Facilitating Robust 60 GHz Network Deployment By Sensing Ambient Reflectors

Teng Wei

Anfu Zhou and Xinyu Zhang

University of Wisconsin–Madison

Beijing University of Posts and Telecommunications



Introduction

- **Massive surge of wireless traffic demand**



Mobile-to-screen Video Cast

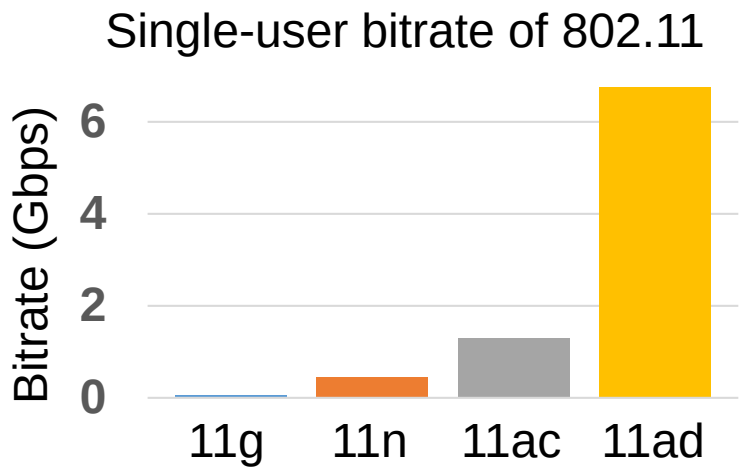


Wireless Virtual Reality



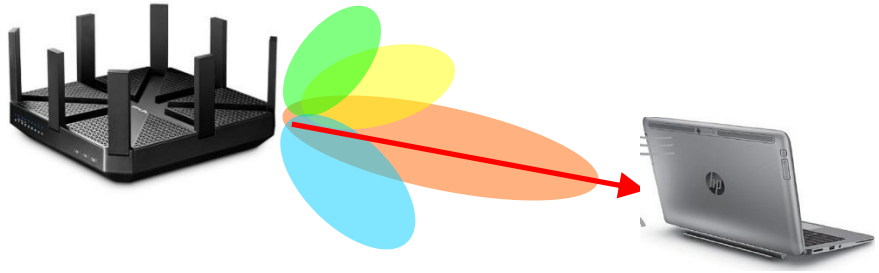
Laptop Docking Station

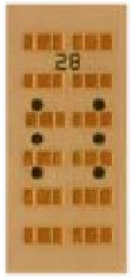
- **60 GHz millimeter-wave networks**
  - Center at unlicensed 60 GHz band
  - Span 14 GHz spectrum



Introduction

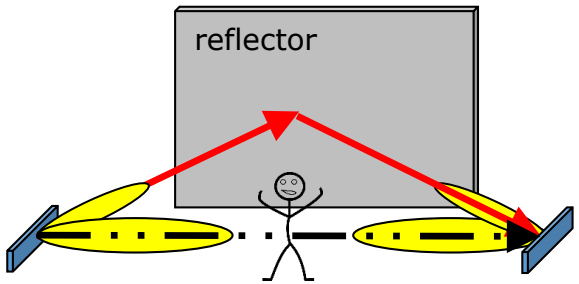
- **Vulnerable to propagation loss and obstacle blockage**
  - Due to ultra-high carrier frequency
- **Directional and electrically steerable beam**
  - Many-element phased array antenna





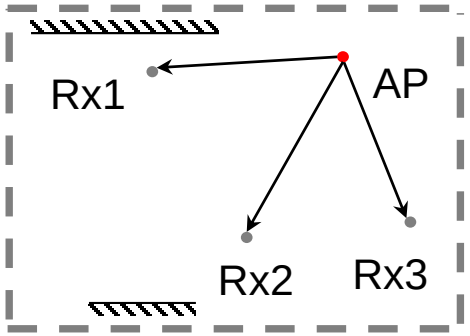
- 15.5 x 7.9 x 2 mm
- 32 RF/Ant chains
  - 12 patches top
  - 6 patches bottom
  - 14 edge dipoles

