BeamSpy: Enabling Robust 60 GHz Links Under Blockage

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The 1000x Challenge

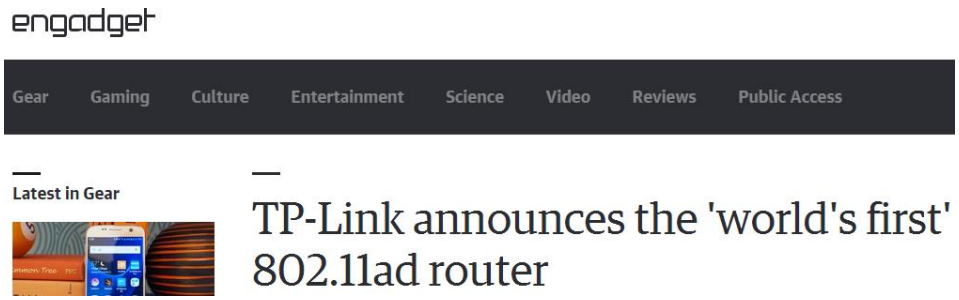
- 1000x explosion of wireless traffic by 2020*
  - Uncompressed video streaming
  - Wireless data centers

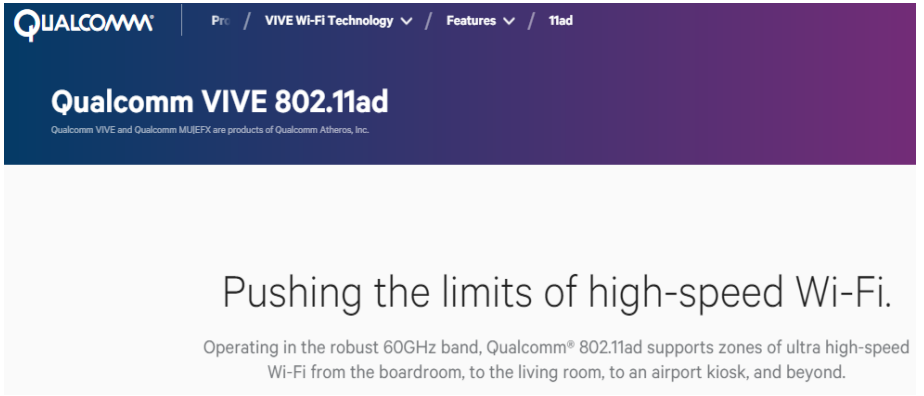
  - P2P snap download
  - 5G mobile broadband access

* Compared to 2012: www.qualcomm.com/1000x

New Opportunity at 60 GHz

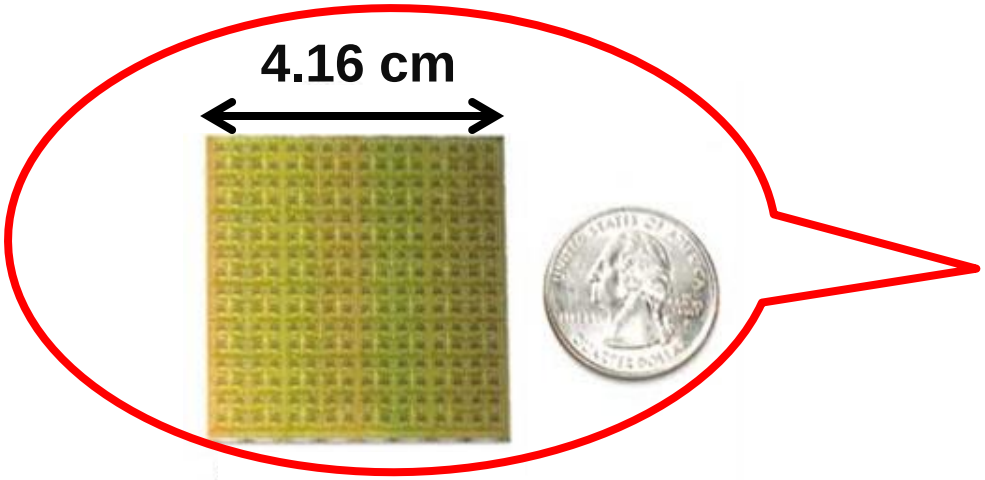
- Large *unlicensed spectrum* at 60 GHz millimeter-wave band
  - 70x wider bandwidth compared to typical LTE
  - 7Gbps of bit-rate
- Standardization activities
  - *IEEE 802.11ad*, IEEE 802.15.3c, ECMA-387





60 GHz Link Challenges

- Challenges:
  - Attenuation: 60 GHz signal strength is 625 times weaker than WiFi!



16x16 phased-array antenna *

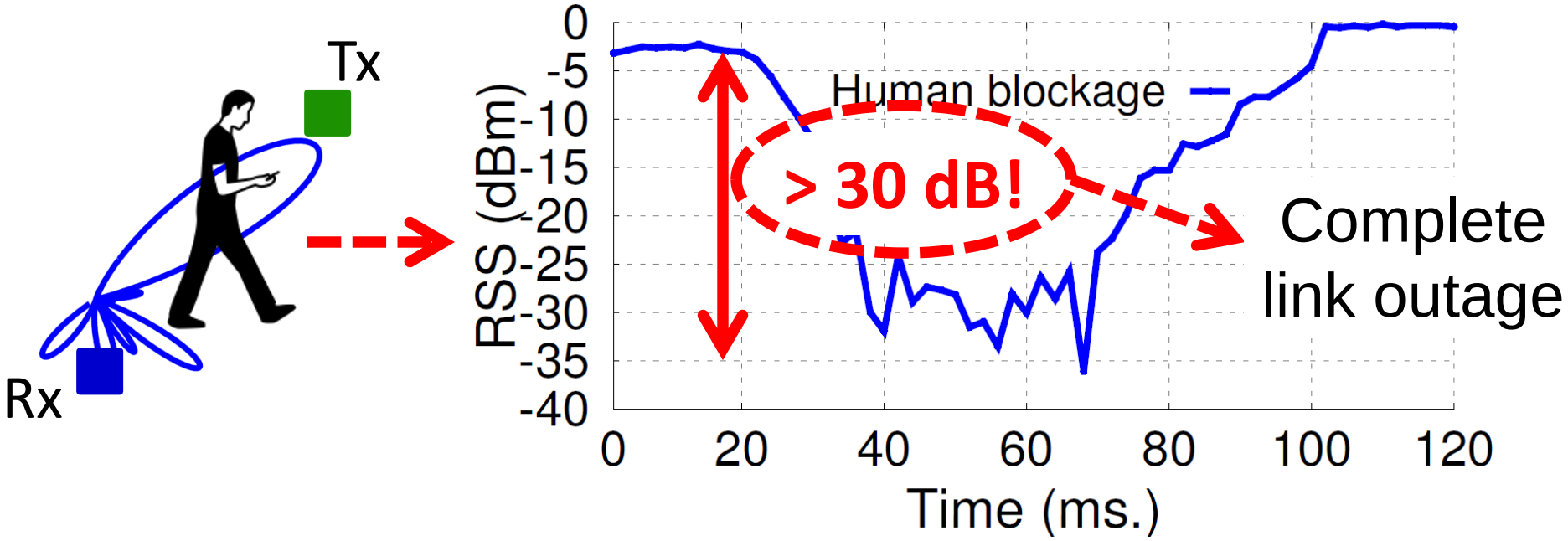
60 GHz beams

  - Directionality: Narrow beamwidth -- new challenges in link *establishment and maintenance*

* http://www.ece.ucsd.edu/node/2812

Human Blockage on 60 GHz Beams

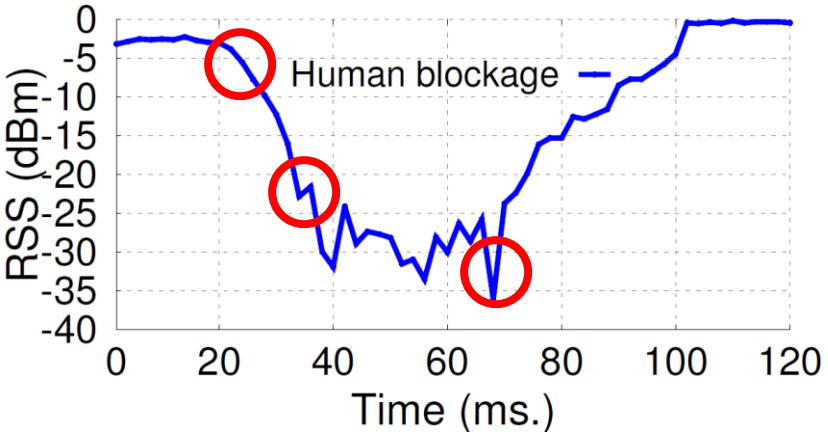
- Human blockage renders *complete link outage*
  - The body absorbs most of the 60 GHz signal energy



BeamSpy enables a robust link under such blockage

Any Issue with Naïve Beam-Searching?

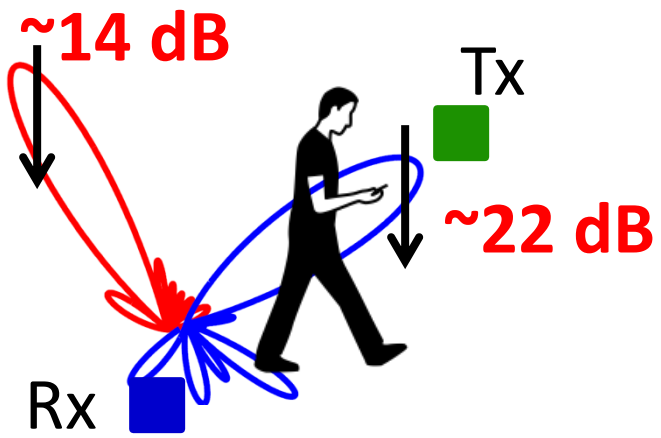
- Searching *overhead* grows with the number of available beam directions
- There is no *optimal trigger-time* for beam-searching

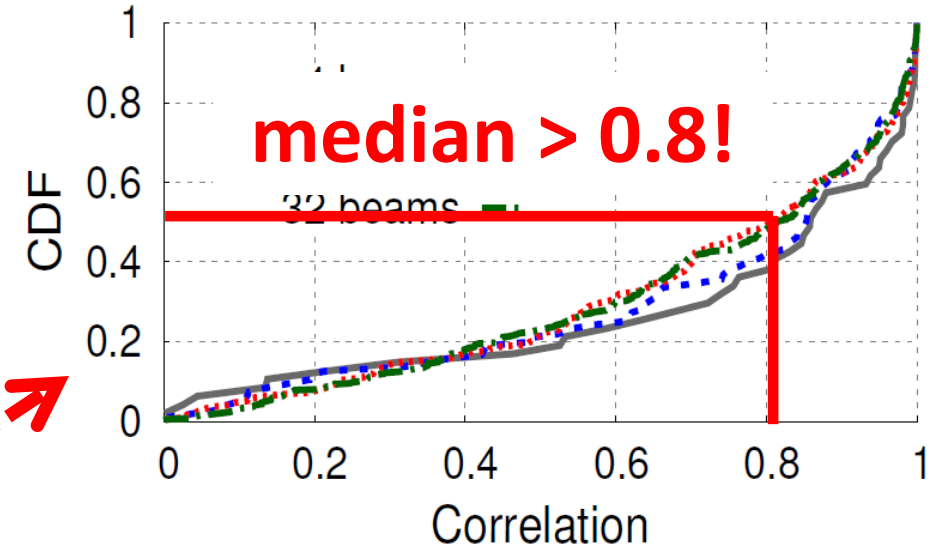


- There is *no guarantee* that beam-searching will find an effective beam direction
  - Can we predict effectiveness of beam-searching?
  - Prevention is always better than cure!

