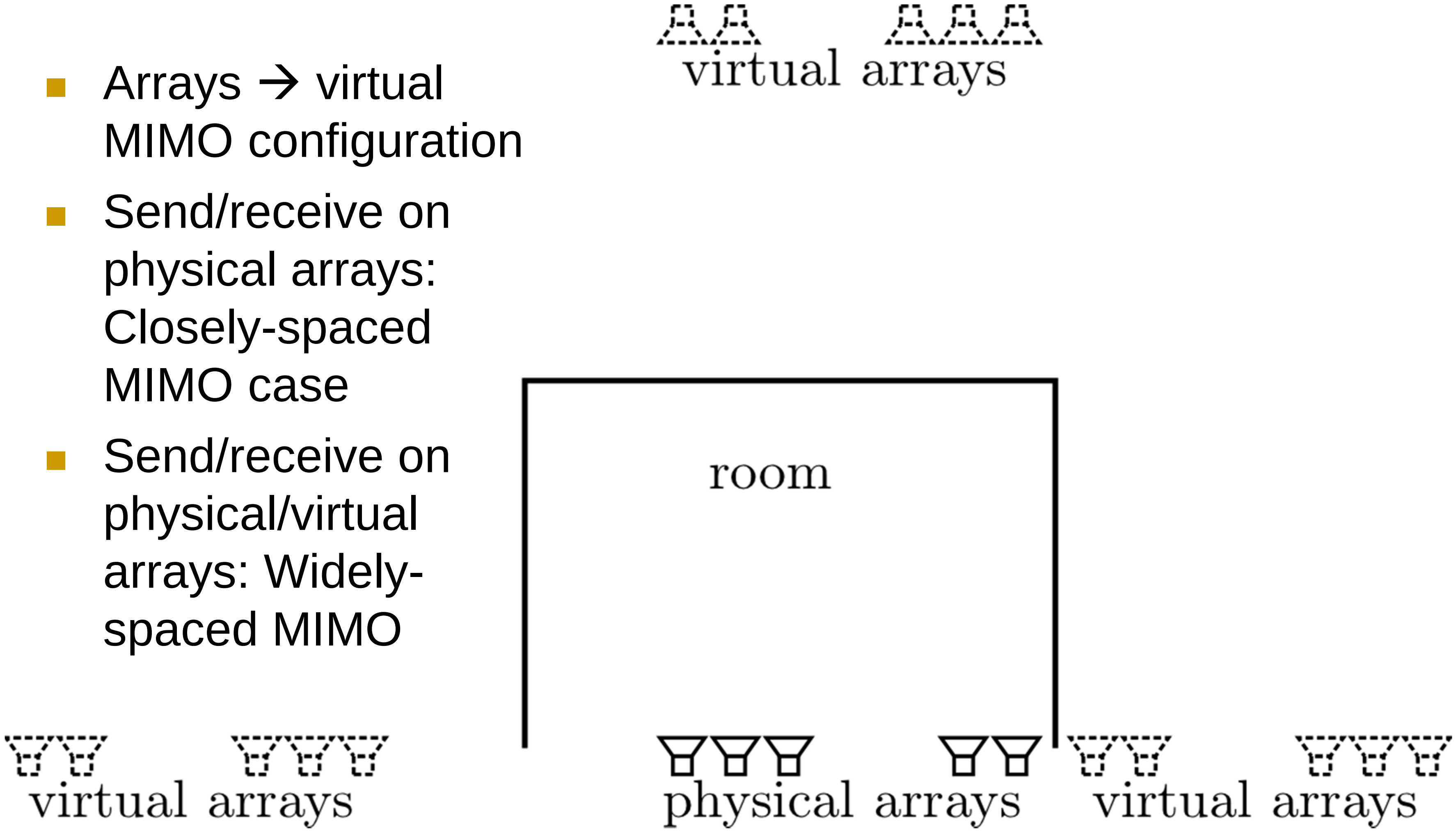
Virtual Antenna View of Multipath

- Multipath can be viewed as virtual antennas
- Target scatters back to physical and virtual antenna



MIMO View of Multipath

- Arrays → virtual MIMO configuration
- Send/receive on physical arrays: Closely-spaced MIMO case
- Send/receive on physical/virtual arrays: Widely-spaced MIMO



MIMO sensing model

- Combine all paths for the multipath model
- Unresolved multipath (superposition)

$$\boldsymbol{z} = \begin{bmatrix} \boldsymbol{\Psi}^{(0)} & \boldsymbol{\Psi}^{(1)} & \cdots & \boldsymbol{\Psi}^{(R-1)} \end{bmatrix} \begin{bmatrix} \boldsymbol{\sigma}^{(0)} \\ \boldsymbol{\sigma}^{(1)} \\ \vdots \\ \boldsymbol{\sigma}^{(R-1)} \end{bmatrix}$$