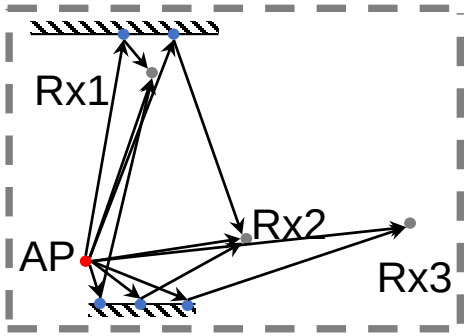
  - Steer around obstacle via reflection



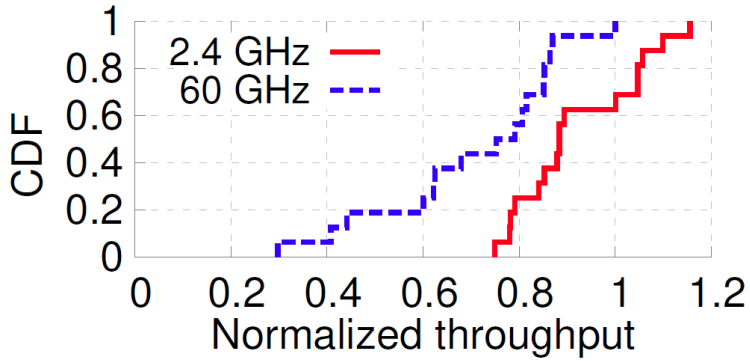
New Problem

- **Network performance sensitive to AP deployment and environmental characteristics**
  - Dependency on directionality and reflectivity





- **Motivation study**
  - COTS tri-band (2.4/5/60 GHz) laptop
  - Random 16 links in an office
  - Normalized throughput $= \frac{\text{Blocked Throughput}}{\text{Unblocked Throughput}}$



E-Mi: Basic Idea

- **How to find out the best AP deployment?**
  - State-of-the-art: blanket site-survey, or war-driving
  - Formidable search space

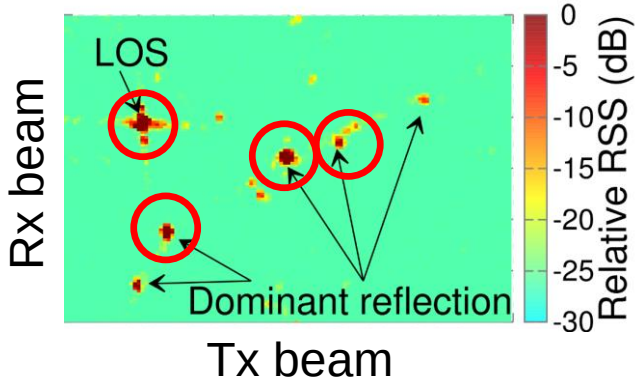


- **E-Mi: sense, predict and optimize the AP placement from a 60 GHz radio's eyes**
  - *Sense* major reflectors from 60 GHz radio's eyes
  - *Predict* the performance of arbitrarily located links
  - *Optimize* the AP placement to maximize capacity and robustness

Challenge: Let Radios “See” the Environment

- **Challenge:** 60 GHz radios extremely low resolution sensors
- **Opportunity:** Sparsity of 60 GHz channel