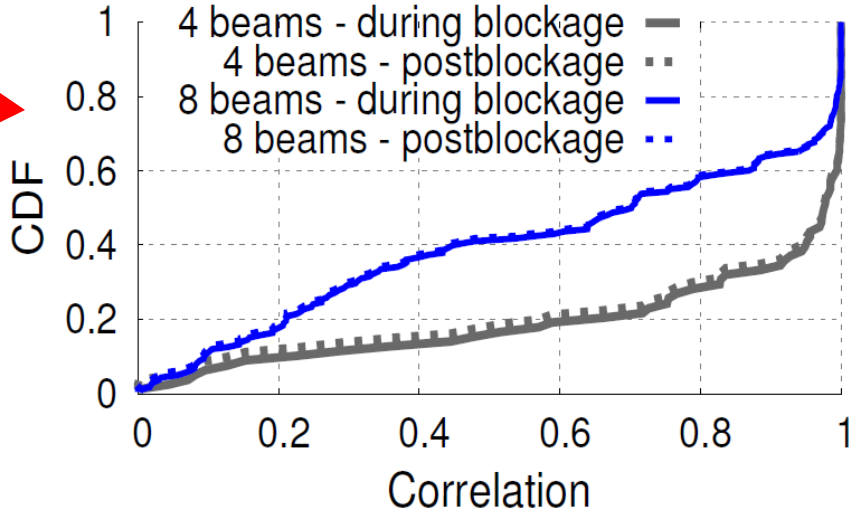
Key Insight: Beams Are Correlated!

- Blockage in a beam *drops performance* of other beams!





RSS drop correlation of other beams w.r.t. strongest beam



- Correlation remain *unchanged* irrespective of blockage!

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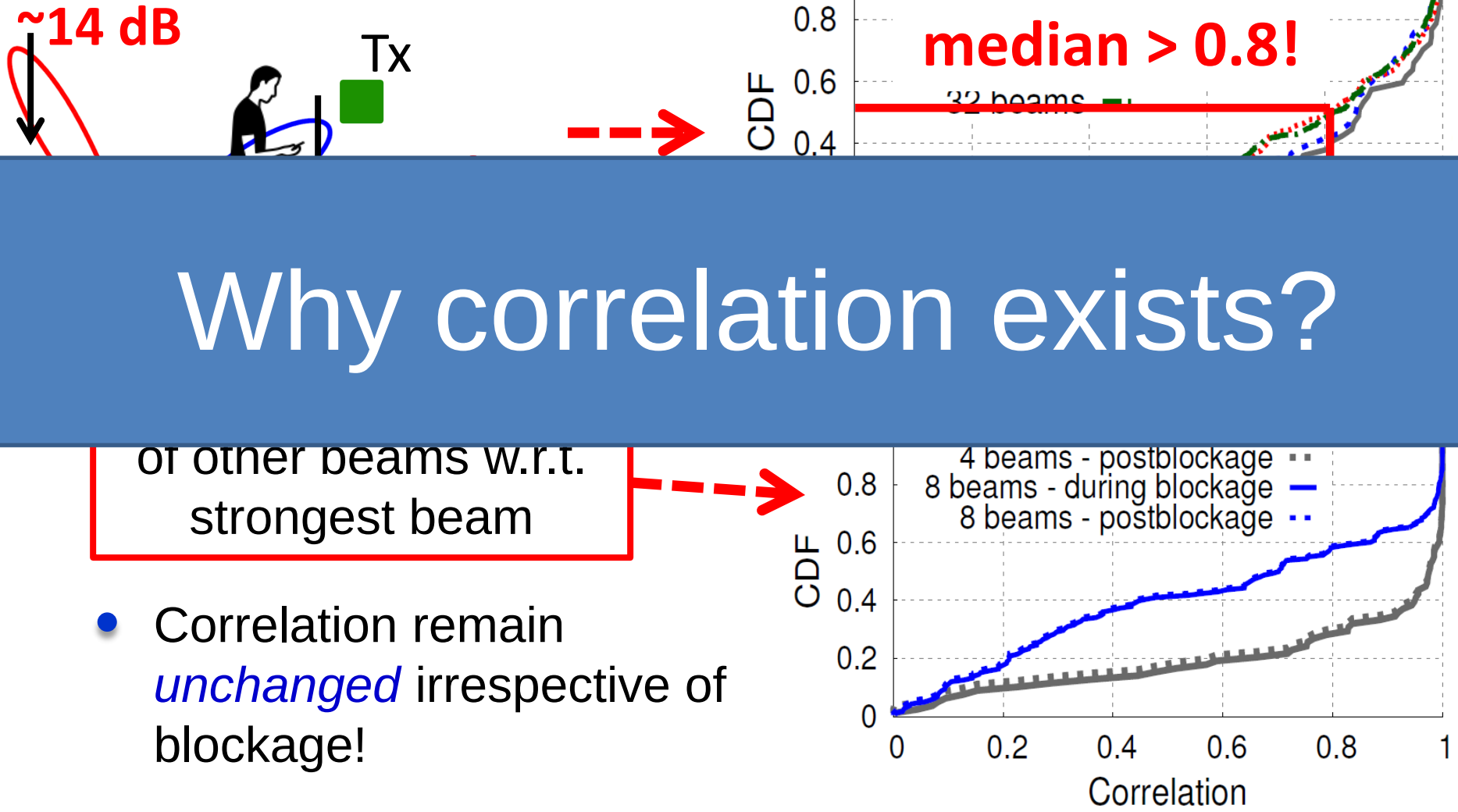
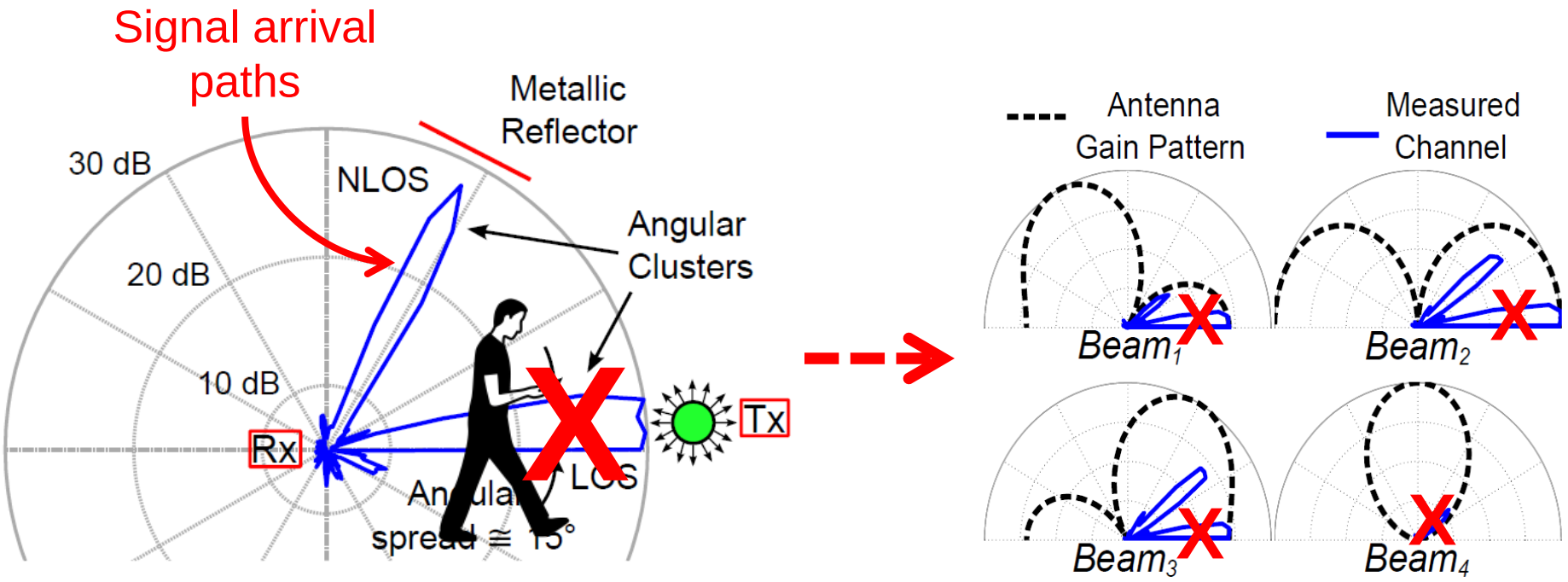


- Correlation remain *unchanged* irrespective of blockage!

