# Fast Millimeter Wave Beam Alignment

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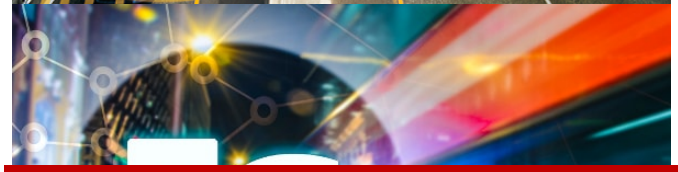
# Emerging Applications

VR stream **7 Gbps** of data from PC to headset

One autonomous car will generate **4TB** of data per day

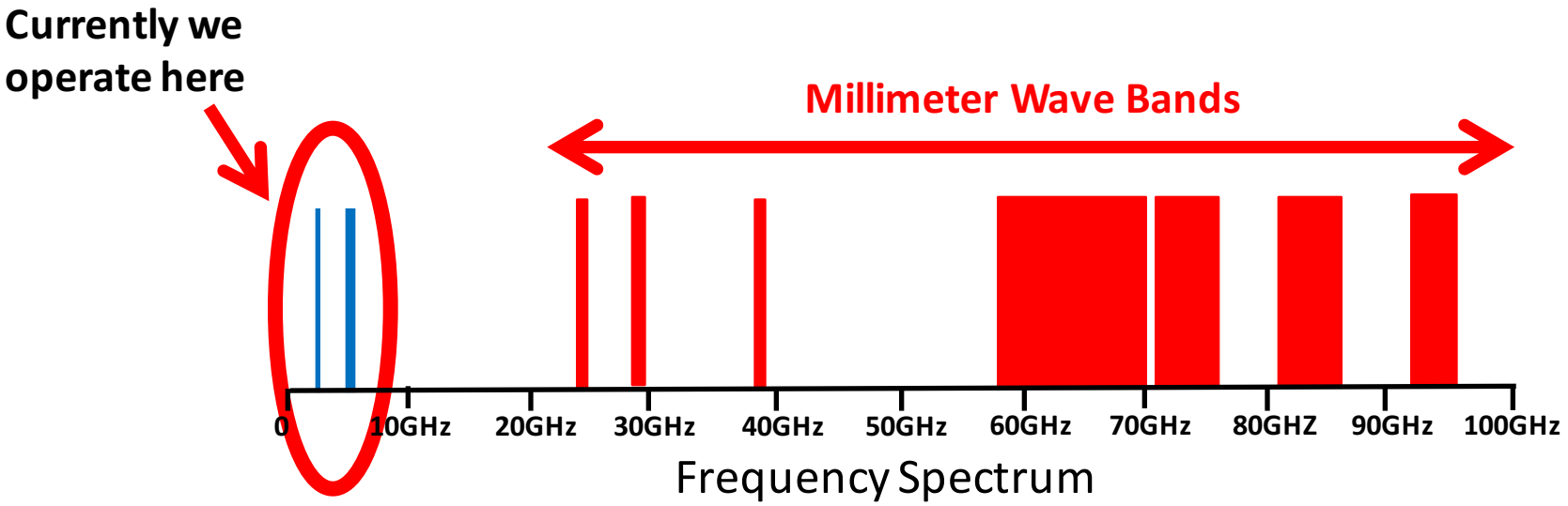


5G promises 1000 times

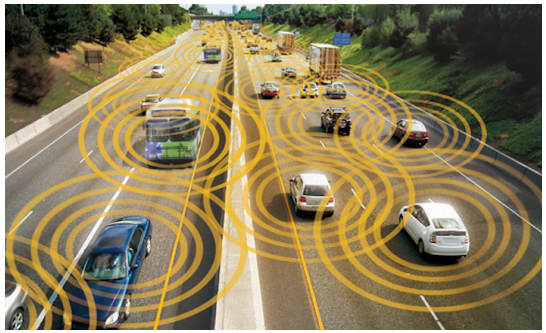
Today's wireless networks can not support future applications