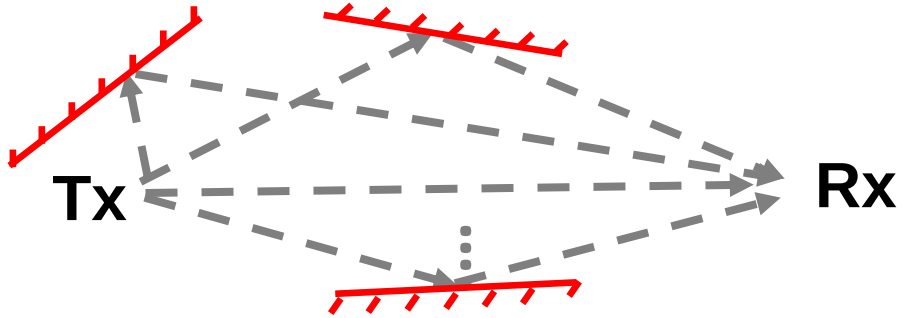
From a 60 GHz radio’s eyes



From a camera’s eyes

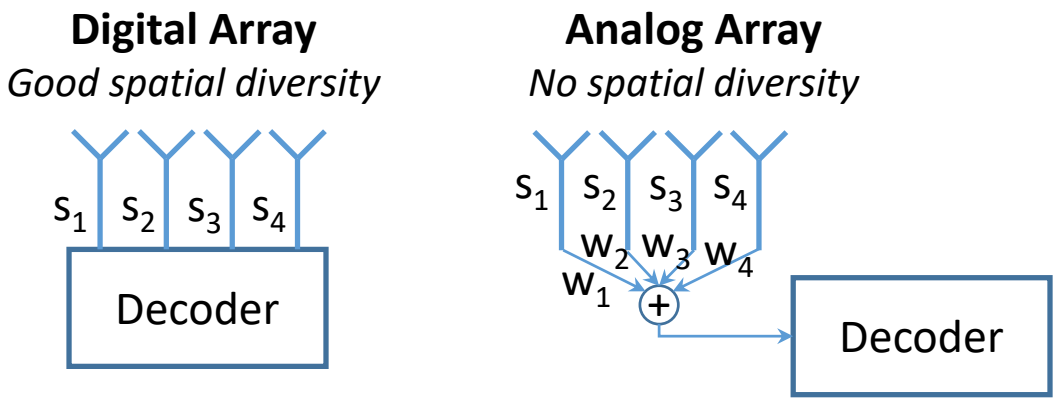


- **Reconstruct the structure by tracing back the invisible propagation paths**



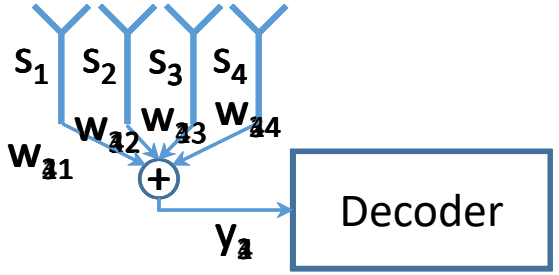
Multipath Resolution Framework

- **Solving AoD/AoA for each path**
  - Conventional ditigal array applies eigen angle analysis
  - Require isolating signals from/to individual antenna elements!
  - Challenge: 60 GHz phased-array merges all signals



Multipath Resolution Framework

- **Our solution: solve for individual signals**
  - Transmit and receive signals using different weights
  - *Recover signals* on each antenna element