Correlation Root Cause: Sparse Channel

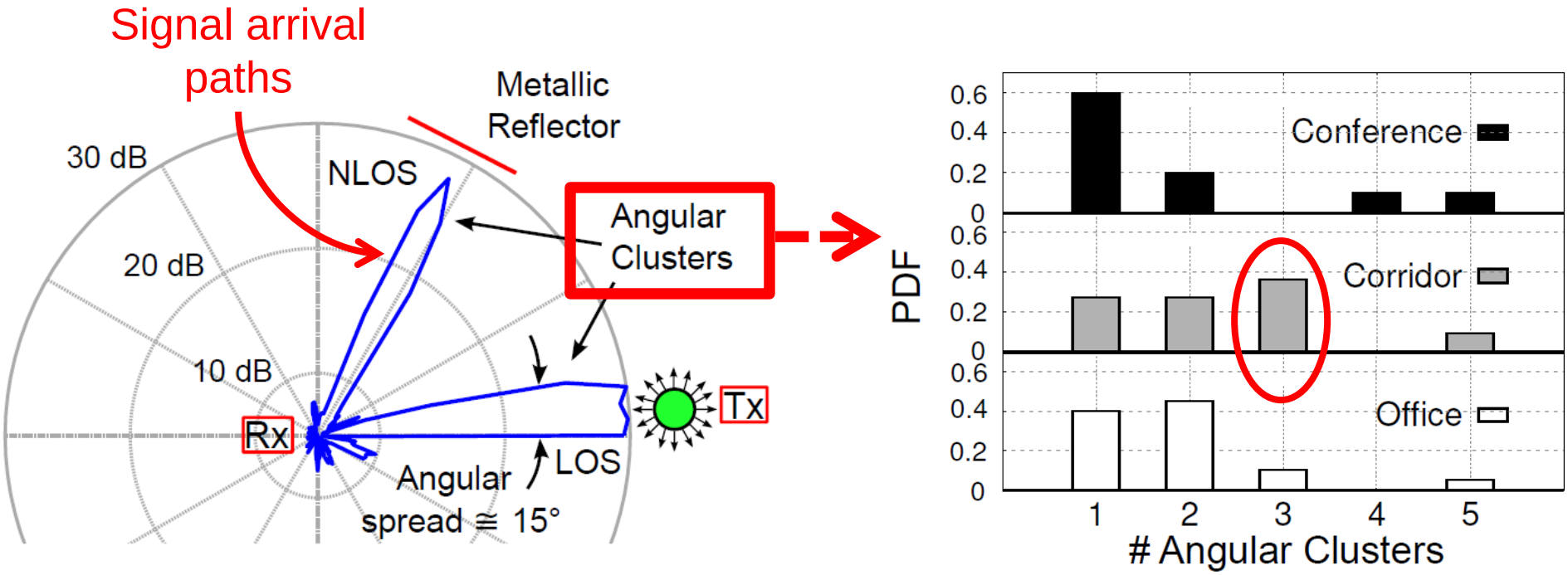
- 60 GHz spatial channels are *sparse*



Sparse signal arrival paths are *shared* between beams, thus blockage causes correlated RSS drop in all beams!

Clustering Effect Across Multi Environments

- Limited number of angular clusters



Sparse clustering effect is prevalent across multiple environments

Clustering Effect Across Multi Environments

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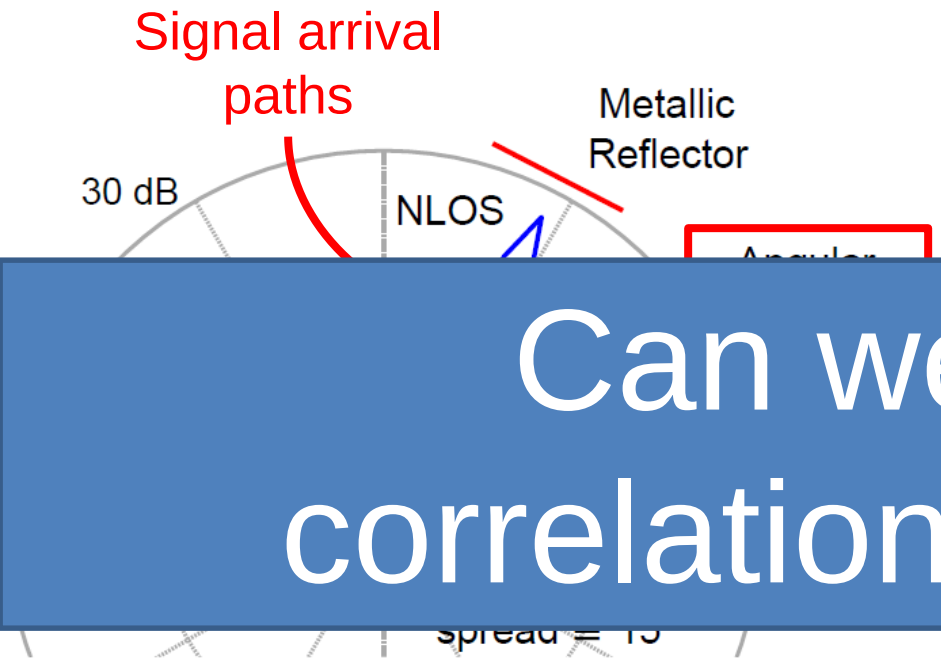
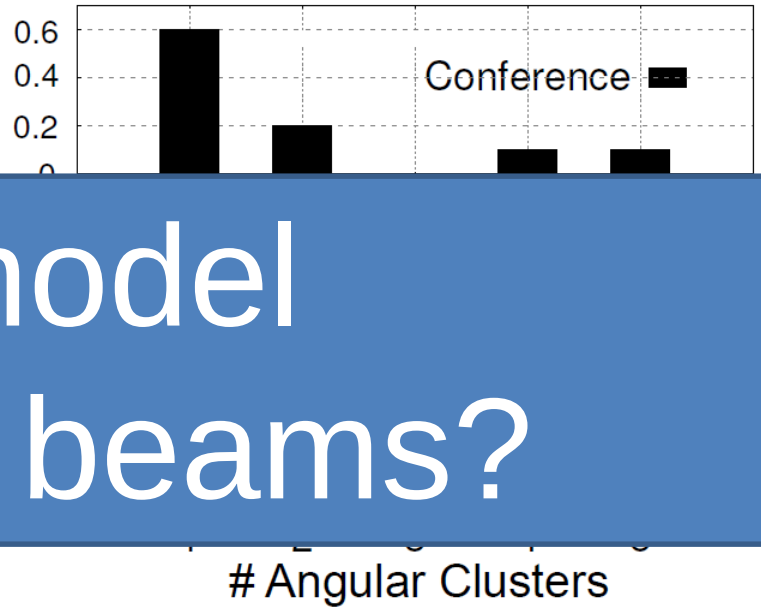


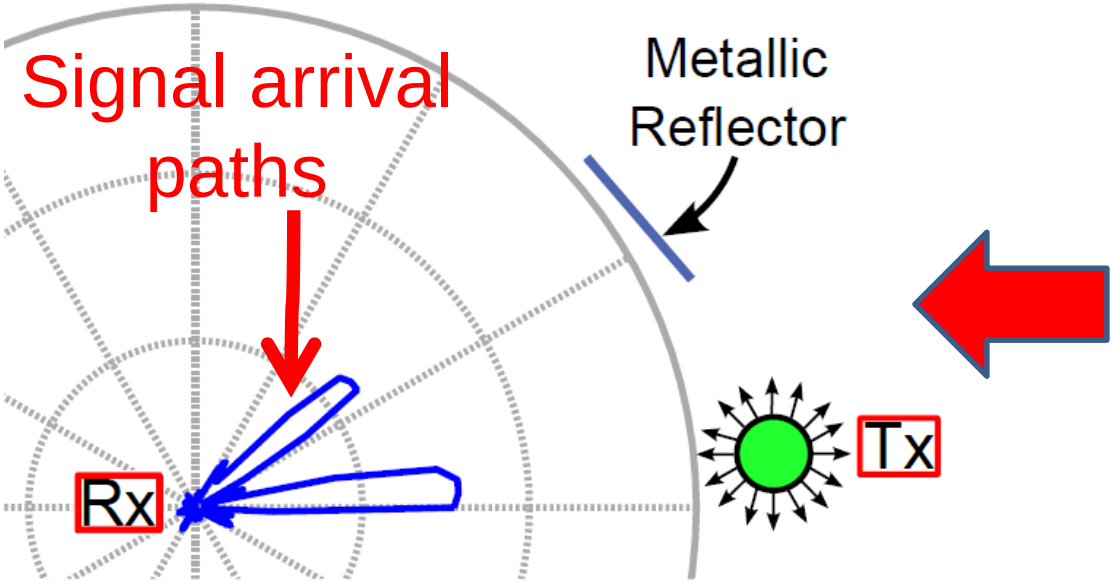


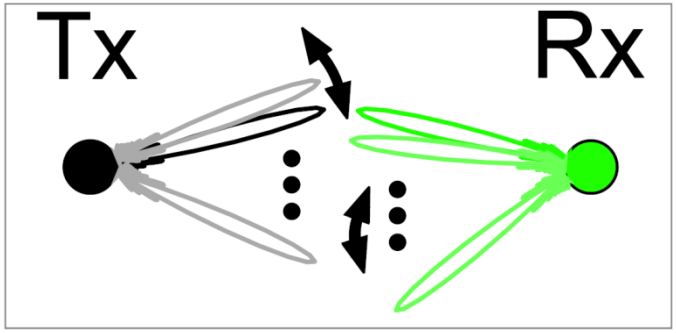
Can we model correlation of beams?

Sparse clustering effect is prevalent across multiple environments

BeamSpy Design

- Modeling the way beams *share* the sparse clusters



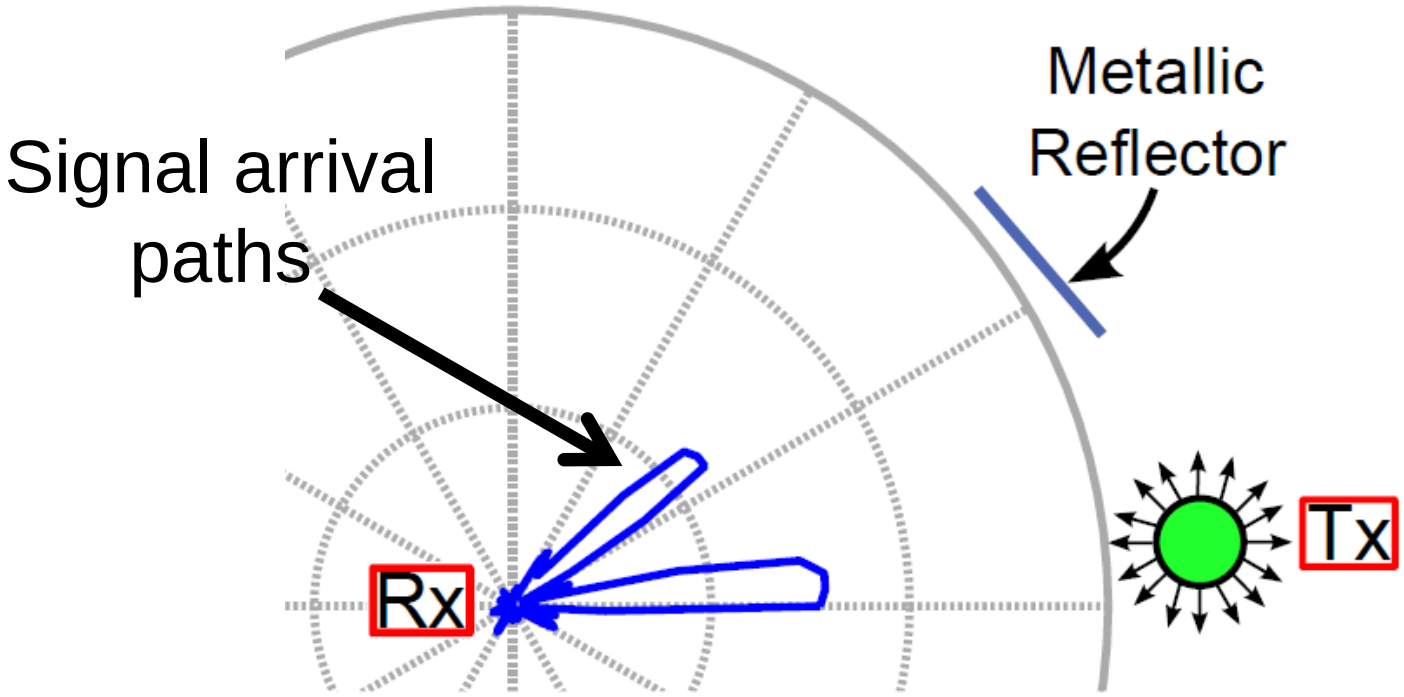


Discrete coarse beam-steering

How to measure *fine-grained* signal arrival paths given that devices can have only *coarse beam-steering*?

