Millimeter Wave Communications:

From Point-to-Point Links to Agile Network Connections

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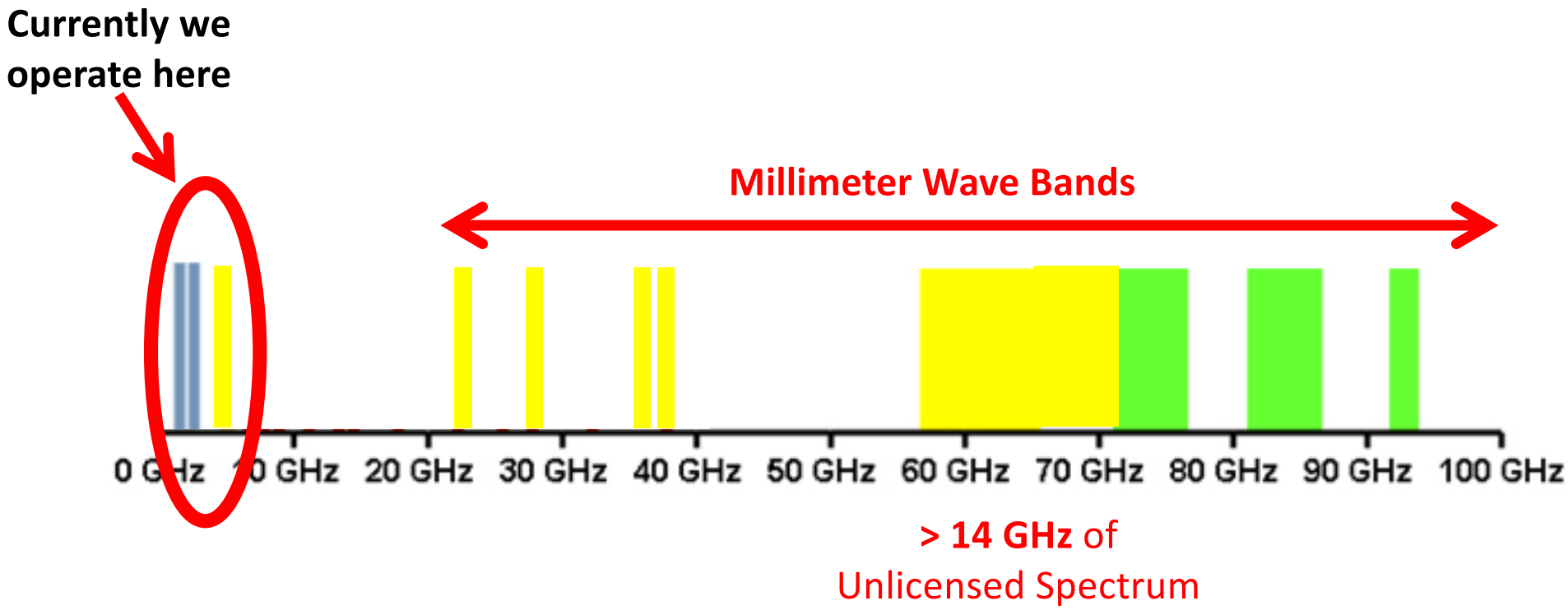
Spectrum Scarcity

Huge bandwidth available at millimeter wave frequencies

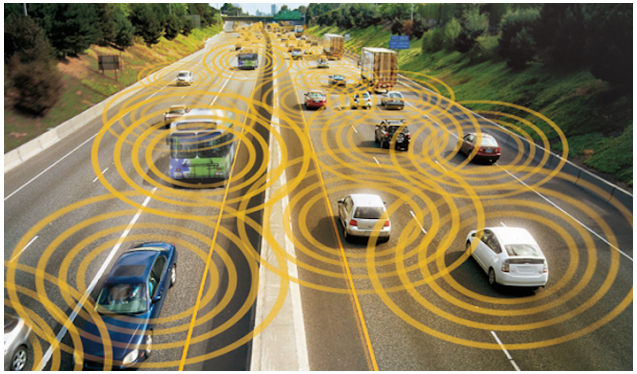


Millimeter Wave Wireless Applications

- Cellular Networks: 5G Picocells, Wireless backhaul
- Wireless LANs: IEEE 802.11ad, IEEE 802.15.3c, ECMA-387, Wireless-HD

Virtual Reality

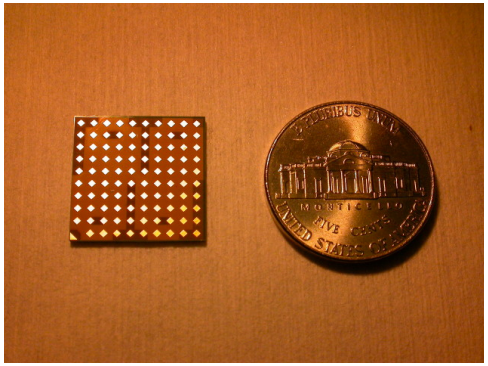
Wireless Data Centers

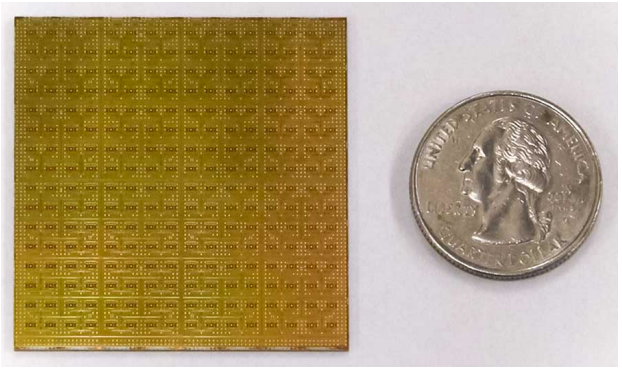


Connected Vehicles

Millimeter Waves Suffer from Large Attenuation

mmWave radios use phased antenna arrays to focus the power along one direction

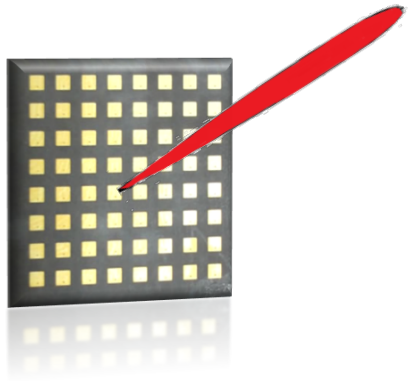




Small Wavelength enables thousands of antennas to be packed into small space

→ Extremely narrow beams

Challenge: How to build wireless networks with very directional links?



Challenge: How to build wireless networks with very directional links?

Communication is possible only when AP and Client beams are aligned!!