# mmWave Technology

# mmWave Technology

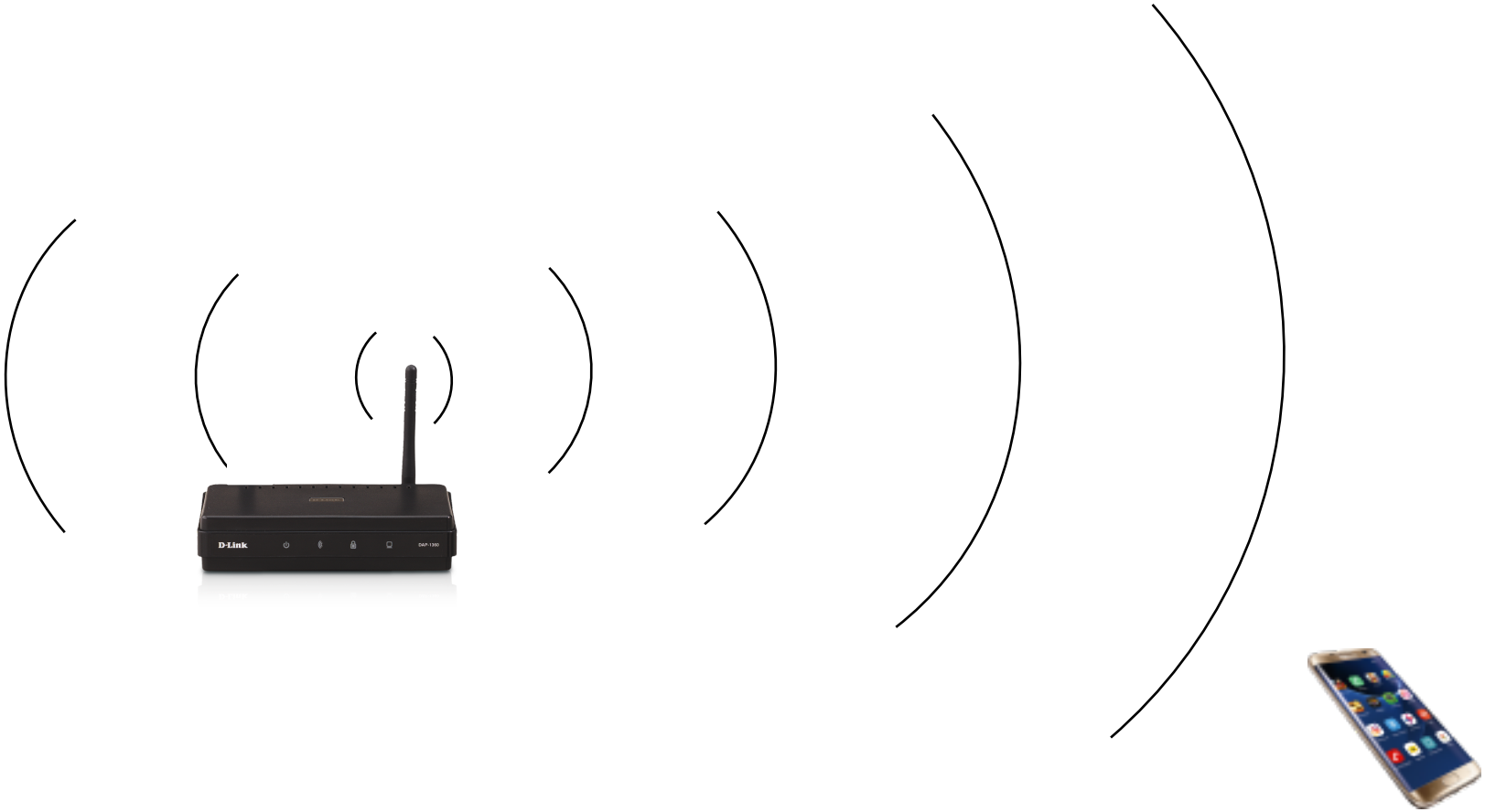



Enable high-throughput wireless links



# mmWave changes how wireless systems operate

**Today: Broadcast**



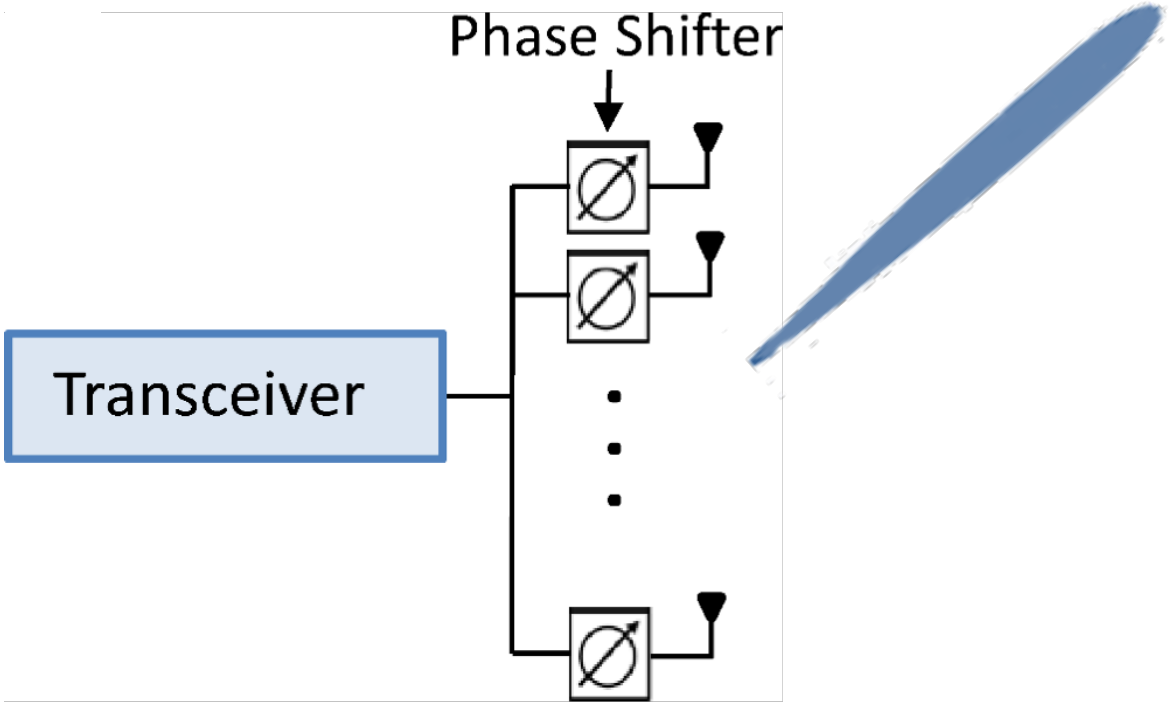
# mmWave changes how wireless systems operate