Path Skeleton to Represent Sparse Cluster

- Track only the *dominating directions* and *strengths*



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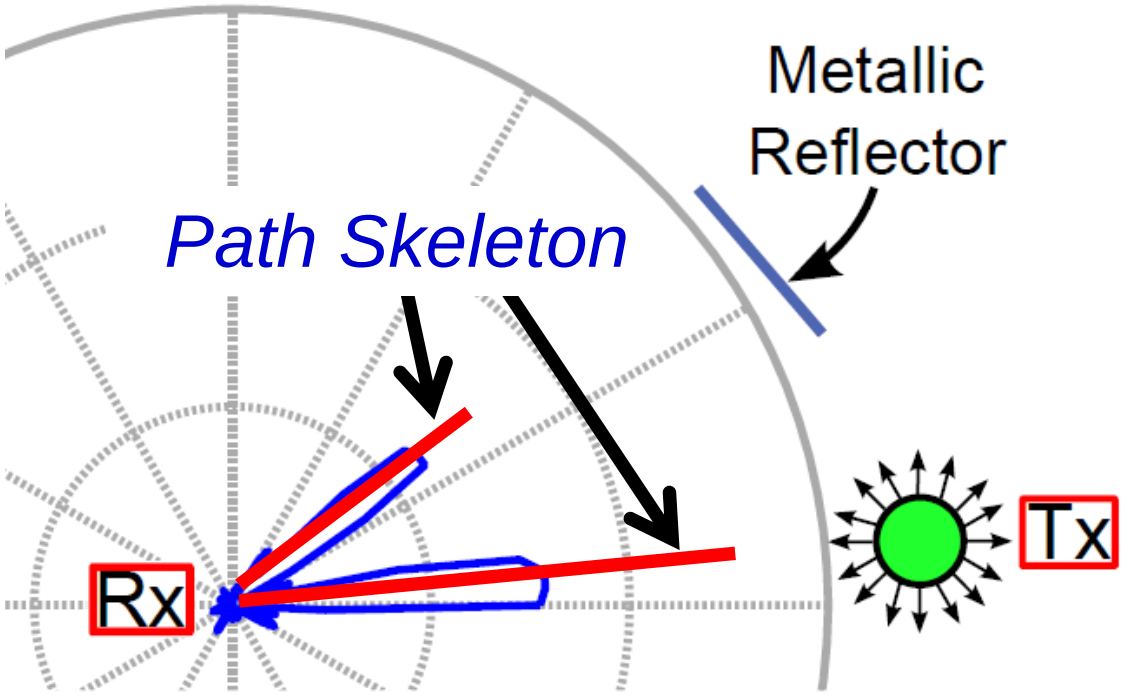

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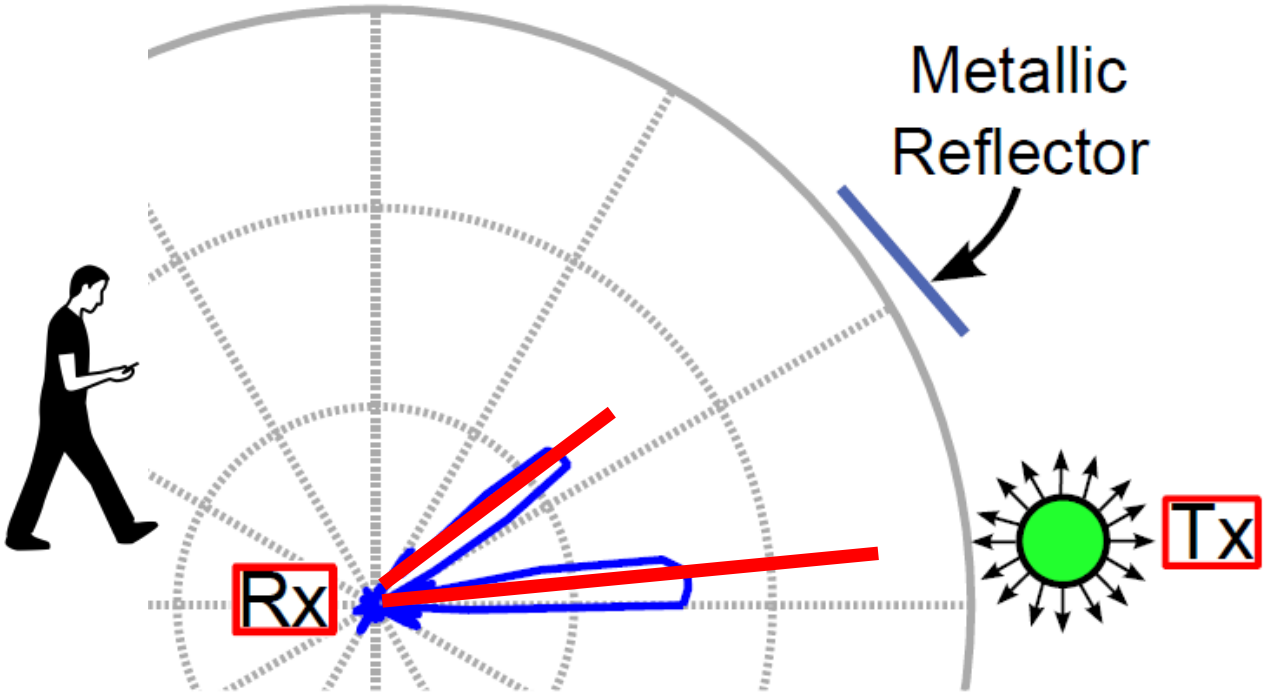

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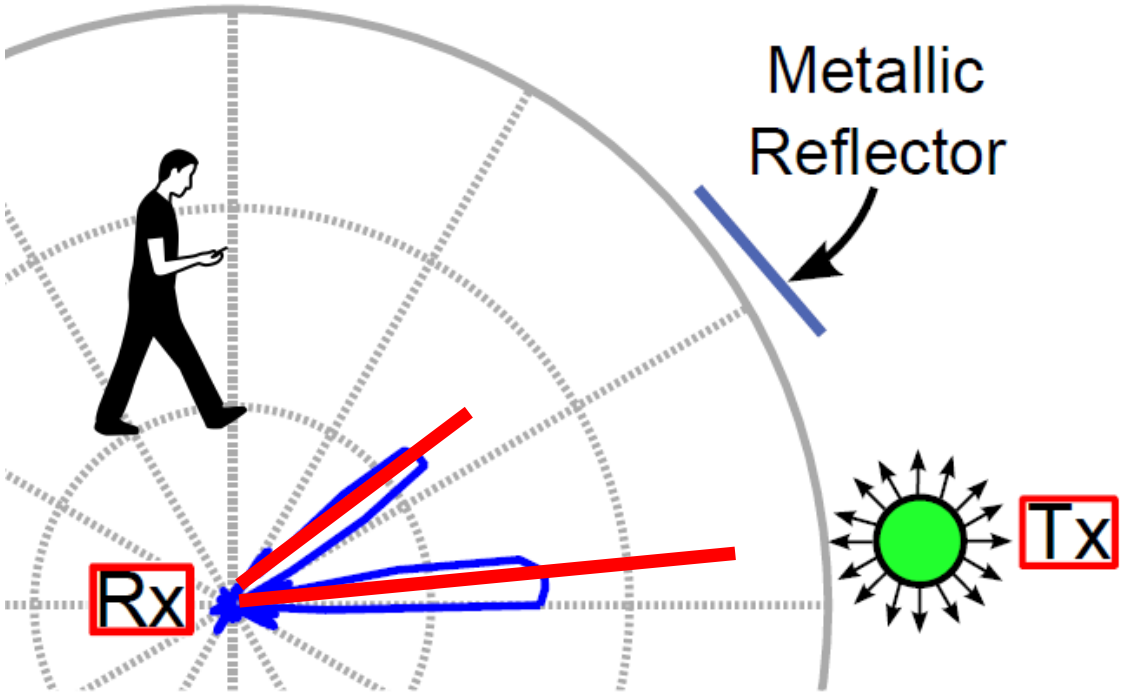