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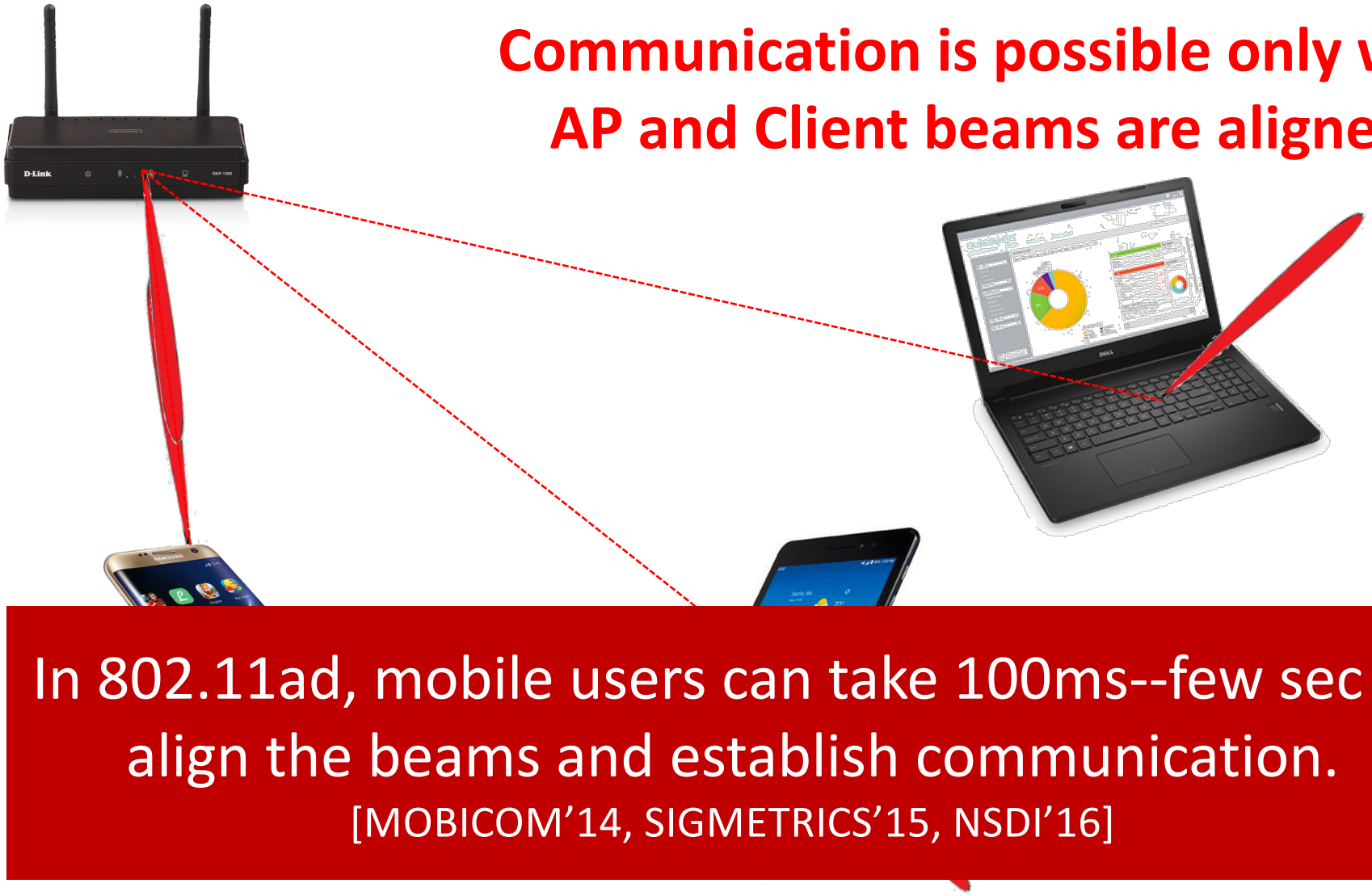


Communication is possible only when AP and Client beams are aligned!!

In 802.11ad, mobile users can take 100ms--few sec to align the beams and establish communication.

[MOBICOM'14, SIGMETRICS'15, NSDI'16]

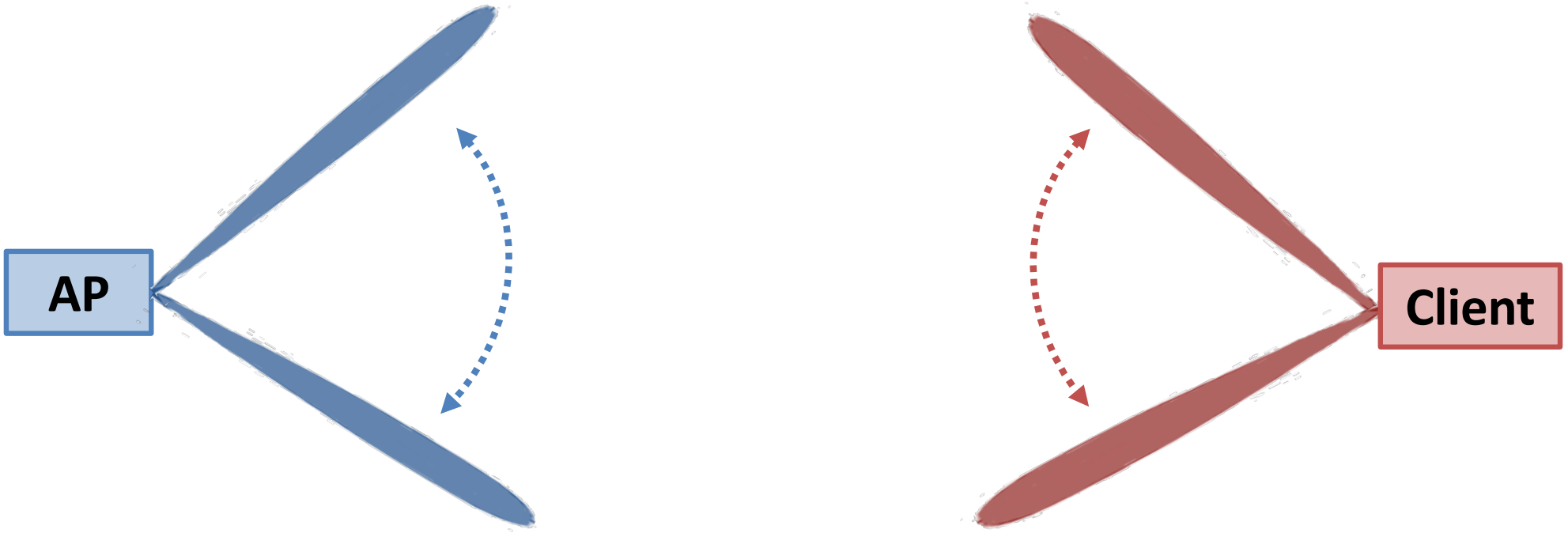
Agile-Link: A millimeter wave system that can quickly align the beams to establish and maintain communication.

Outline

- Background
- Agile Link System
- Evaluation

How to align the beams of the AP and Client?