- Resolved multipath (requires association)
- $$\boldsymbol{z}_{\text{res}} = \begin{bmatrix} \boldsymbol{\Psi}^{(0)} & 0 & \cdots & 0 \\ 0 & \boldsymbol{\Psi}^{(1)} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & \boldsymbol{\Psi}^{(R-1)} \end{bmatrix} \begin{bmatrix} \boldsymbol{\sigma}^{(0)} \\ \boldsymbol{\sigma}^{(1)} \\ \vdots \\ \boldsymbol{\sigma}^{(R-1)} \end{bmatrix}$$

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Downsampling of Measurements

- Efficient data acquisition
- Reduce number of array elements and samples
- → Leave out some transmitters/receivers in array
- → Correlate returns with random signals (random mixing)
- Represented as a downsampling matrix $\boldsymbol{\Phi}$
- Reduced measurement vector

$$\bar{\boldsymbol{z}} = \boldsymbol{\Phi} \boldsymbol{z}$$

Group Sparse Reconstruction

- Stack all unknowns in $\tilde{\boldsymbol{\sigma}}$
- Combine all dictionaries in $\tilde{\boldsymbol{\Psi}}$
- Combined multipath model

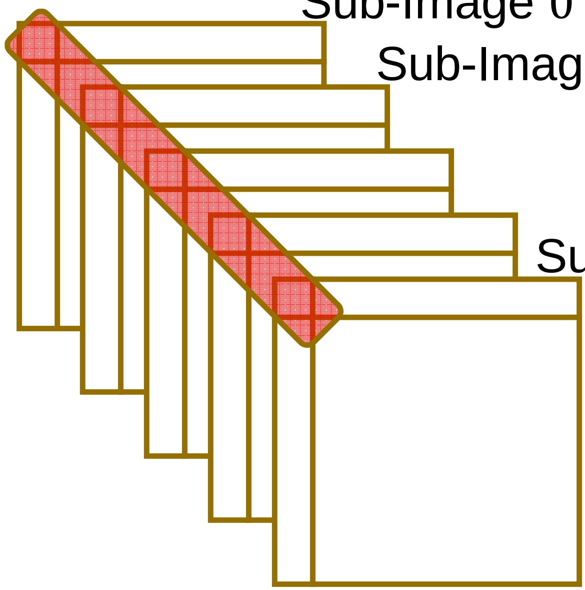
$$\bar{\boldsymbol{z}} = \boldsymbol{\Phi}\tilde{\boldsymbol{\Psi}}\tilde{\boldsymbol{\sigma}}$$

- Group sparse reconstruction

$$\hat{\boldsymbol{\sigma}} = \arg\min_{\tilde{\boldsymbol{\sigma}}} \left\| \bar{\boldsymbol{z}} - \boldsymbol{\Phi}\tilde{\boldsymbol{\Psi}}\tilde{\boldsymbol{\sigma}} \right\|_2 + \lambda \|\tilde{\boldsymbol{\sigma}}\|_{1,2}$$

Concept of Group Sparsity

- All sub-images describe the same ground-truth
- The support of those images must be equal
- Grouping of corresponding pixels across path index



- Achieved by mixed norm term in reconstruction

$$\|\tilde{\boldsymbol{\sigma}}\|_{1,2} = \sum_{p=0}^{N_x N_y N_v - 1} \left\| \left[\sigma_p{}^{(0)}, \sigma_p{}^{(1)}, \dots, \sigma_p{}^{(R-1)} \right]^T \right\|_2$$