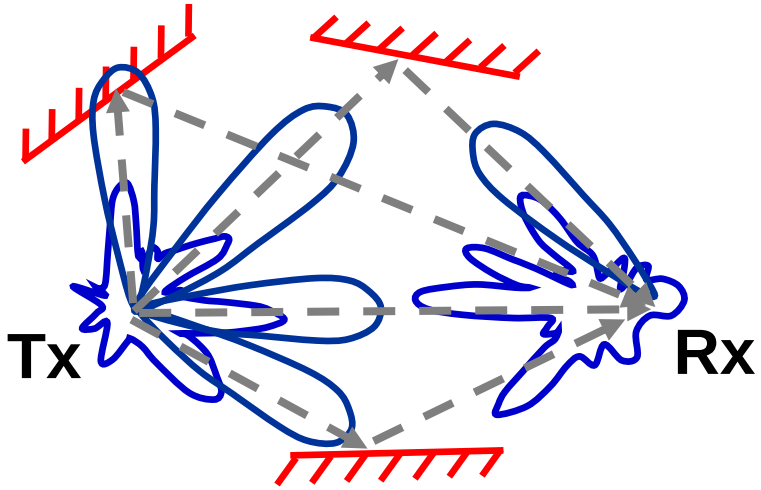


$$\left.\begin{aligned} s_1w_{11} + s_2w_{12} + s_3w_{13} + s_4w_{14} &= y_1 \\ s_1w_{21} + s_2w_{22} + s_3w_{23} + s_4w_{24} &= y_2 \\ s_1w_{31} + s_2w_{32} + s_3w_{33} + s_4w_{34} &= y_3 \\ s_1w_{41} + s_2w_{42} + s_3w_{43} + s_4w_{44} &= y_4 \end{aligned}\right\} \Rightarrow \begin{pmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{pmatrix} = \boldsymbol{W^{-1}} \begin{pmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{pmatrix}$$

Proposition: If W is orthogonal matrix, then signals on individual antennas, **S**, can be recovered with optimal SNR, through sequential beam switching.

Multipath Resolution Framework

- **AoAs/AoDs do not have pairwise mapping**
- **Our Solution:** AoA-AoD matching
  - Match AoA with AoD along the same path
  - Virtual beamforming: Offline “steering” signal towards eigen angles



Now we can isolate signals along each path!

Matching metric:

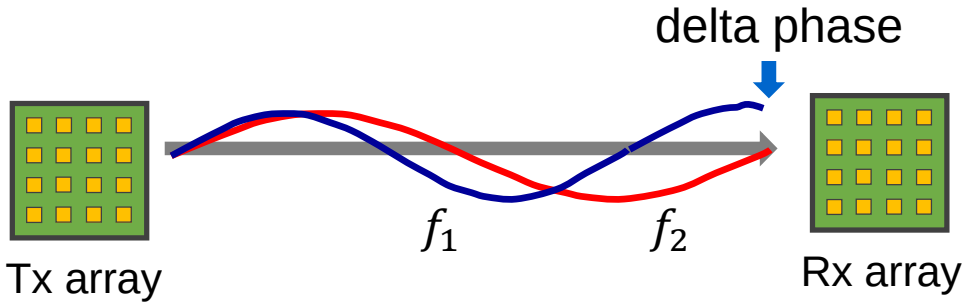
$$F(i,j) = \boldsymbol{E}[\left|\boldsymbol{a_r}(AoA_i).\boldsymbol{S}.\boldsymbol{a_t}(AoD_j)\right|^2]$$

0.1	0.8	0.03	0.07
0.79	0.05	0.1	0.0
0.04	0.09	0.97	0.12
0.03	0.01	0.14	0.85

High-value entries correspond to matching AoA and AoD pairs

Multipath Resolution Framework

- **Estimate the path length:** Multi-Tone Ranging
  - OFDM modulates signals across *different frequency tones*
  - Phases of different frequencies diverge over distance

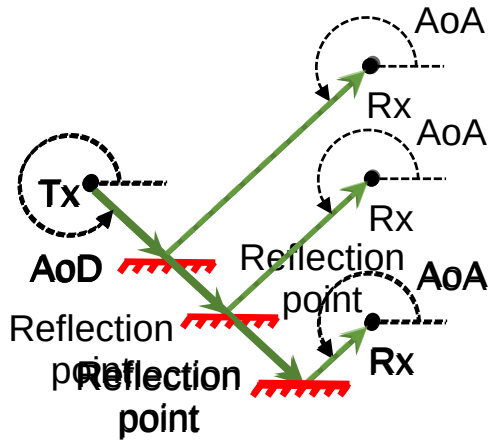


  - Map *delta phase* back to distance

$$d^* = \arg\min_d \sum_{i=1}^{L} [\theta_i - \theta_i' - mod(\frac{2\pi f_i (d - d_0)}{c}, 2\pi)]^2$$