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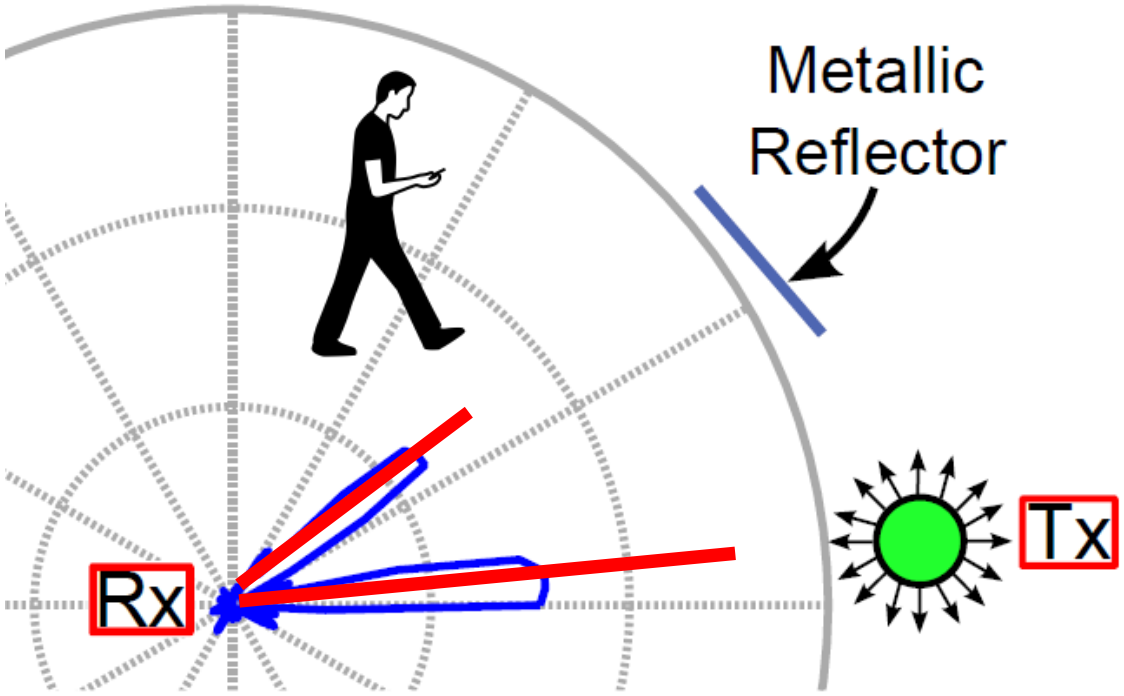

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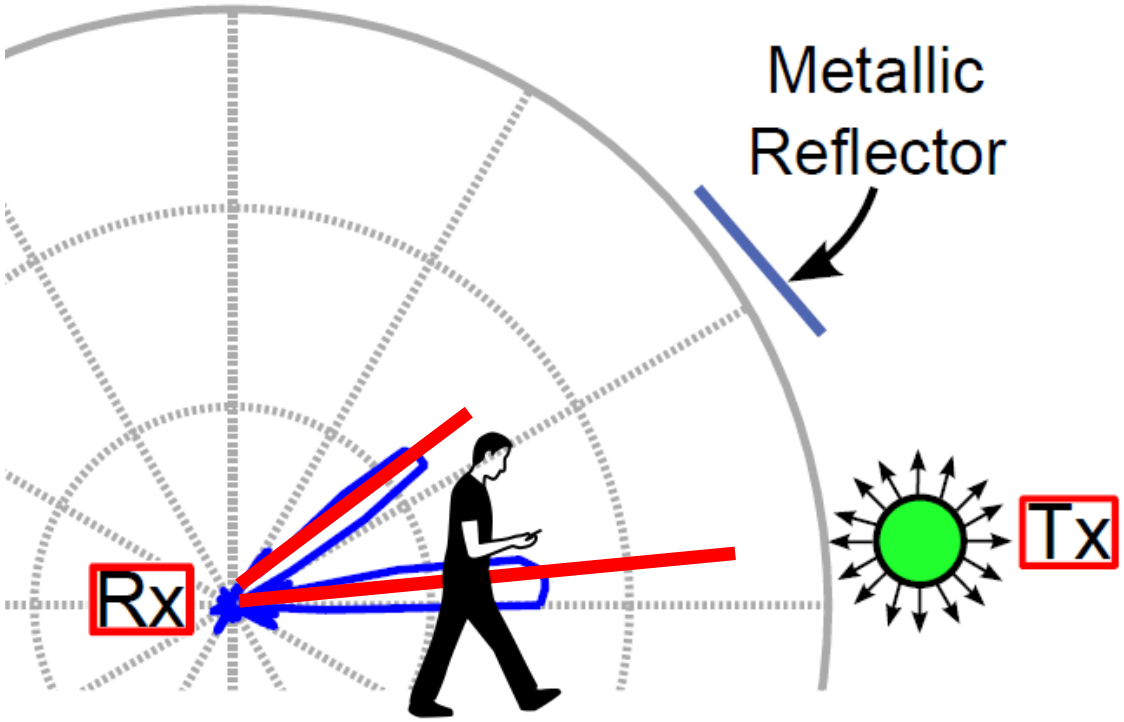
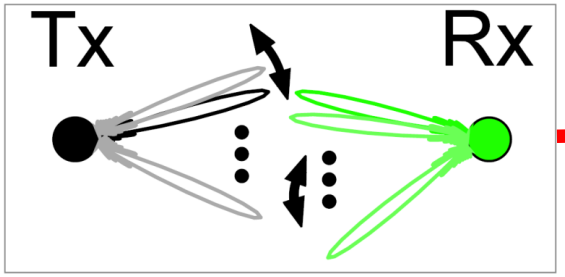


Predicting the Best Beam during Blockage

At deployment time



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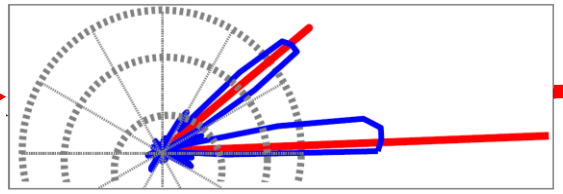
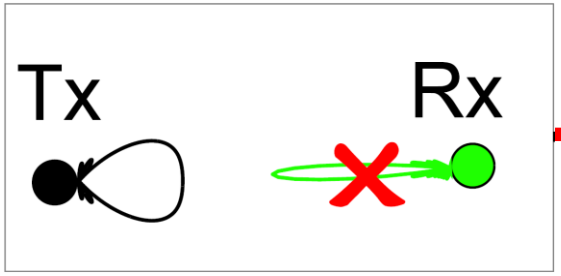


Model Sparse Clusters

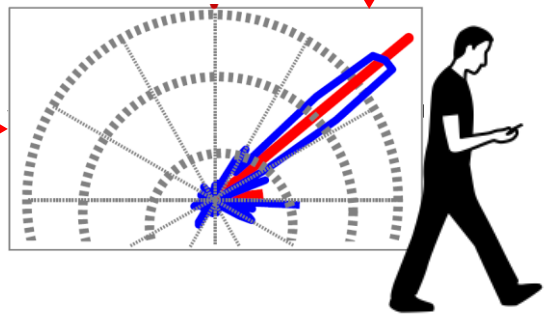
Store one *path skeleton* for each Tx beam

Track Path Skeleton

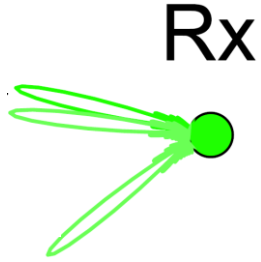
At run time



Beam is blocked



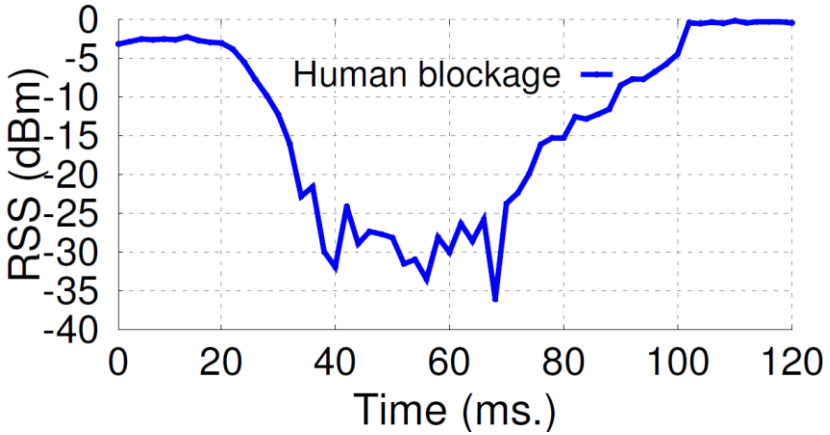
Identify state of Path Skeleton



Predict RSS of other beams from new state

Does prediction solve beam-searching problem?

- Searching *overhead* grows with the number of available beam directions
- There is no *optimal trigger-time* for beam-searching



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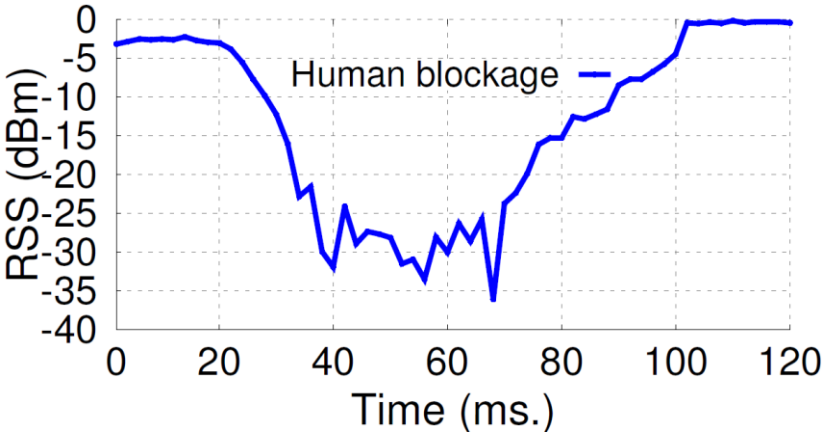

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  - Can we predict effectiveness of beam-searching?
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Does prediction solve beam-searching problem?

- Searching *overhead* grows with the number of available beam directions

Predicting *no beam* works during blockage does not help much!

effective beam direction

- Can we predict effectiveness of beam-searching?
- Prevention is always better than cure!

Does prediction solve beam-searching problem?

- Searching *overhead* grows with the number of available beam directions

Can we do something better?

effective beam direction

- Can we predict effectiveness of beam-searching?
- Prevention is always better than cure!