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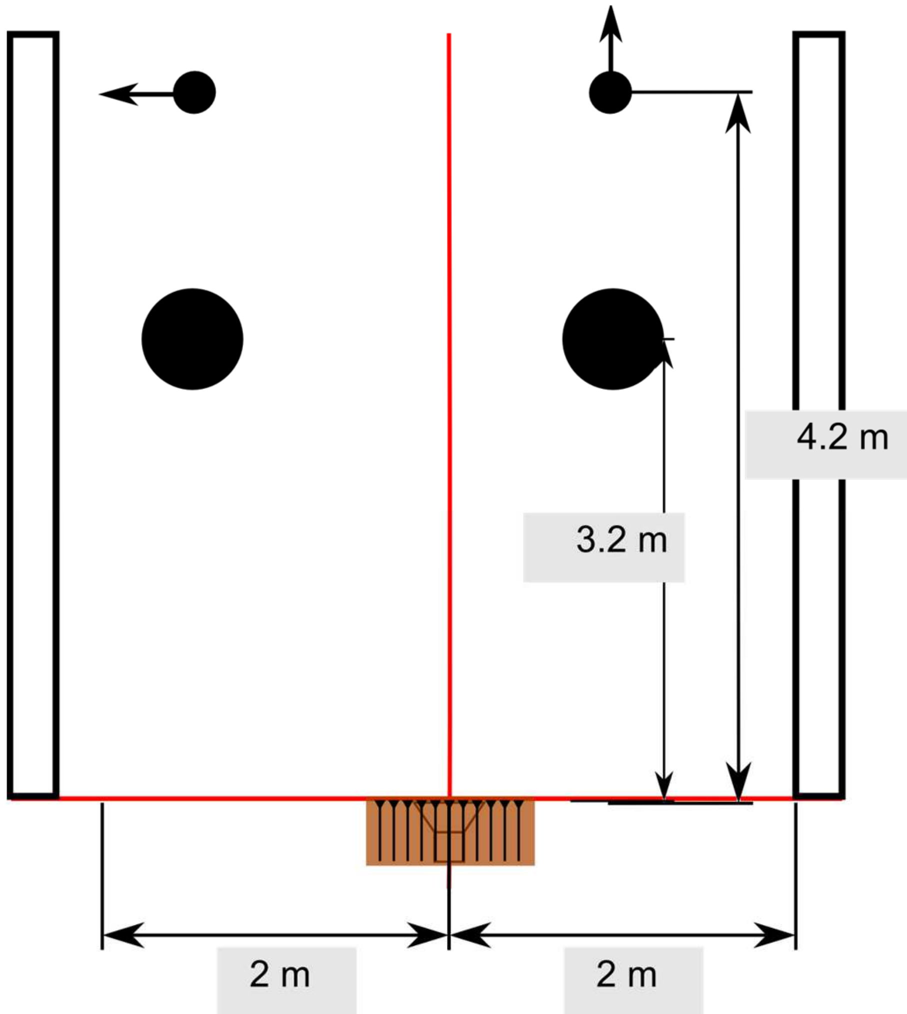
Simulation Setup

- Array: $M = 1$, $N = 11$, element spacing $5\ \mathrm{cm}$, stand off distance $3\ \mathrm{m}$, bistatic
- Front wall: thickness $20\ cm$, $\varepsilon_r = 7.66$
- Interior walls: left and right side walls at $\pm 2\ \mathrm{m}$ cross range
- Transmit signal: Gaussian pulse with $f_c = 2\ \mathrm{GHz}, 50\%$ bandwidth and $100\ \mathrm{Hz\ PRF}$
- Data recording parameters: $T = 150, f_s = 4\ \mathrm{GHz}$ and $K = 15$
- Downsampling to: $K_d = 12, N_d = 8, T_d = 20$, i.e. 7.8%