Dominant Reflector Reconstruction

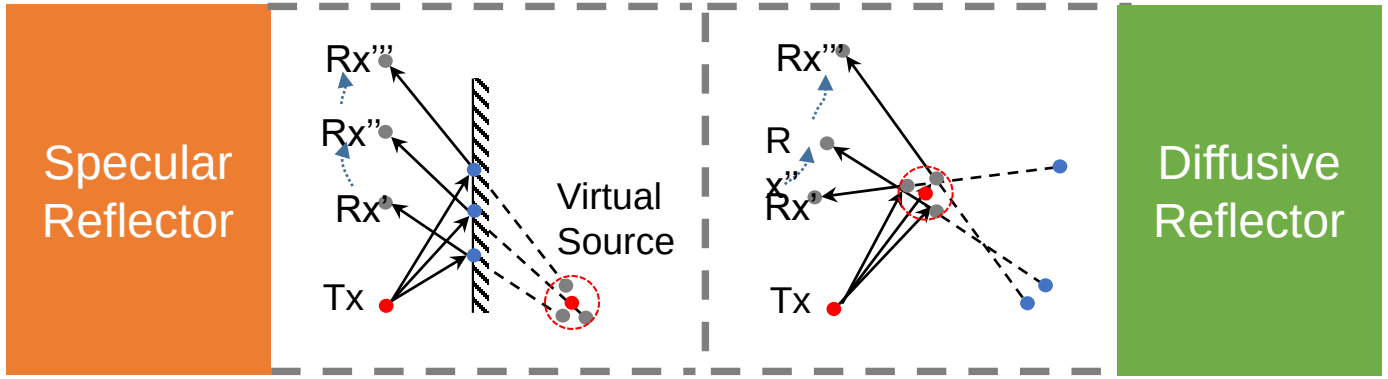
- **Locating reflecting points**
  - Trace back <AoA, AoD, length> of all paths to locate reflecting points and Rx position



  - Two paths can resolve the ambiguity
  - **Solution:** Formulated as a *least-square optimization* problem
- **Problem:** higher-order reflections
  - Filter out higher-order reflection that exhibits a larger deviation

Dominant Reflector Reconstruction

- **Model the reflector layout**
  - 2-D cross section of the environment using a sparse set of reflecting points
  - Abstract reflectors into two categories



- **Estimate the reflector reflectivity**
  - Model the reflection loss of each path

$$RSS = Tx_{power} + Antenna_{gain} - Oxygen_{loss} - Reflection_{loss} - 20\log_{10}(distance)$$

  - Using the LOS path as *reference calibration* to cancel unknown factors

How to Predict?

- **60 GHz Parametric Ray-tracing**
  - A fine-grained way to model 60 GHz signals
  - Input: layout/reflectivity for dominant reflectors
  - Track how each signal path is attenuated over distance and reshaped by reflectors
  - Output: RSS for arbitrary AP and client locations

Environment-Aware mmWave Networking

- **Case Study: Environment-aware multi-AP deployment**
  - To mitigate blockage/coverage problems
- **Solution principle**