## mmWave: Pencil-beam Antennas


**Problem Statement:**

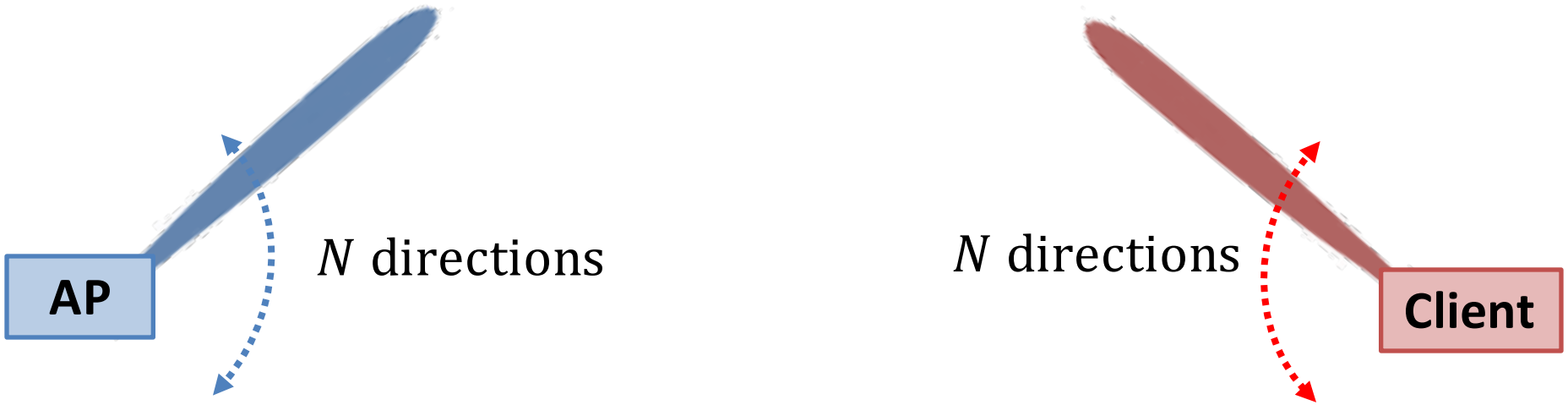
how can we align the beams to establish a link?

# mmWave radios use phased arrays to create a beam



# Naïve Approach: Exhaustive Scan

$N$ : number of possible directions




$O(N^2)$ measurements → Too slow

# 802.11ad Scan

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

# 802.11ad Scan

**Stage 2: AP uses omni-directional; client scans directions**


$O(N)$ measurements →Still Too Slow

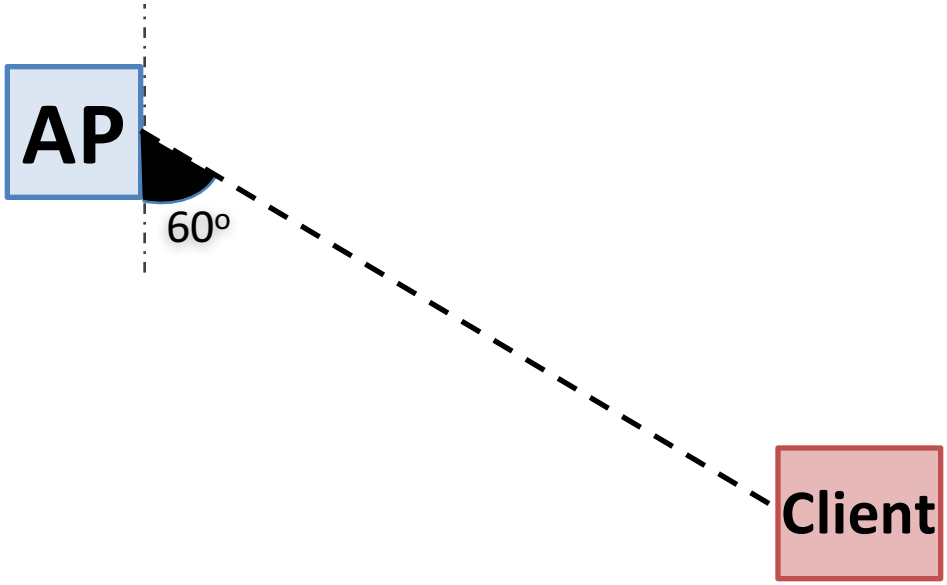
[MOBICOM'14, SIGMETRICS'15, NSDI'16]