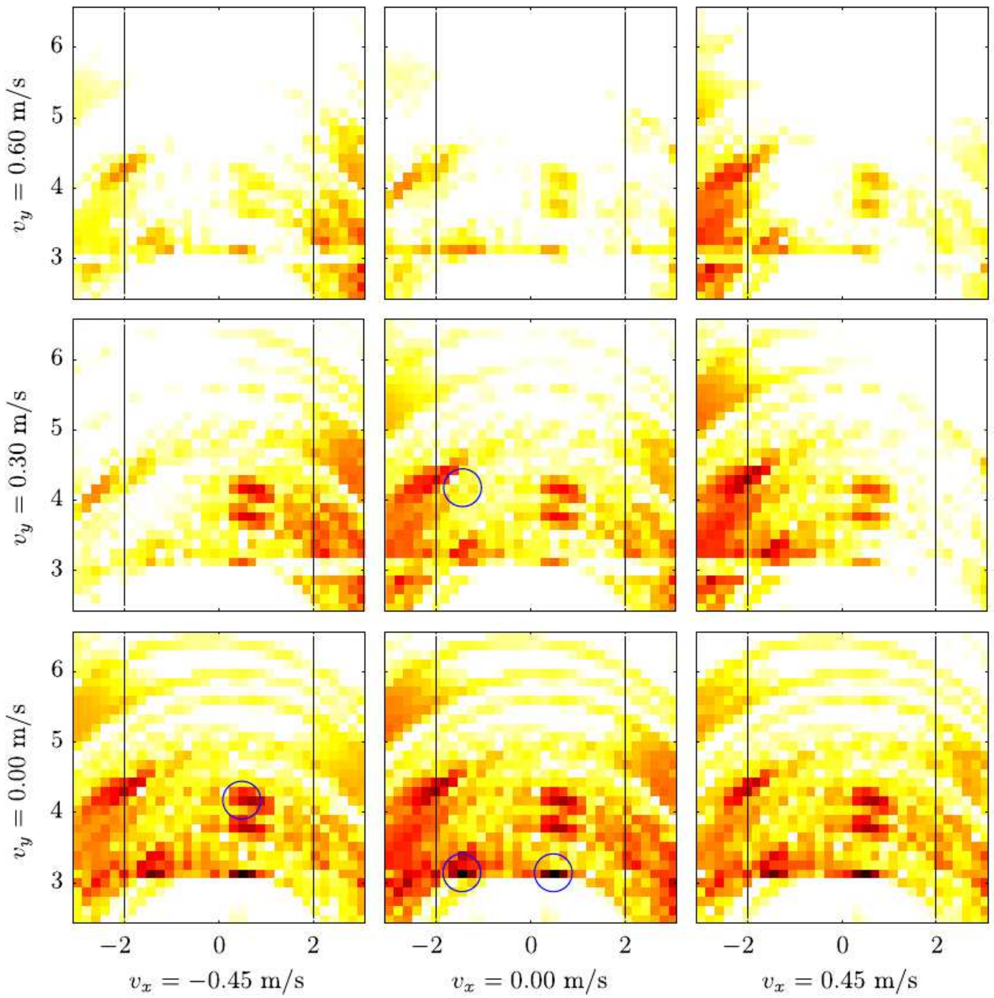
Simulation Results: Scene Layout

- Can we recover objects with blocked direct paths?
- Large stationary objects in the front
- Small moving target behind (no line of sight)
- Reflections from left and right side walls



Conventional Beamforming (full data)