N : number of possible directions



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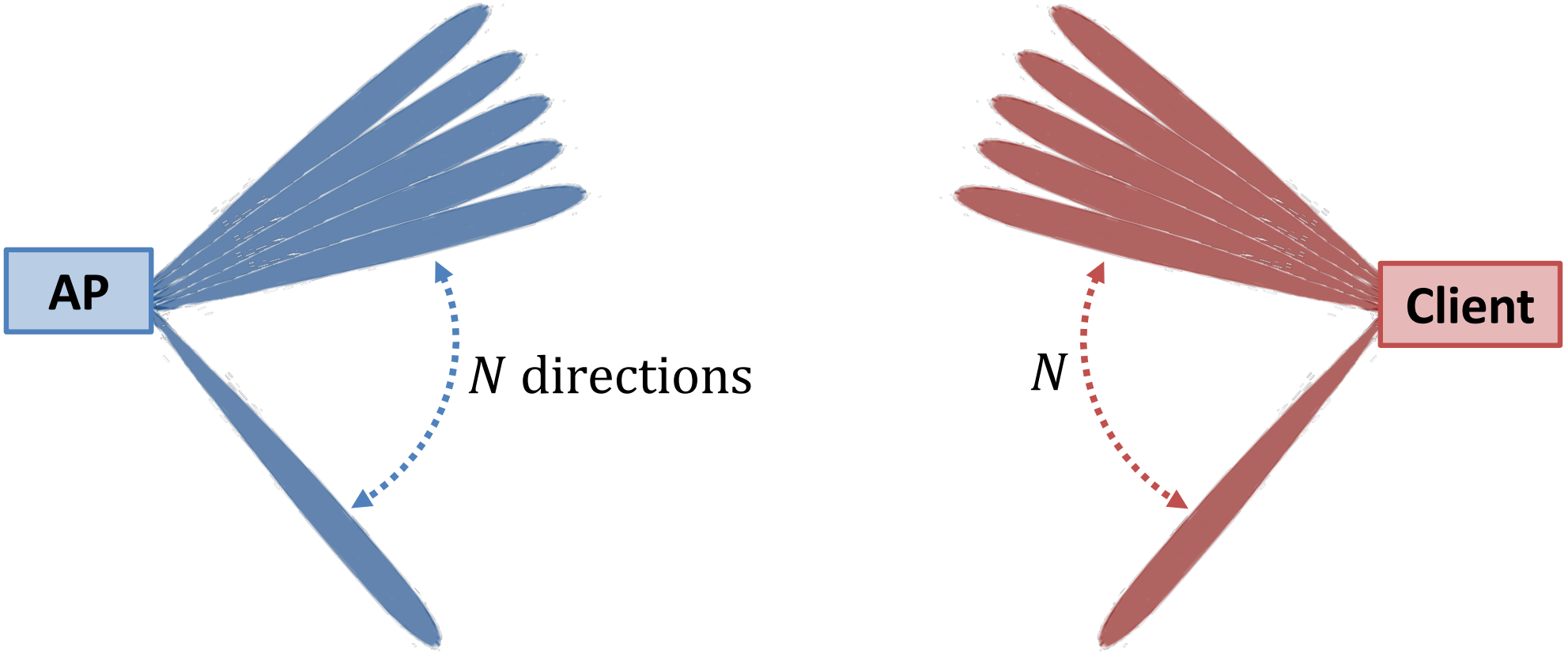
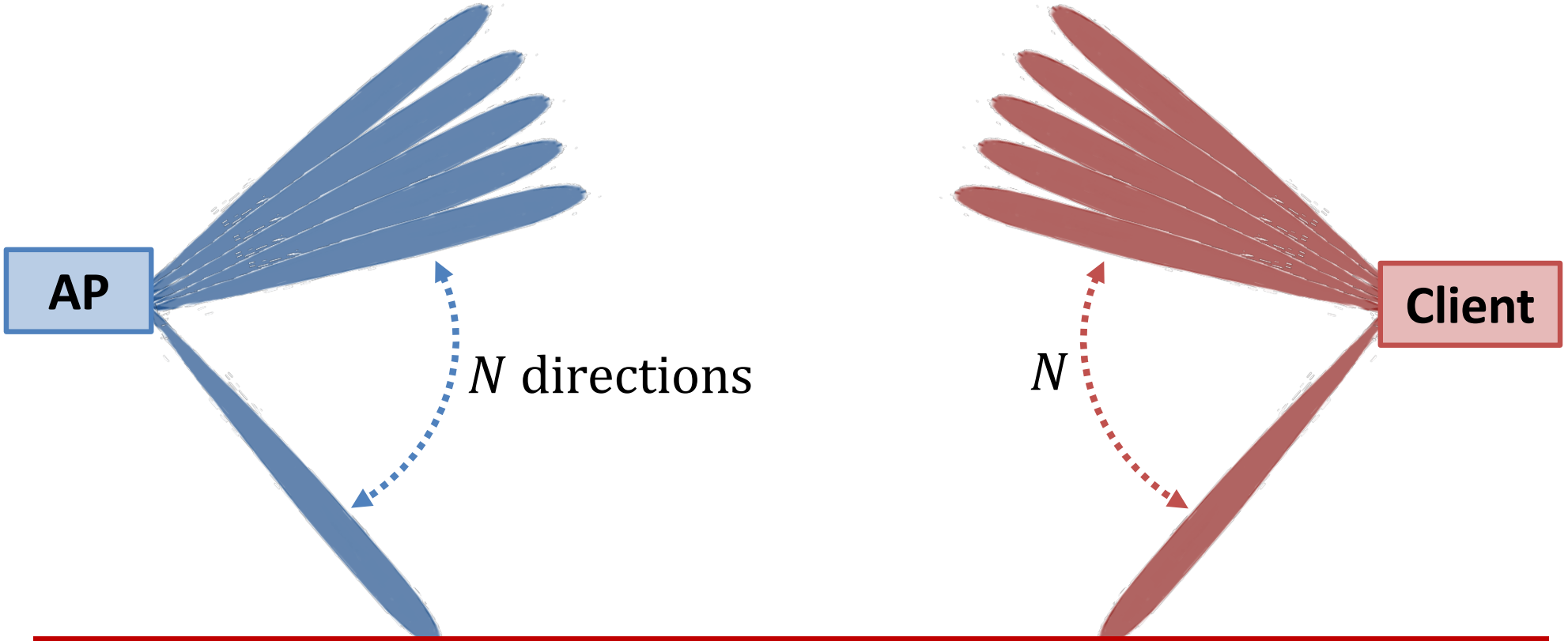


Naïve Algorithm: Exhaustive Scan

N : number of possible directions



$O(N^2)$ Beacon Packets → Too expensive

802.11ad: Multi-Stage Scan

Stage 1: Client uses omni-directional; AP scans directions

802.11ad: Multi-Stage Scan

Stage 2: AP uses omni directional; client scans directions

$O(N)$ Beacon Packets

→ Still Too Slow [MOBICOM'14, SIGMETRICS'15, NSDI'16]

How can we find the right alignment in sublinear time without scanning all directions?