Link Outage Risk Assessment

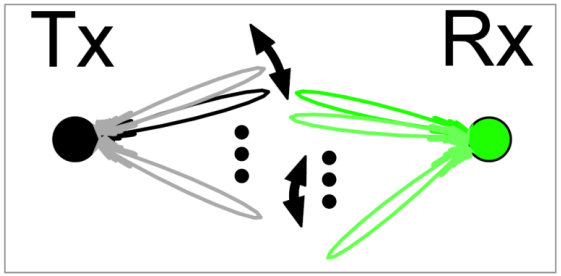
Assess a *probabilistic outage risk* of a link during placement and even before blockage occurs

In other words

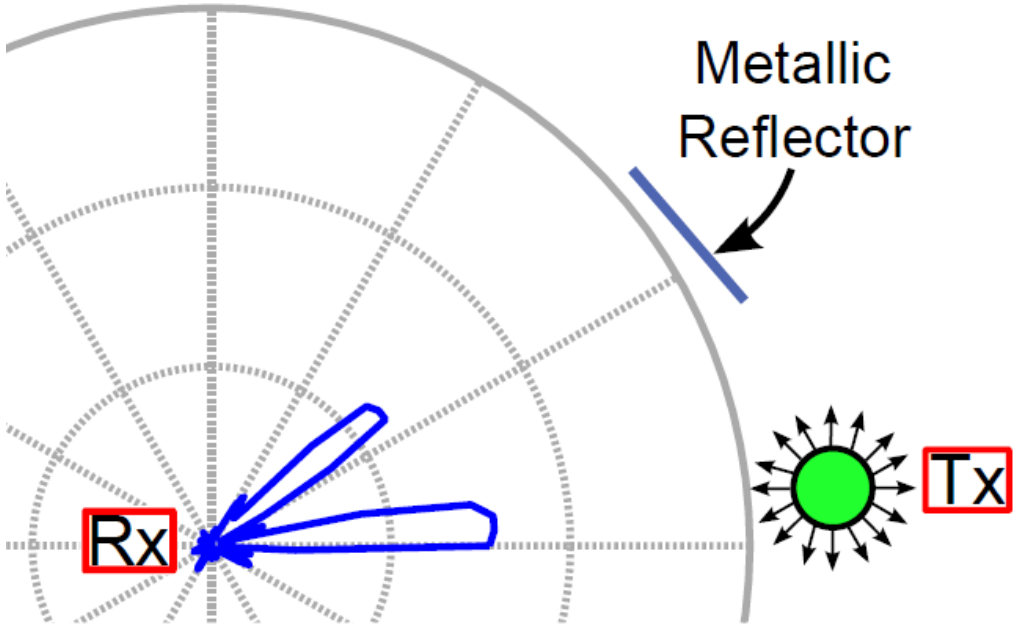
What is the *likelihood* that no beam will work in a future blockage?

Link Outage Risk Assessment

- Emulate *virtual blockage* during link placement on sparse clusters



Discrete coarse beam-steering



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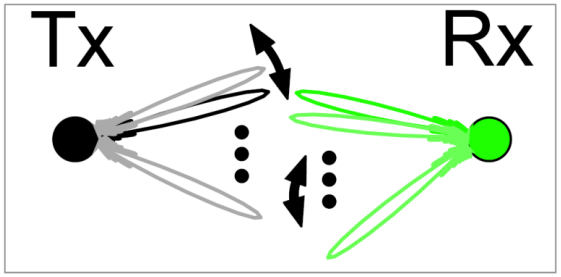

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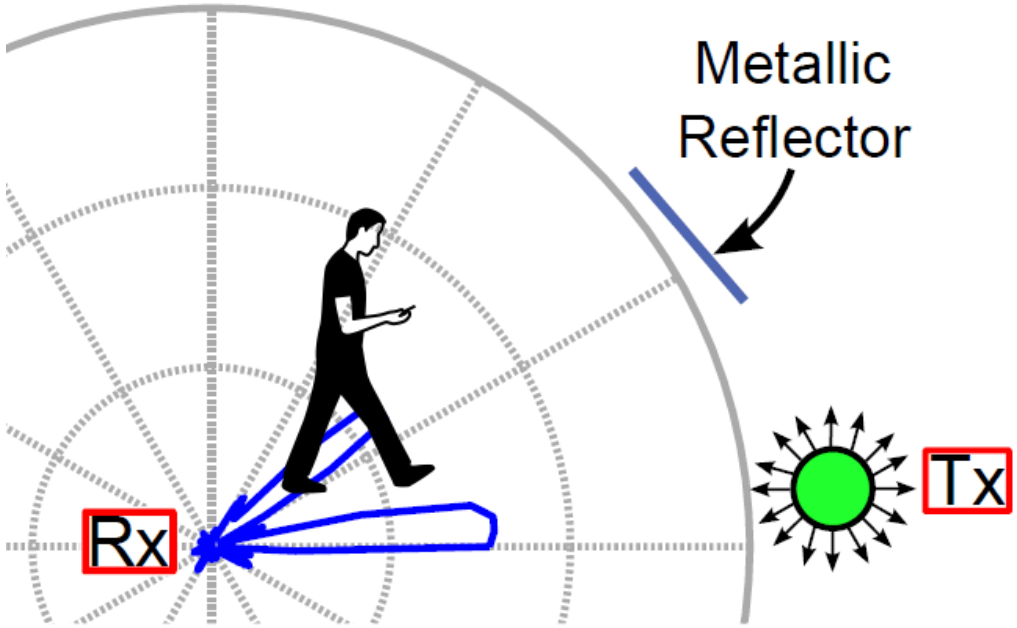

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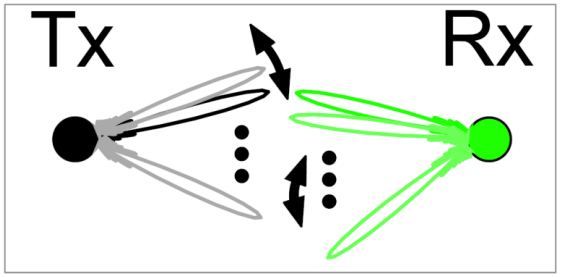

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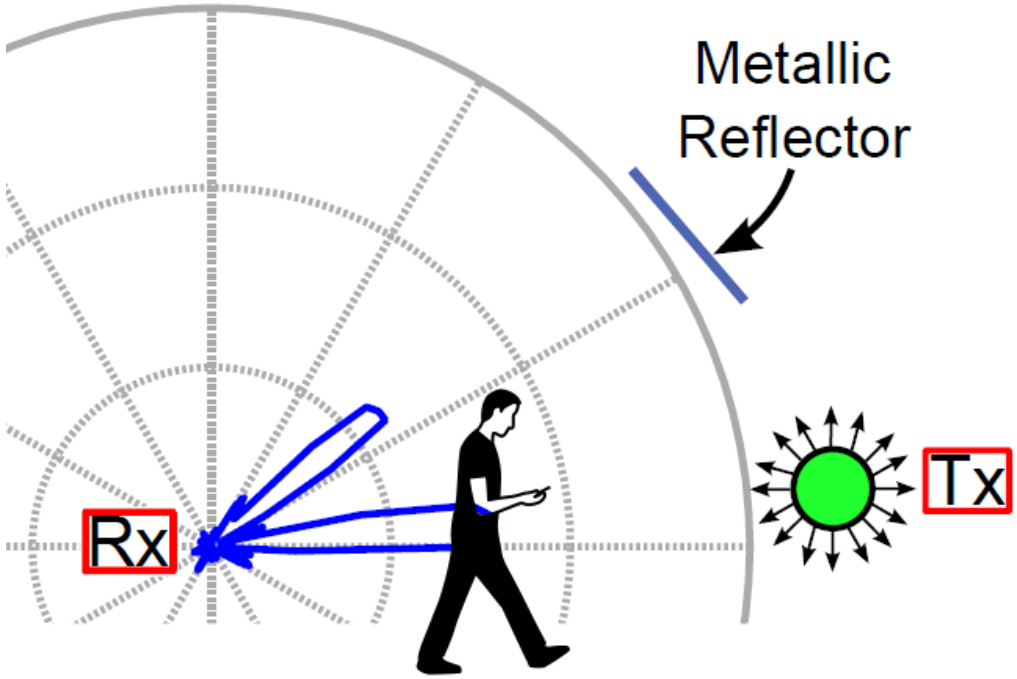

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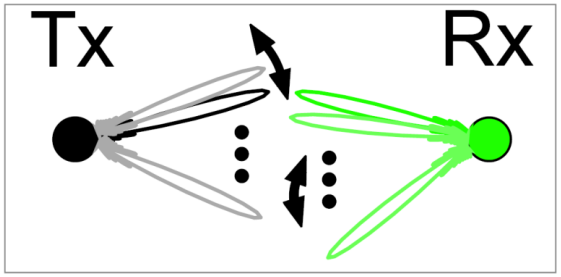

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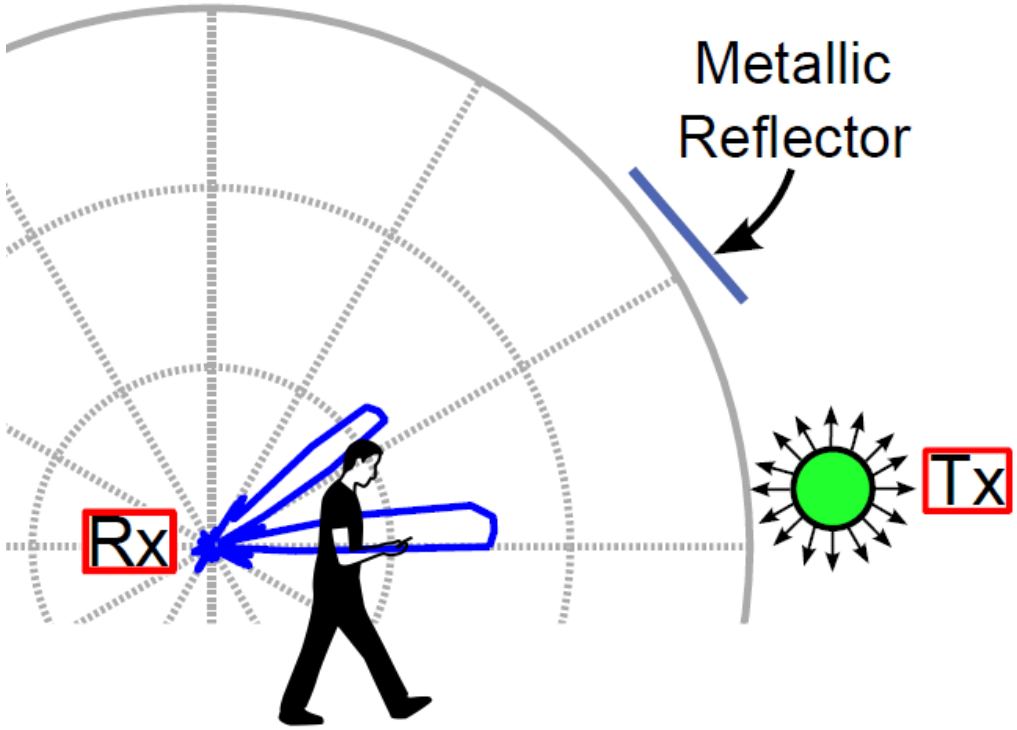
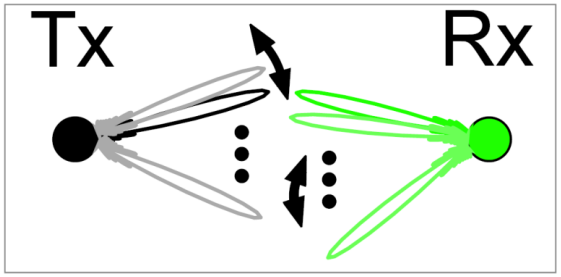


$$\text{Outage Risk} = \frac{\#\ \text{Virtual Link Outage}}{\#\ \text{Emulation}}$$