- Each subfigure is matched to a certain target velocity



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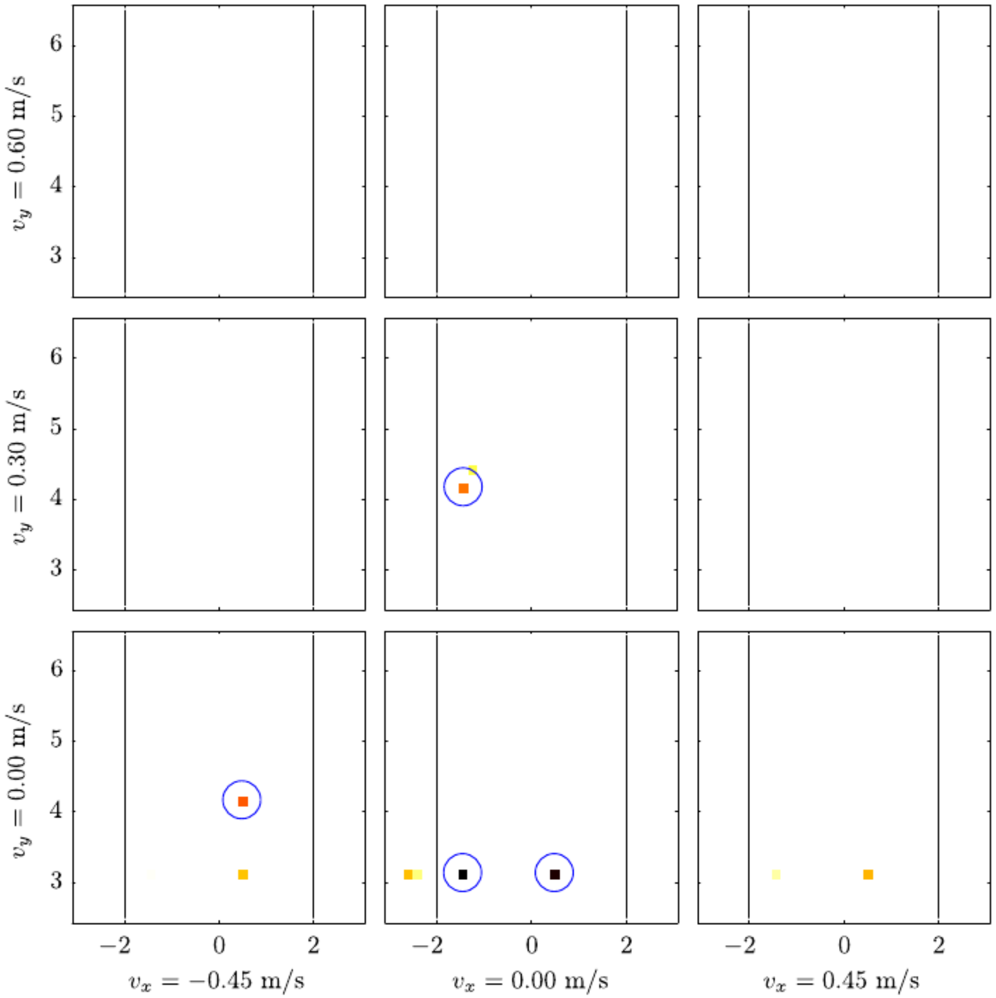
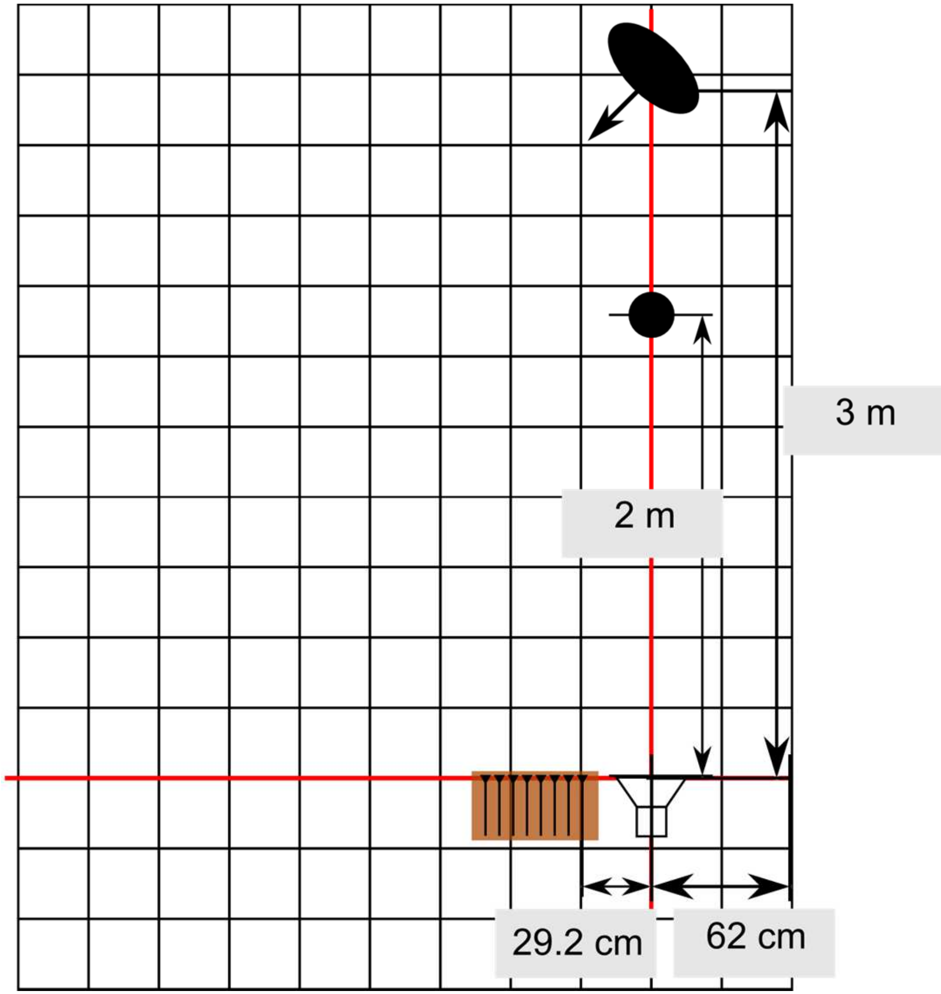
Group Sparse CS Reconstruction