Input

- Reconstruct environment



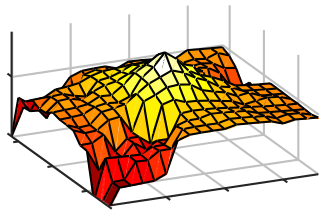
Performance metric

- Average bitrate among all client spots

$$D = \frac{1}{W}\sum_{i=1}^{W} T(RSS_i)$$

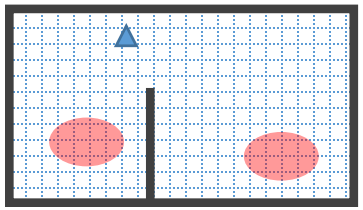
Procedure

- Predict the performance of all candidate position combinations



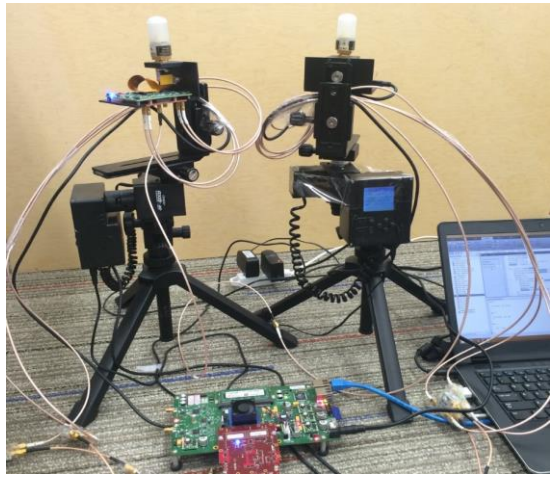
Output

- Best topology that maximizes the metric

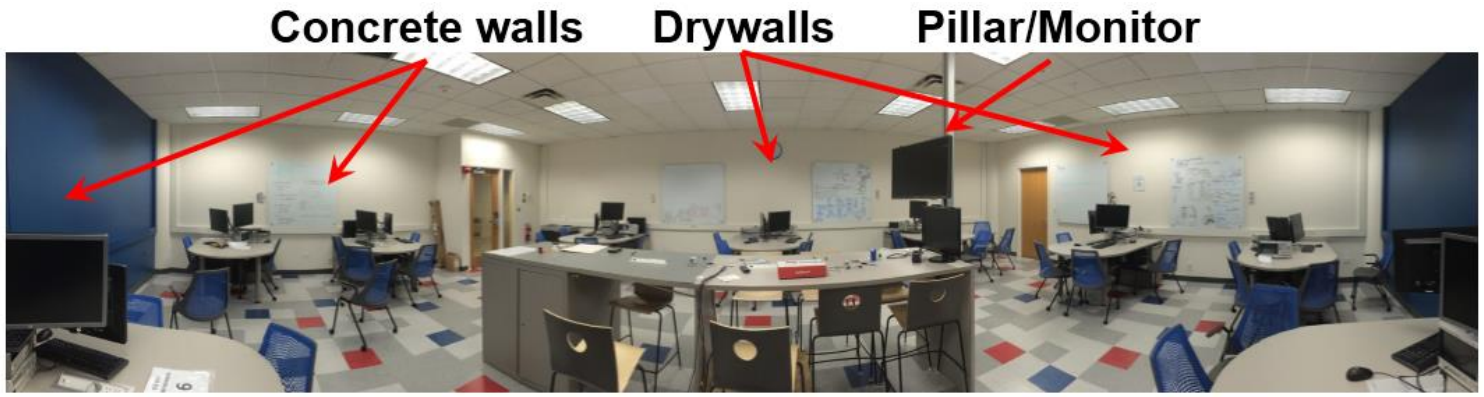


Implementation

- **Hardware**
  - Custom-built 60 GHz software-defined radio testbed

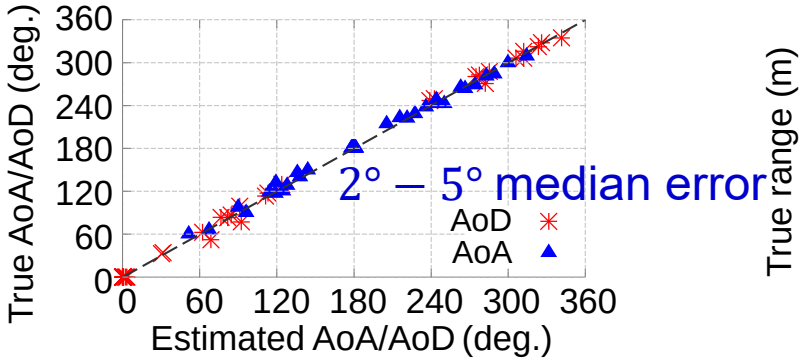


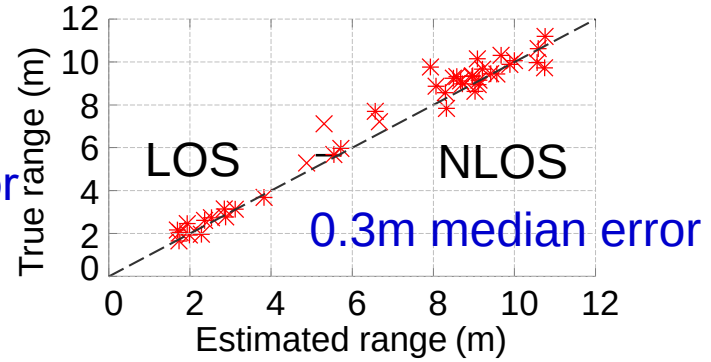
- **Evaluation environment**
  - Sparse reconstruction of an office
  - using only 15 Rx positions