Link Outage Risk Assessment

- Due to sparse cluster, there are *discrete zones* where blockage affects the link's quality



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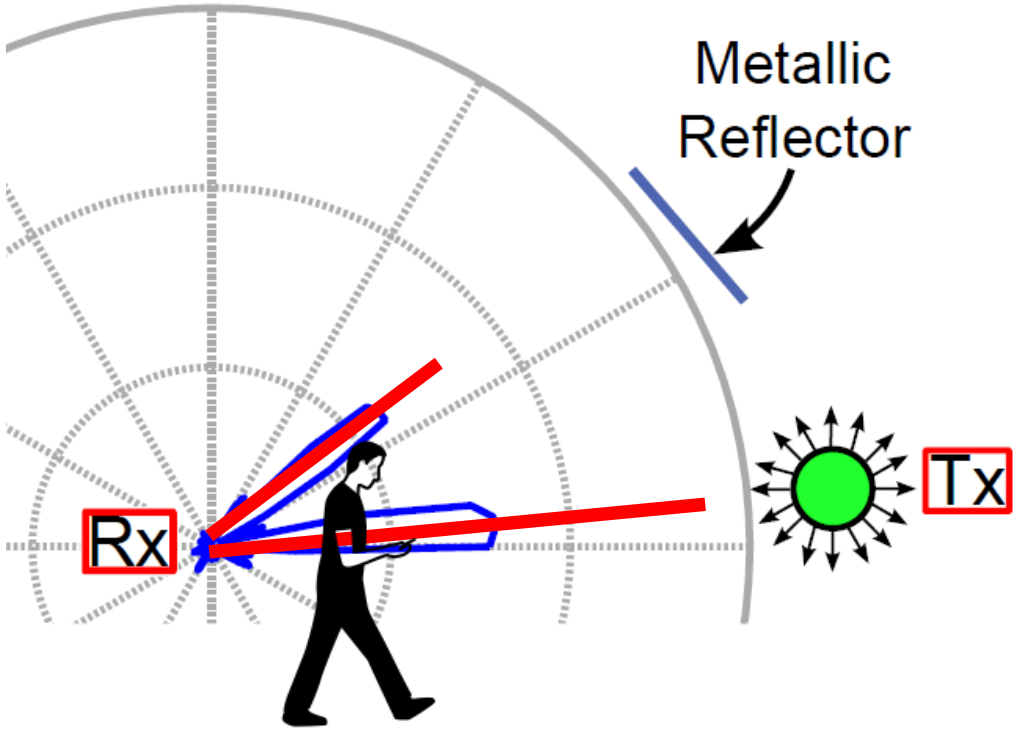
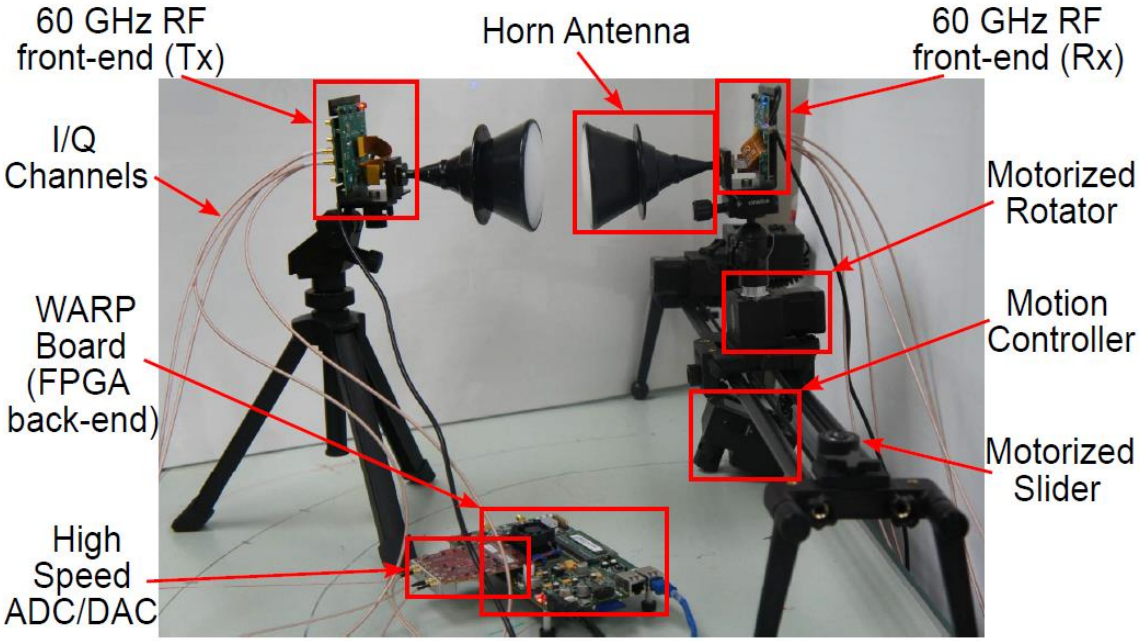


Testbed and Implementation

- *WiMi* custom-built 60 GHz software-defined radio

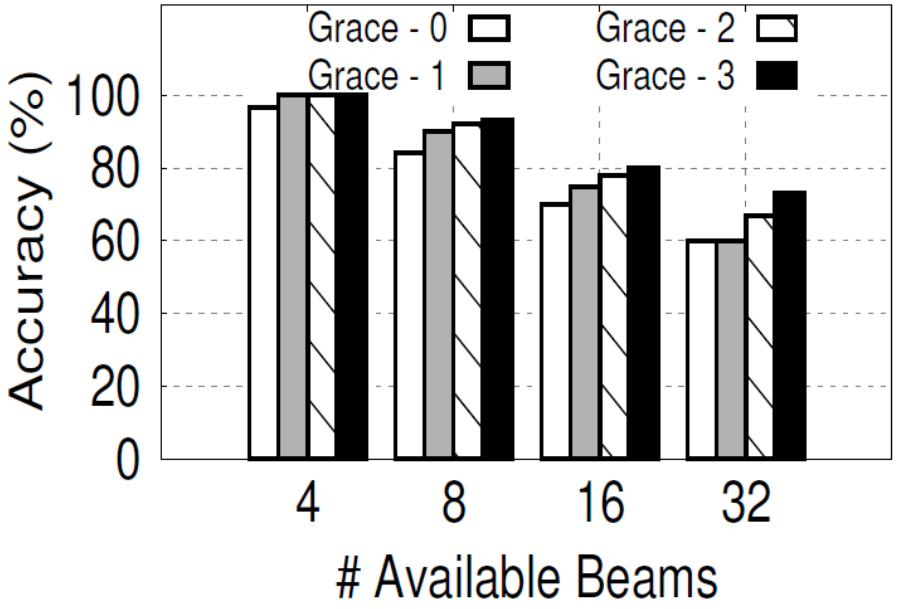


- Emulated phased-array beamforming through spatial channel measurements
- Simulated 802.11ad MAC layer, replayed channel traces on *DummyNet* to emulate transport/applications

Evaluation: Micro-benchmarks

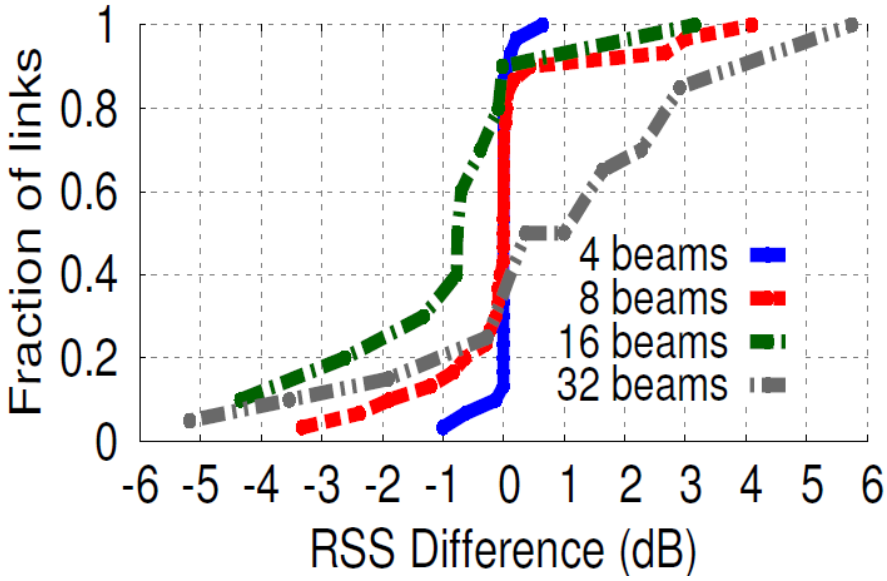
- *Accuracy* of best beam direction prediction under blockage

Close to 70% even with 32 beams!