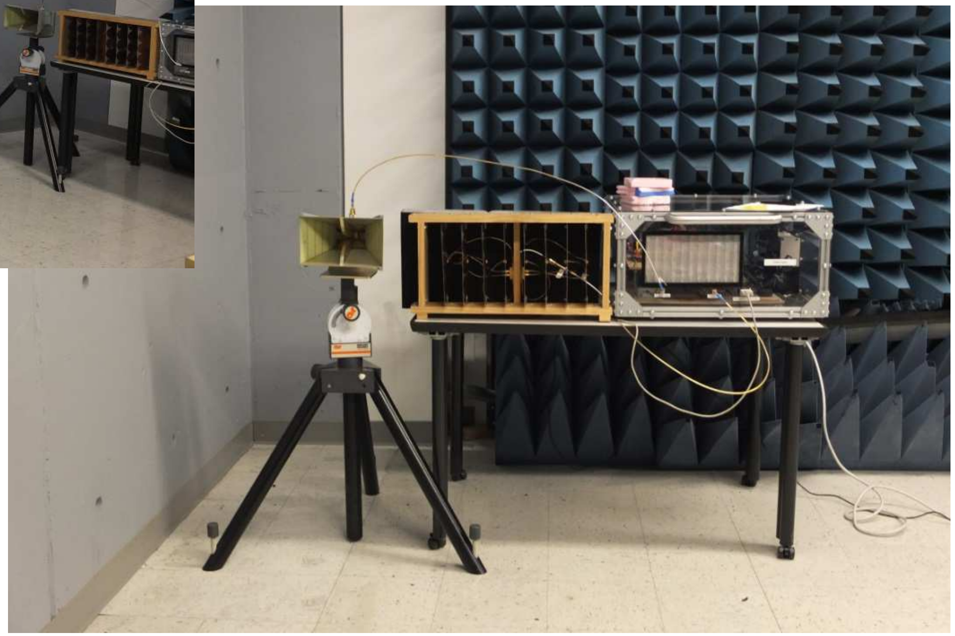


Experimental Results: Scene Layout

- Experimental setup in Radar Imaging Lab
- Human walking diagonally towards radar
- Small stationary object in front of human
- Reflection from right side wall