Outline

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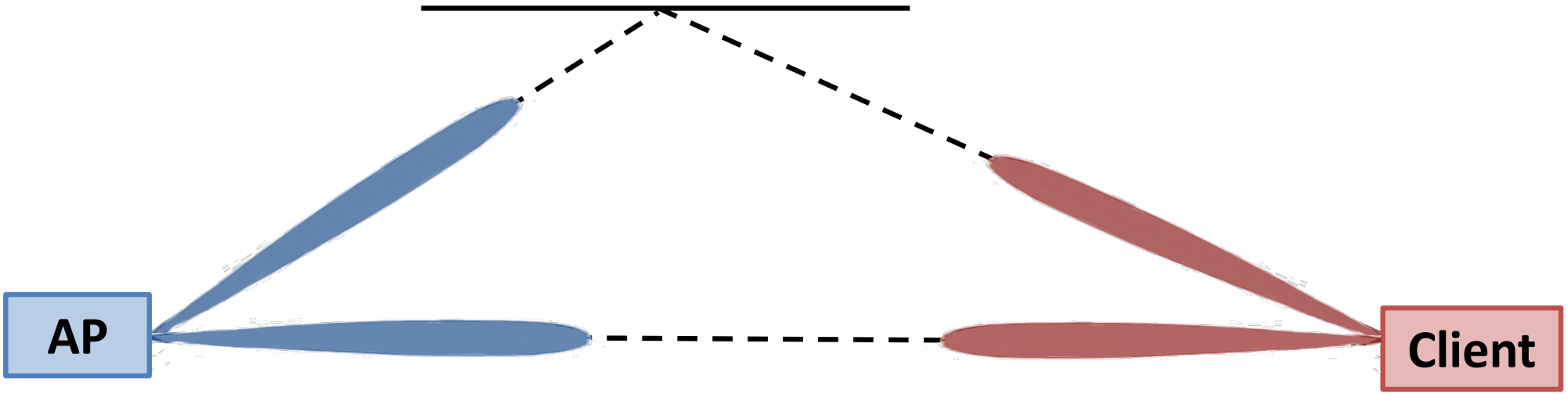
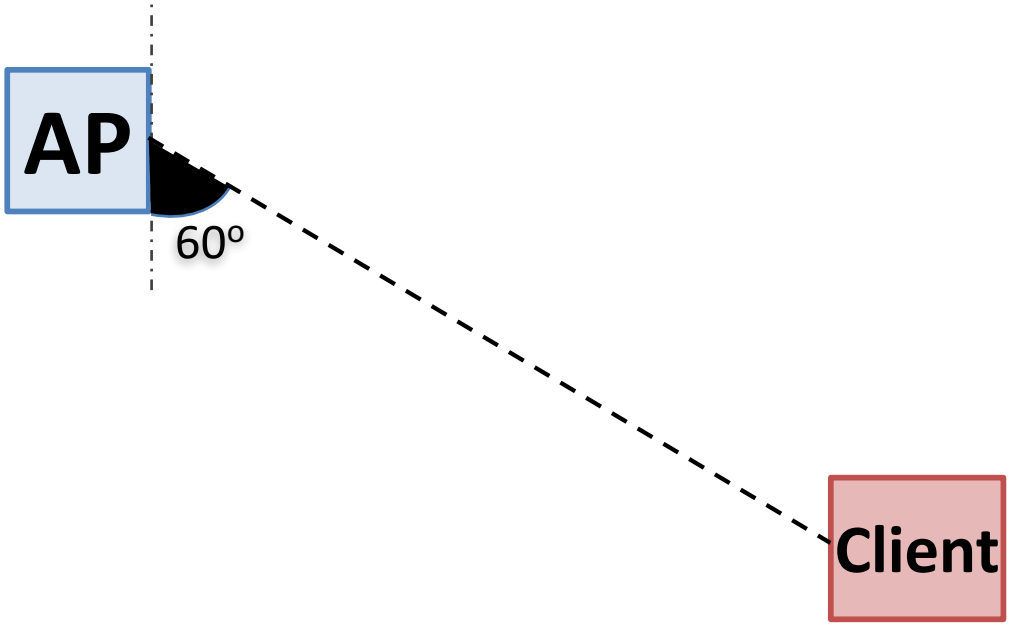
Idea: Leverage Path Sparsity



- In mmWave, signal travels only along few paths from TX to RX
- At most 2-3 paths exist in practice [ICC'14, Proc. of IEEE'14, SIGMETRICS'15, NSDI'16…]

Idea: Leverage Path Sparsity



Potential Direction of the Client:

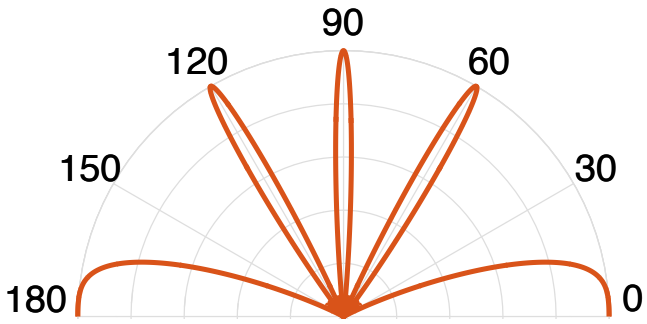
0°, 60°, 90° or 120°

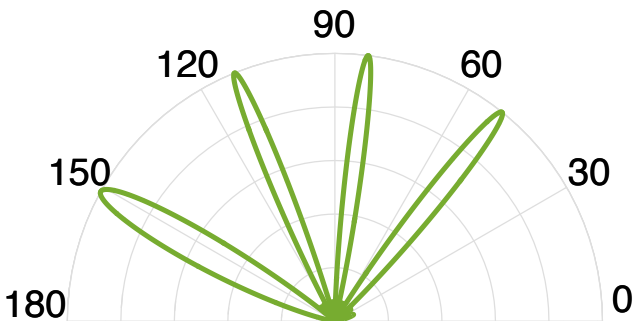
40°, 60°, 100° or 150°

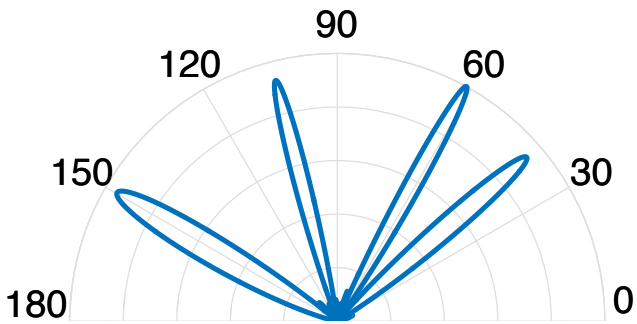
60° is direction of client

Construct a Multi-Armed Beam:

Simultaneously collects signals from multiple directions.





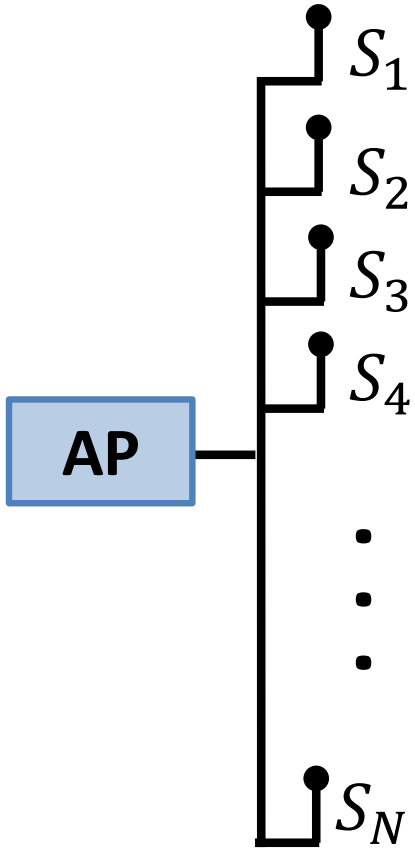


1. How can we generate multi-armed beams?

2. What is the best choice of multi-armed beams to quickly find the right direction?

How can we generate multi-armed beams?