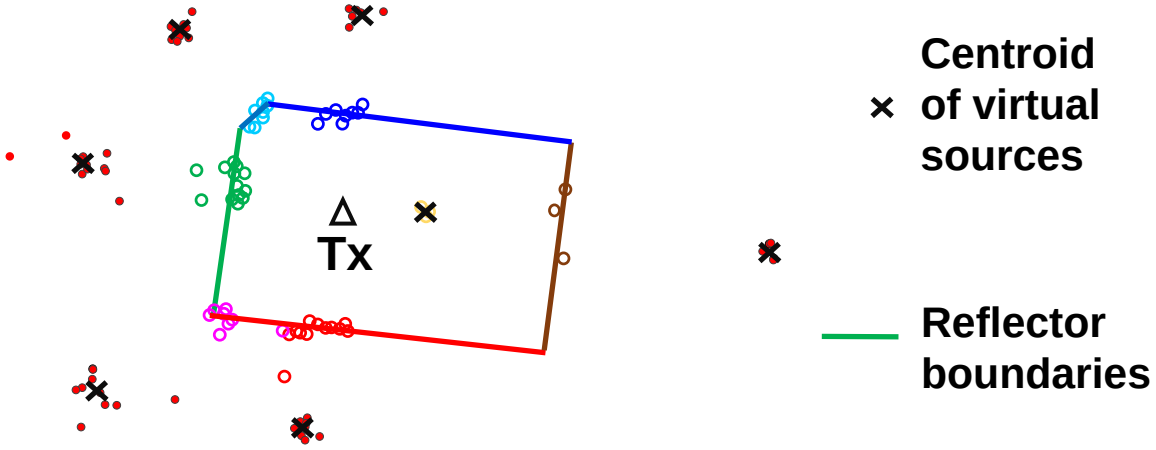
Effectiveness of Environment Sensing

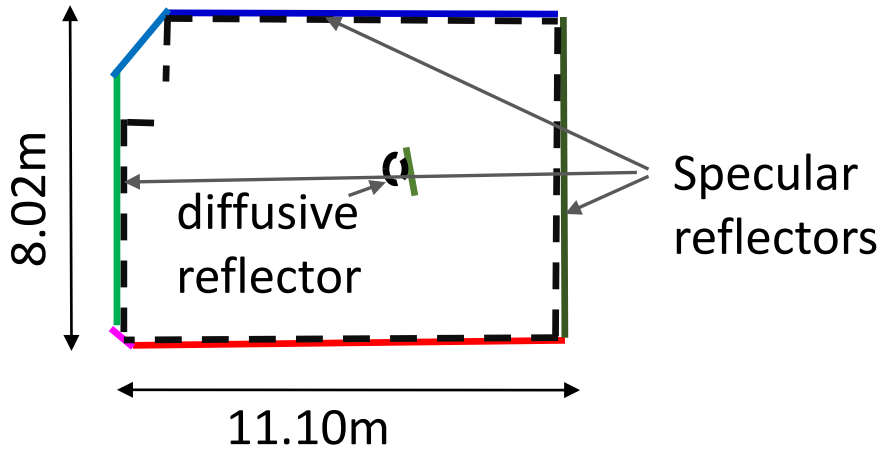
- **Accuracy of multipath resolution**





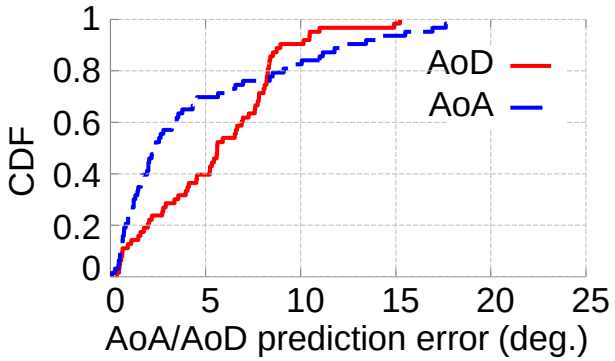
- **Reconstructing environment structures**

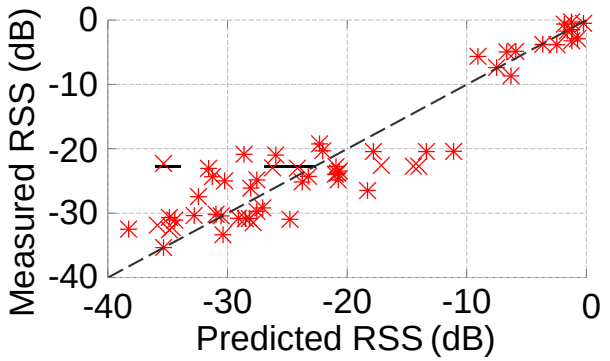




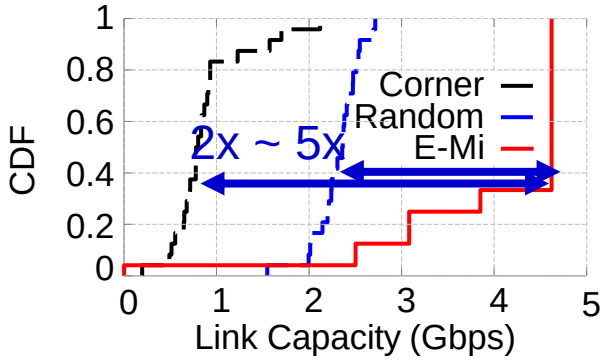
Predict Network Performance

- **Accuracy of link performance prediction**

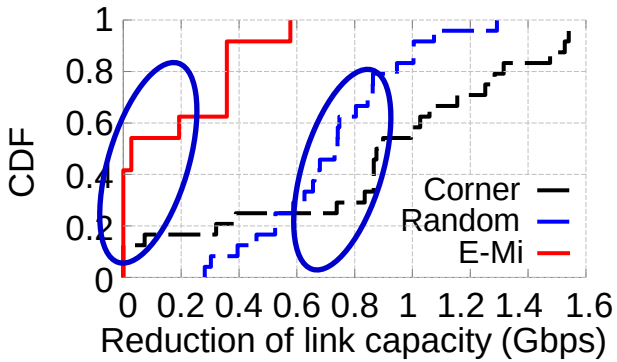




- **Case study: environment-aware 60 GHz Networking**



Coverage



Robustness

Conclusion

- **E-Mi: a *sensing-assisted* paradigm to facilitate 60 GHz networks**
- **A computational approach to *radio environment reconstruction* and *network performance prediction***
  - Multipath resolution framework
  - “Reverse-engineer” the geometry/reflectivity of dominant reflectors
  - Predict and optimize the AP placement
- **Testbed experiments and case studies**
  - Augment network planning and protocol reconfigurations

Questions?



Thank you