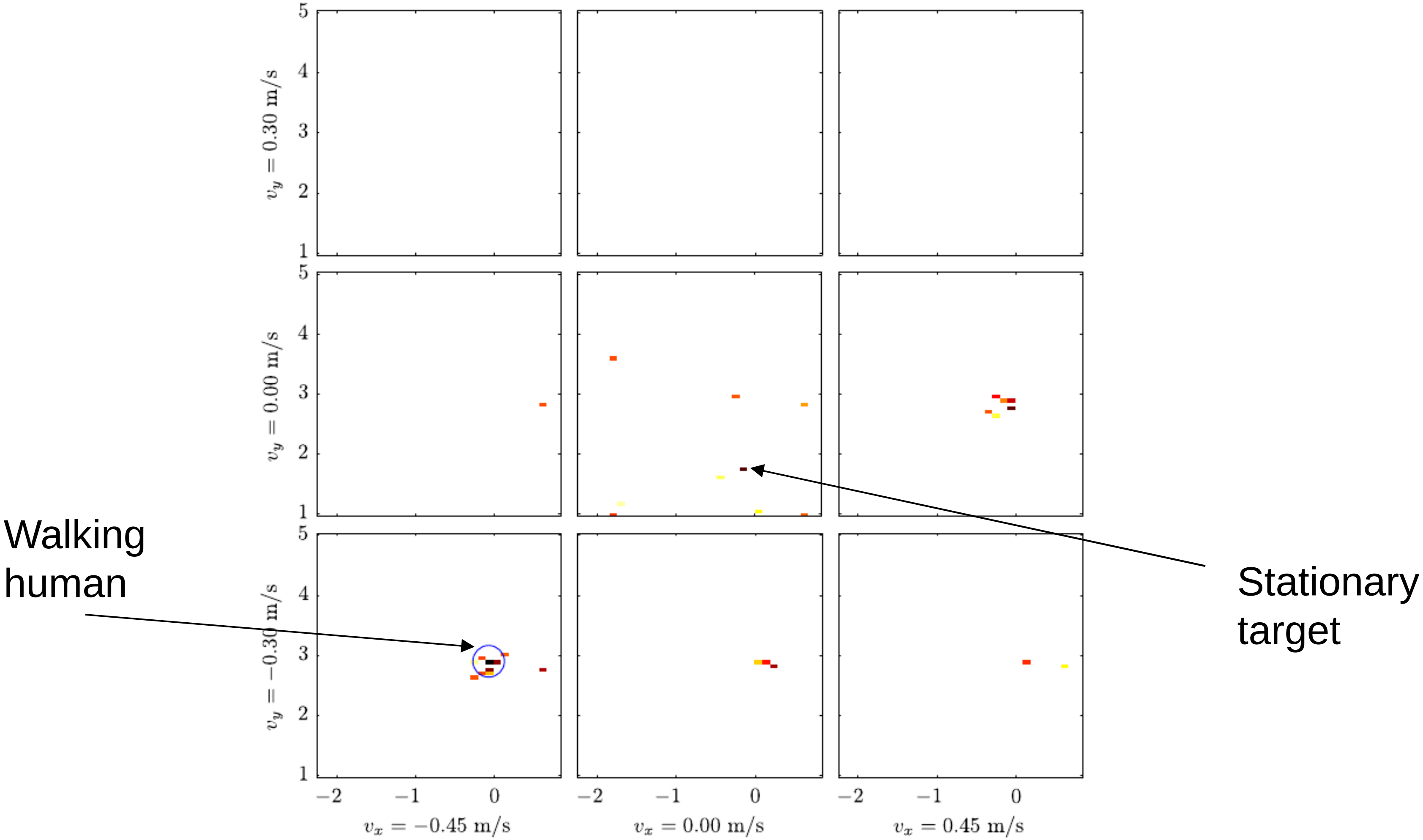


Experimental Results: Scene Layout



- Measurement Parameters:
- $N = 8, N_d = 5$
- $T = 153, T_d = 50$
- $K = K_d = 15$
- Total: 20% of Nyquist

Experimental Result



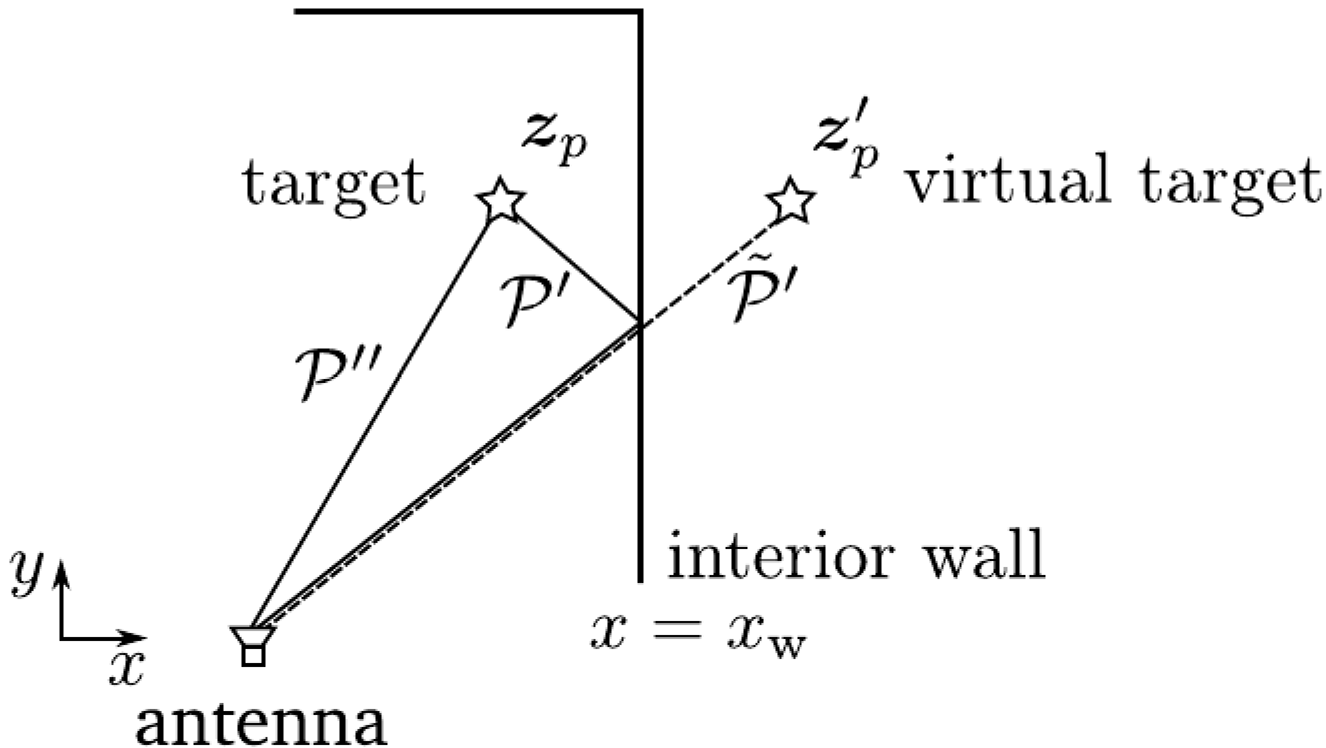
Conclusion

- Modeling of stationary and moving targets
- Multipath via reflections at interior walls → MIMO
- Group sparse reconstruction based on joint model
- Clean images and suppressed ghosts
- Even targets with blocked line-of-sight can be recovered

Thank you!