Phased Array



To beam along direction θ,

Array Equation: $P(\theta) = \sum_k S(k) e^{-j2\pi k cos(\theta)/2}$

FFT Equation : $\hat{X}(f) = \sum_t X(t) e^{-j2\pi f t}$

Phased Array is a Fourier Transform

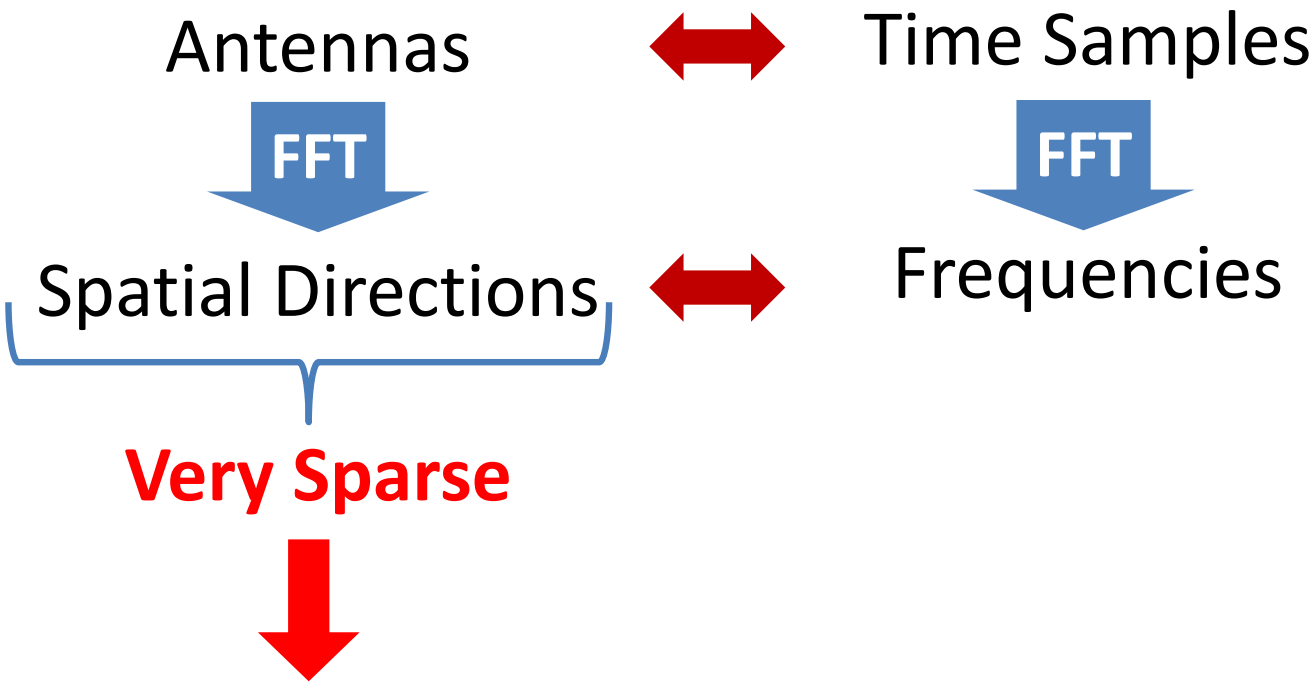
Antennas ⟷ Time Samples

FFT FFT

Spatial Directions ⟷ Frequencies

How can we generate multi-armed beams?

Phased Array is a Fourier Transform



Create multi-armed beams using Sparse Fourier Transform techniques.

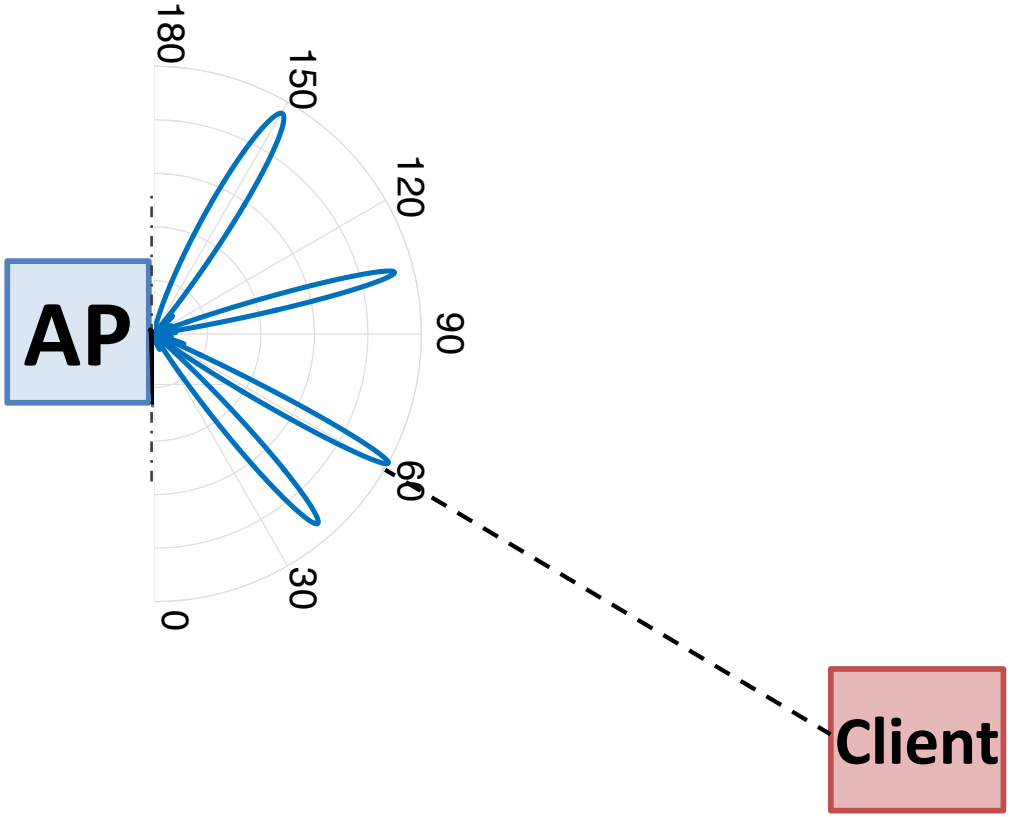
1. How can we generate multi-armed beams?