- *Predicting RSS* of the best beam under blockage

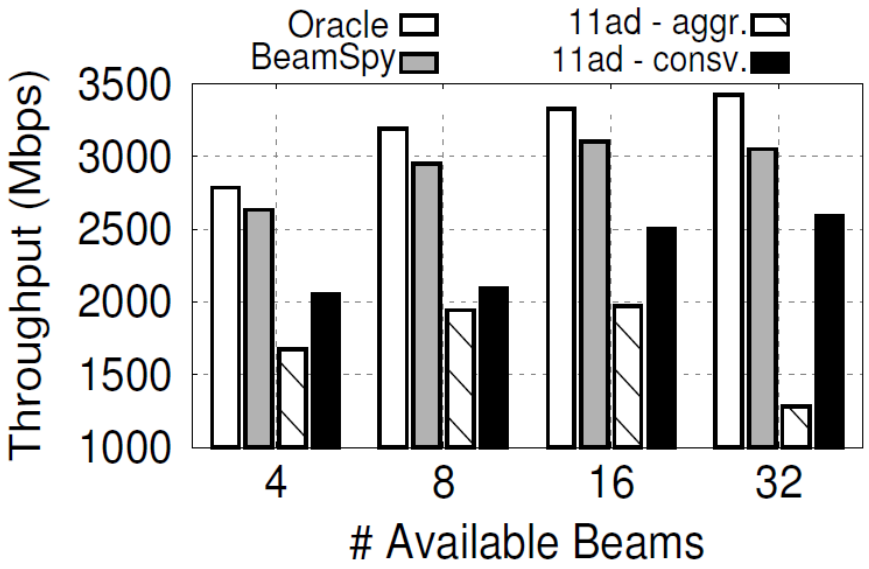
Prediction error (90%-ile) is within ±3 dB for 32 beam



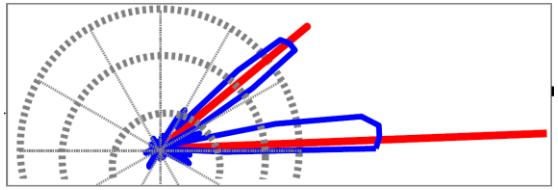
Performance Gain and Temporal Stability

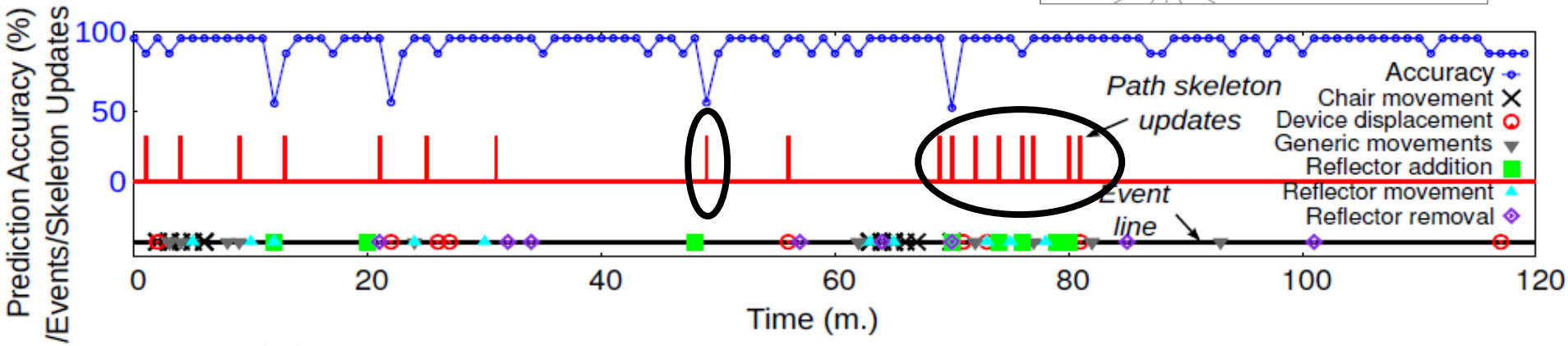
- Link *performance gain* under blockage

Throughput performance ~13% lower than oracle



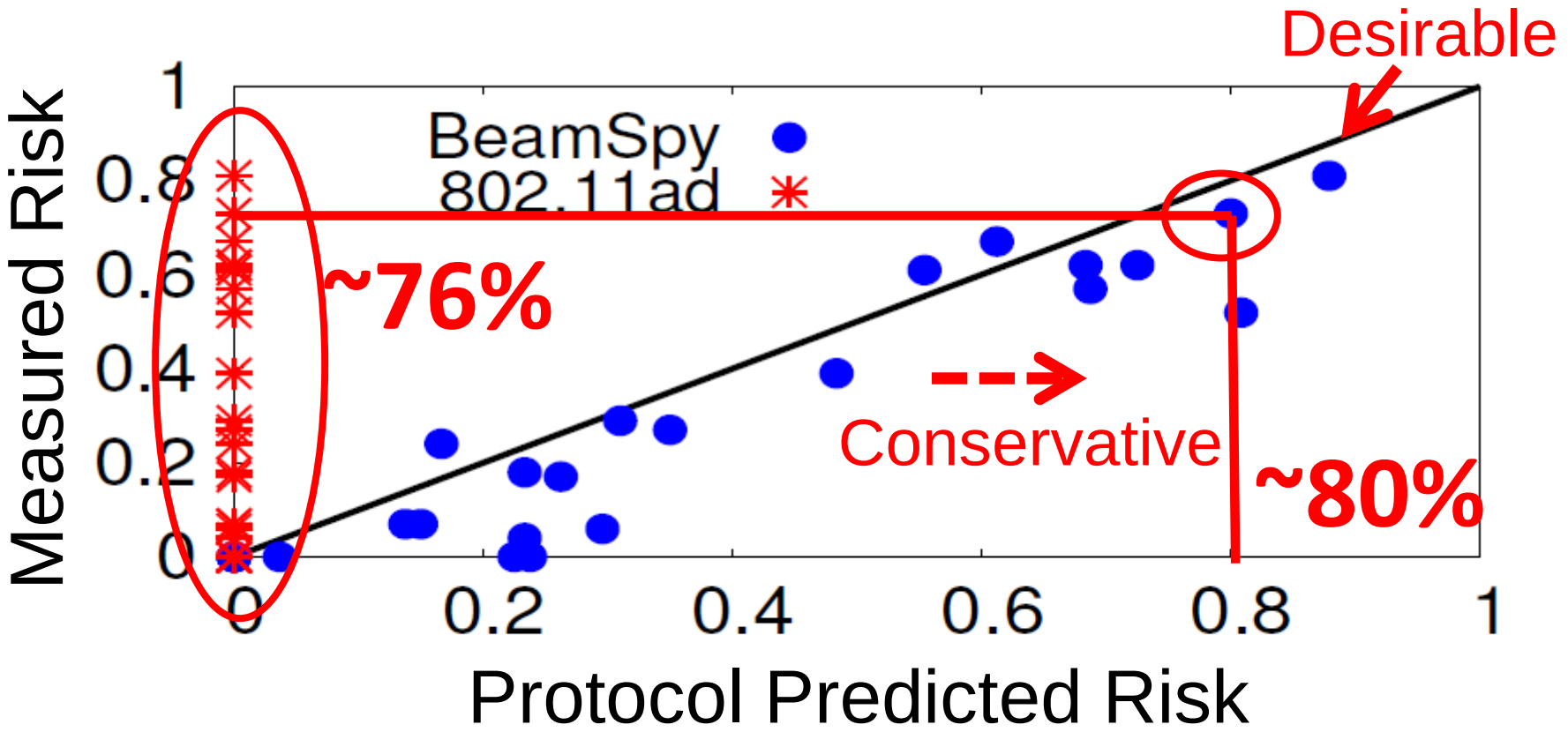
- How *stable* the *prediction accuracy* remains *over time*?





Link Outage Risk Assessment

- Effectiveness of *Risk-Assessment* algorithm

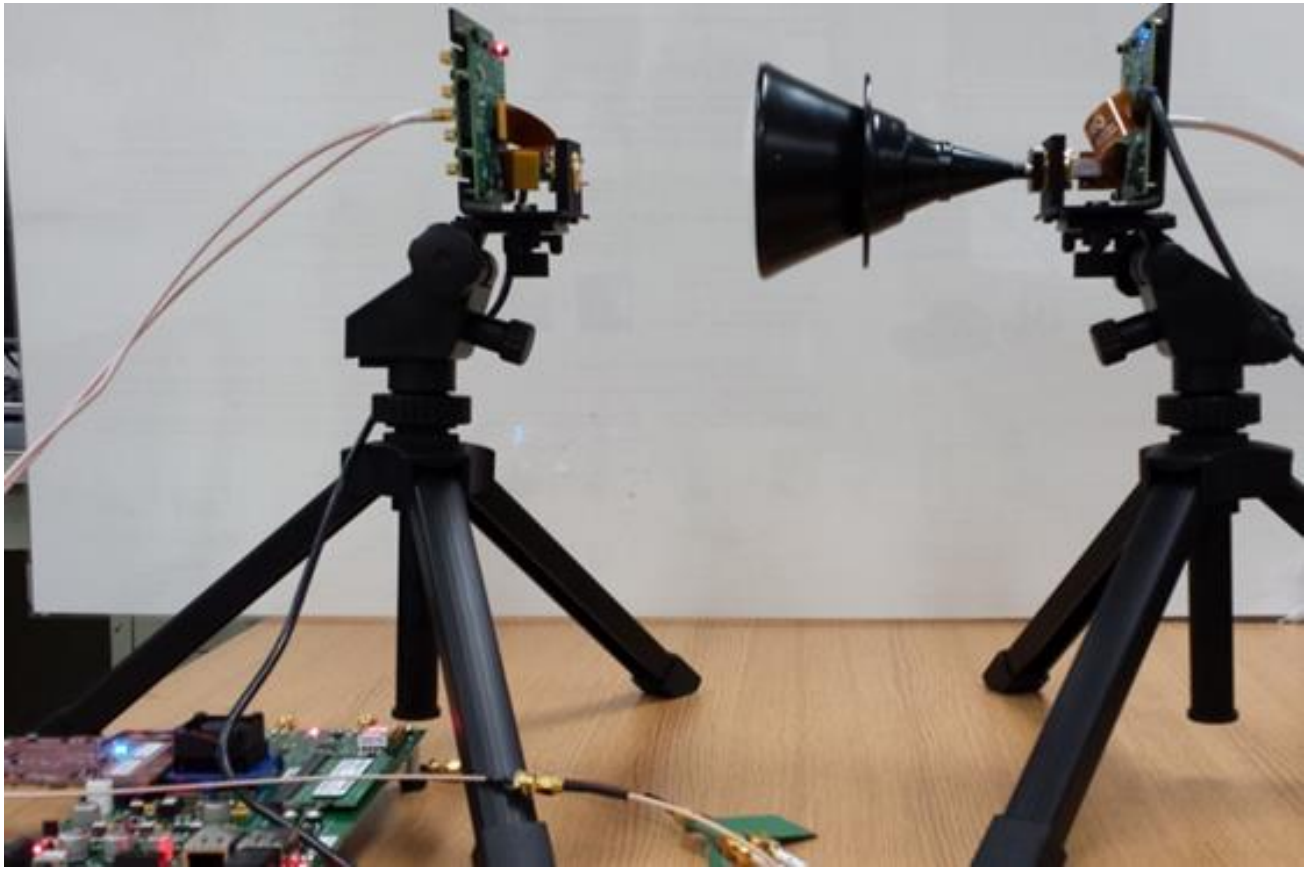


Summary

- BeamSpy predicts best beam under human blockage by leveraging *correlation* between beams
  - Correlation occurs due to unique *sparse channel* and phased-array characteristics at 60 GHz
- Closely identifies *likelihood* of link outage and urges deployment towards *blockage-proof* way

Wisconsin Millimeter-wave Software Radio (WiMi)

http://xyzhang.ece.wisc.edu/wimi



Thank you!