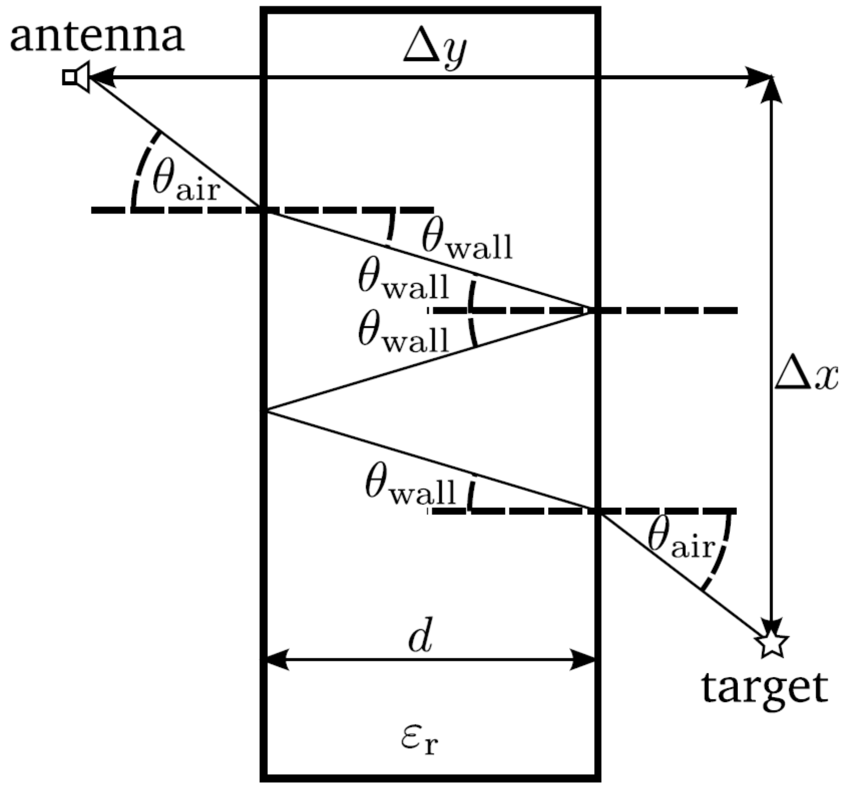
Multipath via Internal Wall

- Reflection at wall causes multipath propagation
- Can be treated as a virtual target



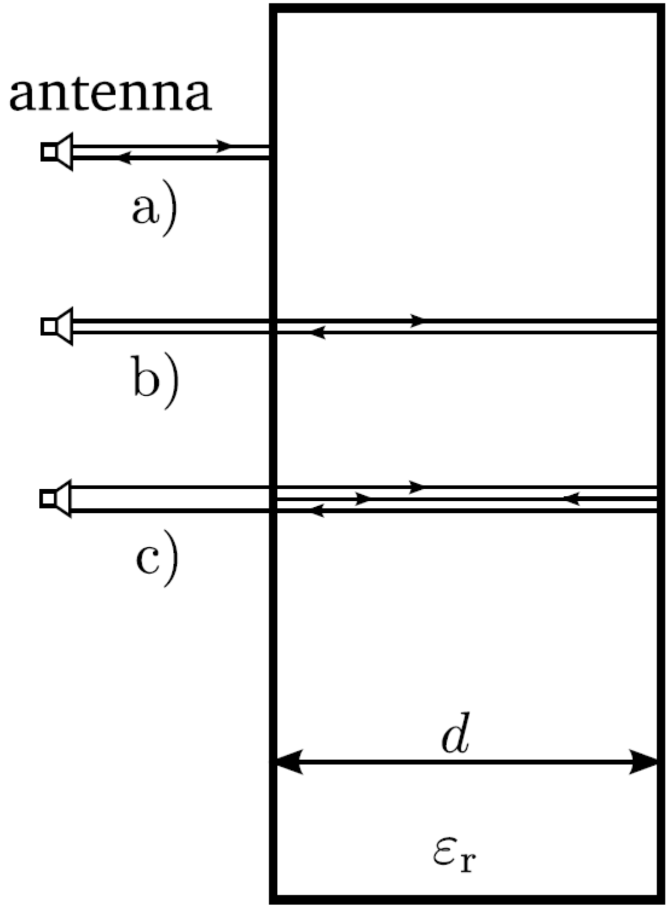
Wall Ringing Multipath

- Multiple reflections within wall
- Interaction with target(s)
- Causes additional delay and attenuation
- Superimposed on direct path propagation



Wall Returns

- Wall returns stem from various types of reflections
    a) Reflection at front face
    b) Reflection at back face
    c) Multiple reflections within wall (wall reverberation)
- Different delays and reflectivities associated
- Superposition of all cases is received as wall return



Apparent Doppler Velocity