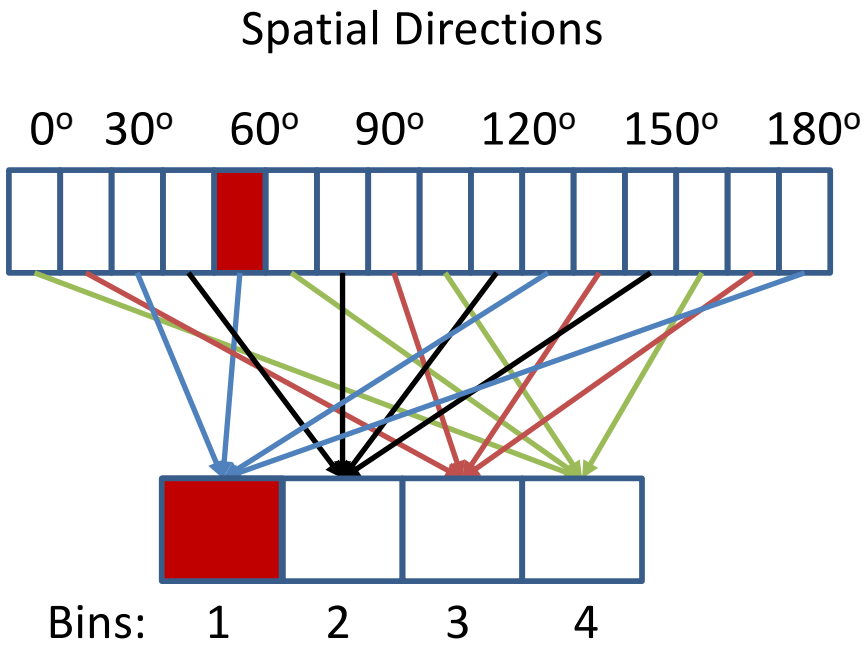
Use Sparse Fourier Transform

2. What is the best choice of multi-armed beams to quickly find the right direction?

What is the best choice of multi-armed beams?

Multi-Armed Beam ⟷ **Random Hash**





- Pick multi-armed beams to create random hash functions
- Estimate the true direction using voting

1. How can we generate multi-armed beams?

Use Sparse Fourier Transform

2. What is the best choice of multi-armed beams to quickly find the right direction?

Randomized Hashing & Voting

Complexity

- N: # of spatial directions $\propto$ # of phased array antennas

- Number of beacon packets needed to discover direction of alignment:

Exhaustive Scan	802.11ad	Agile-link
$O(N^2)$	$O(N)$	$O(\log N)$

Agile-Link finds the correct alignment without scanning the space from only O(log N) packets

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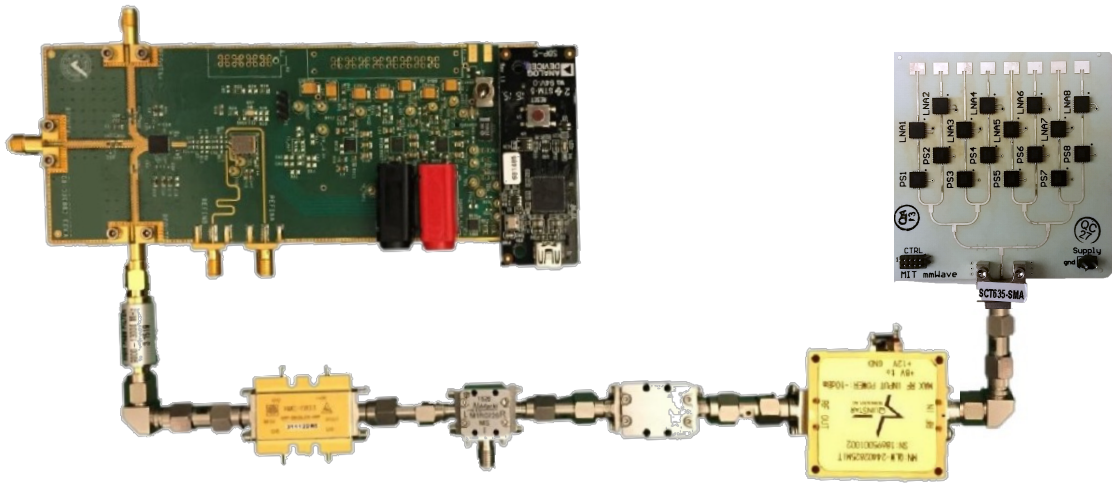
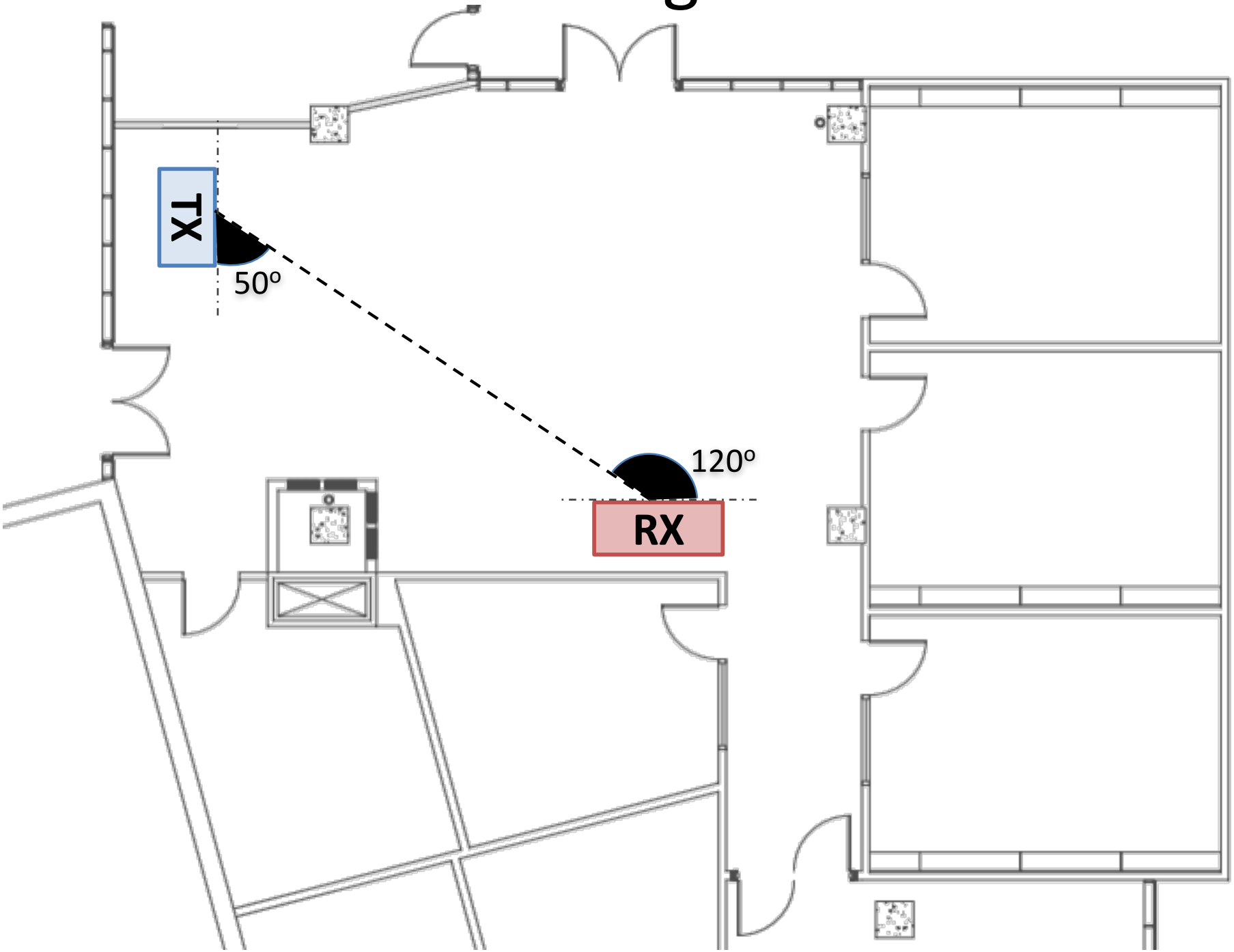
Implementation

Built Millimeter Wave Radio Front-End with a Steerable Phased Array.

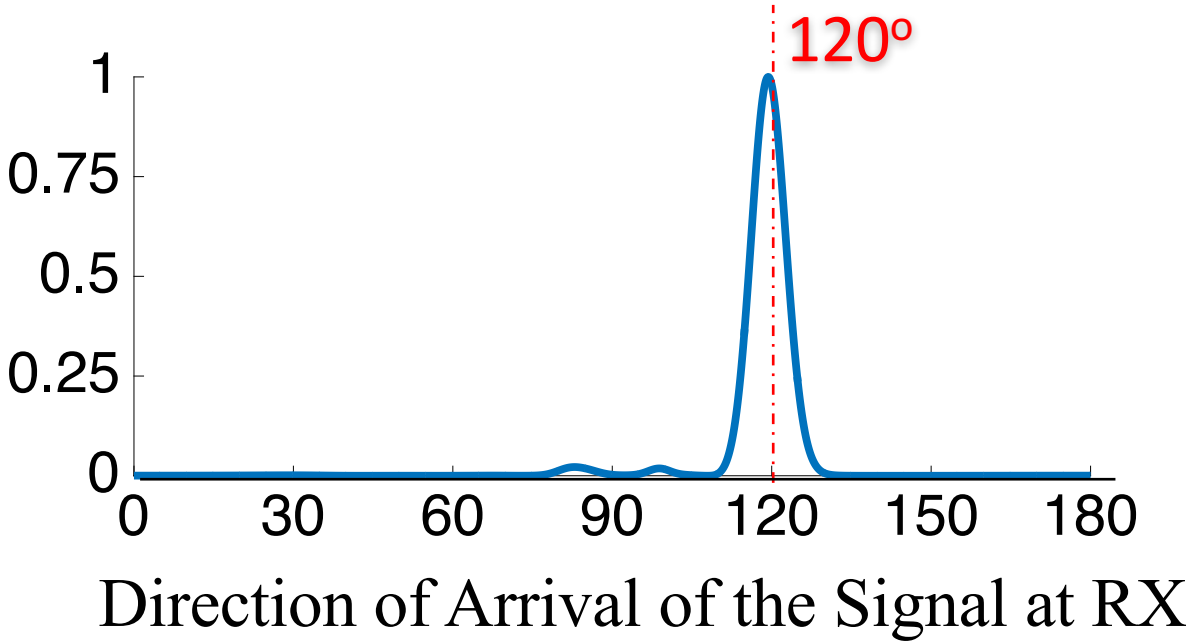


Correct Alignment

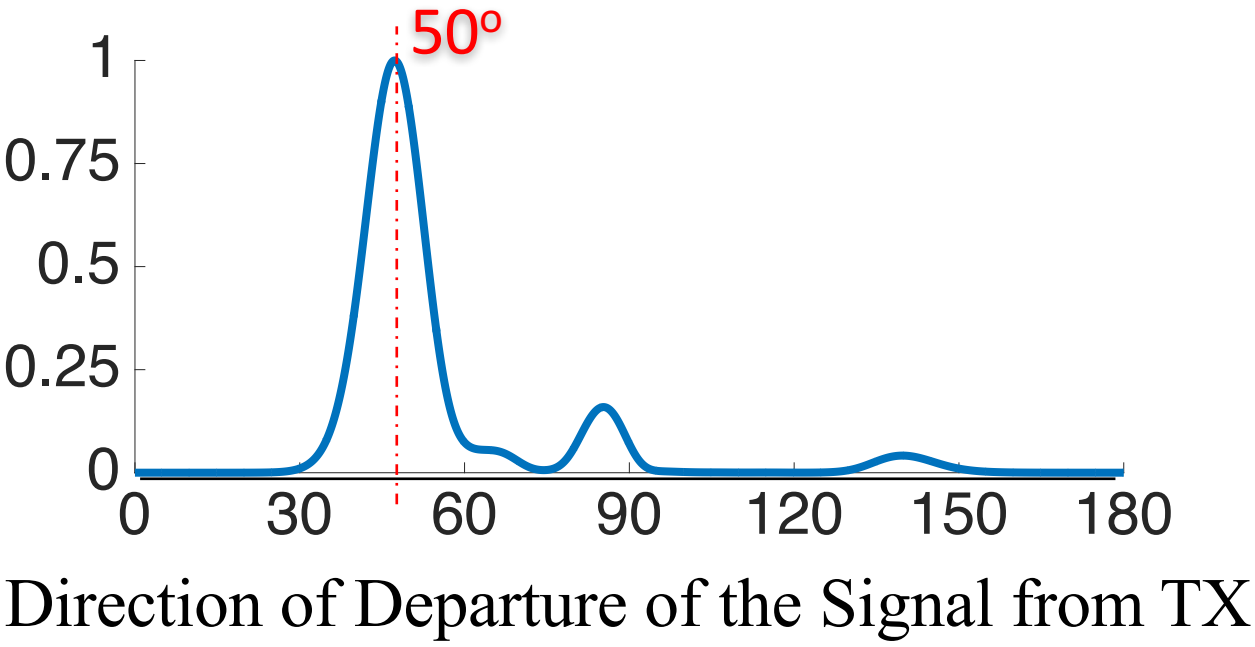


Correct Alignment

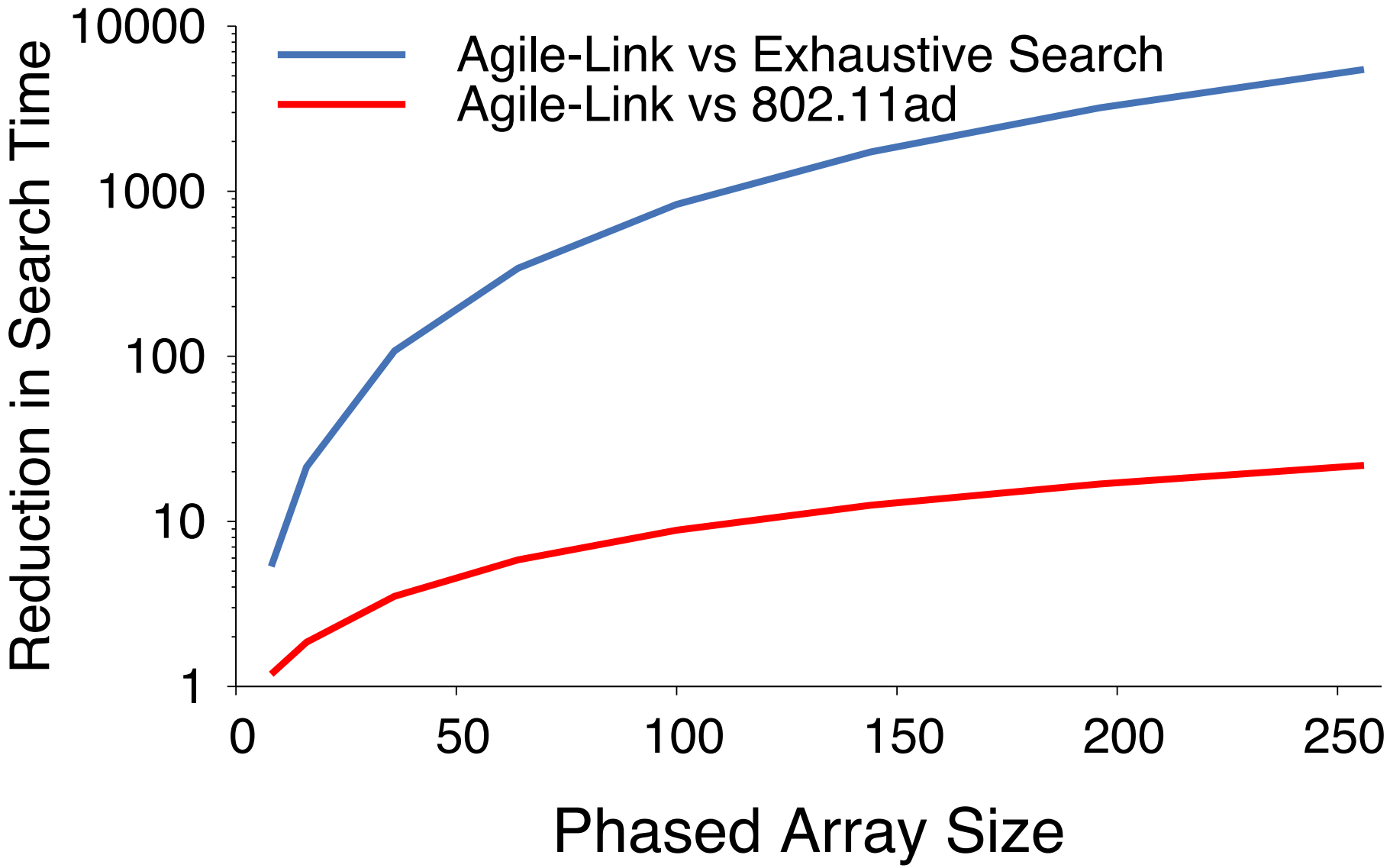
TX at 120° relative to RX



RX at 50° relative to TX



Beam Alignment Latency (Simulations)



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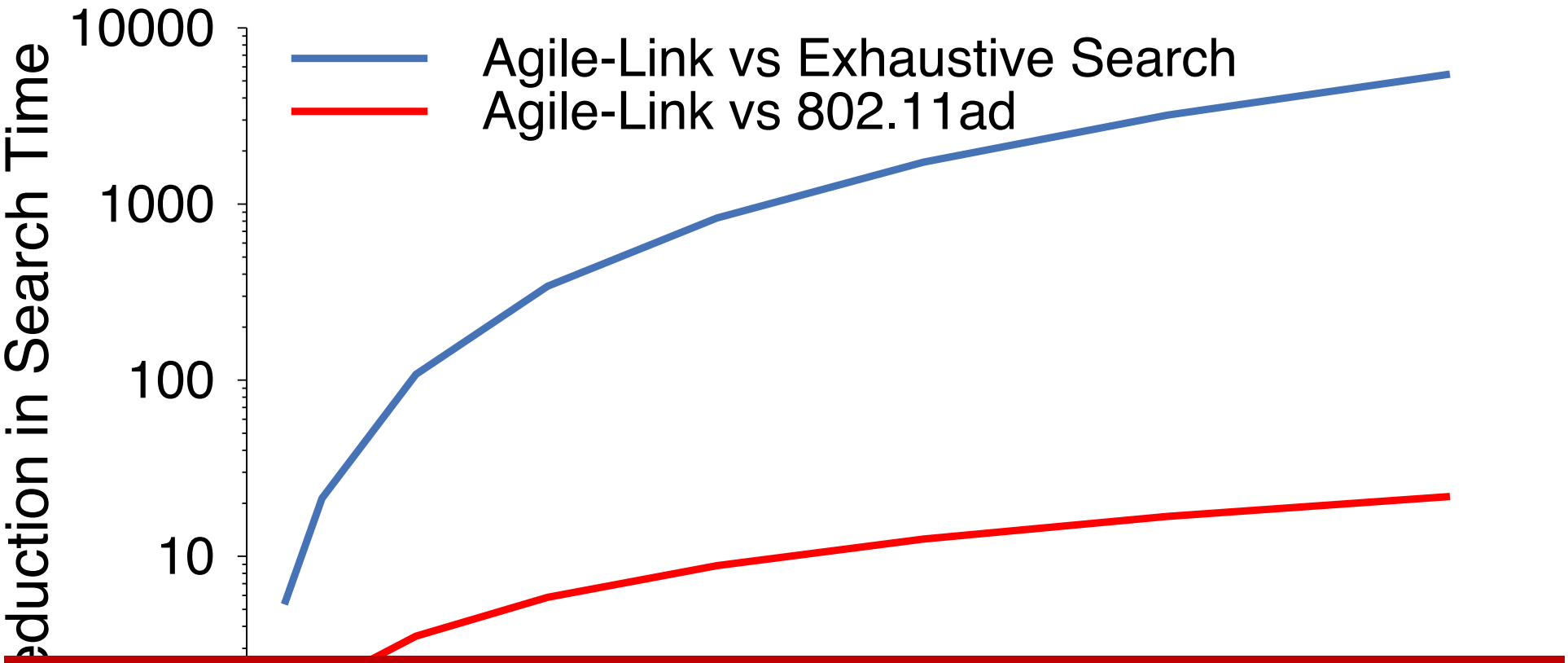

Agile-Link is up to 10x faster than 802.11ad and orders of magnitude faster than exhaustive search.

Related Work

- **Point-to-point mmWave communication with horn antennas**
  Wireless Data Centers [NSDI'16, SIGCOMM'12, SIGCOMM'11], Cellular Picocells and WiFi [SIGMETRICS'15, MobiCom'14]

- **Avoid Searching For the right alignment**
  BeamSpy [NSDI'16], MOCA [MobiHoc'16], BBS [INFOCOM'15]

- **Simulation based beam searching methods**
  Hierarchical Scan [PIMRC'15, EUSIPCO'14, J. Com. & Net.'14, Trans. Com.'13, GlobeCom'11, PIMRC'12], Compressed Sensing [Allerton'12, WCNC'13]

Conclusion

- Establishing communication links in millimeter wave networks is challenging due to directionality.
- Agile-Link: millimeter wave system that can quickly establish a link without having to scan the space.
- Exciting time for millimeter wave networks!
  - Rules of the game has changed.
  - Need new networking protocols: PHY, MAC .... App.