Can we find the best beam alignment without scanning the space?

# Agile-Link

- A millimeter wave system that can quickly establish a link without scanning the space
- Works within the existing 802.11ad standard, and can support both clients and access points
- Implemented and evaluated in practical settings

# Agile-Link Idea




Potential Direction of the Client:

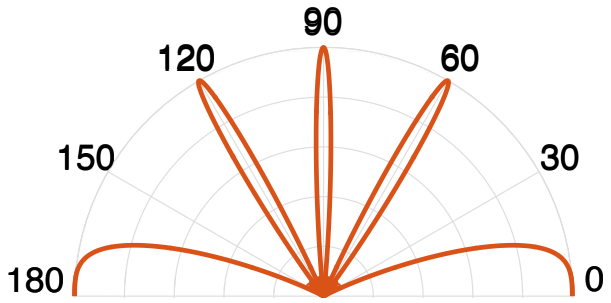
0°, 60°, 90° or 120°

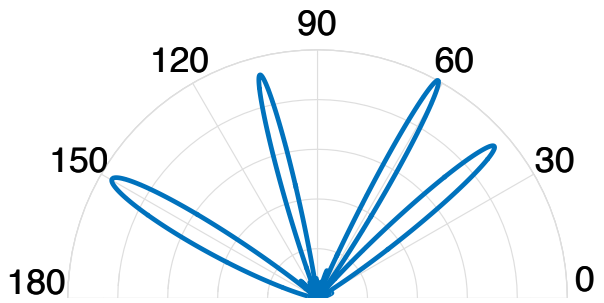
40°, 60°, 100° or 150°

60° is direction of client

**Construct a Multi-Armed Beam:**

Simultaneously collects signals from multiple directions.

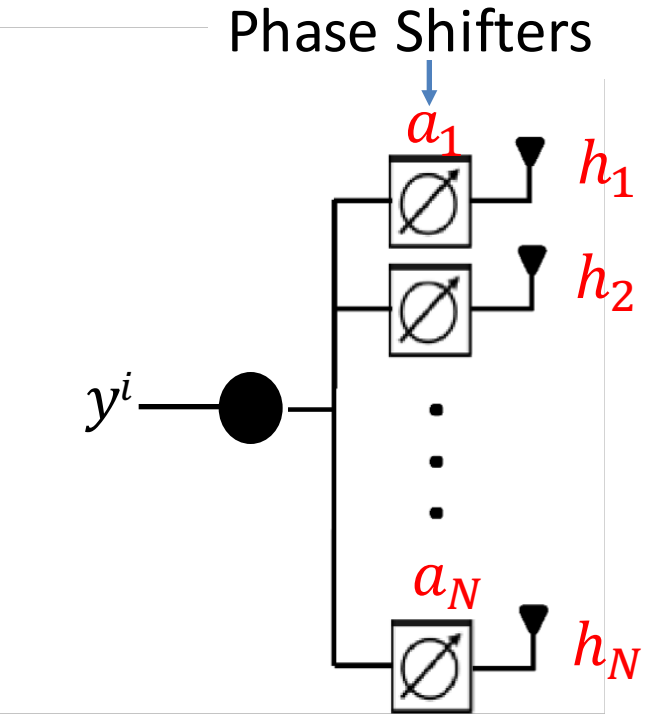


1. How do we create multi-armed beams?

2. What is the best choice of multi-armed beams to minimize the number of measurements?

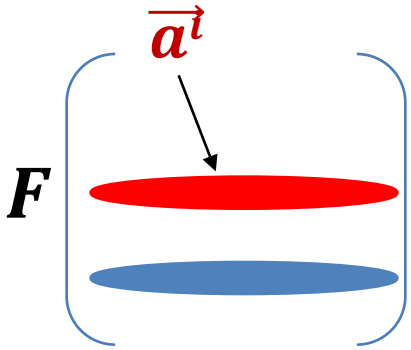
# Creating Multi-Armed Beams

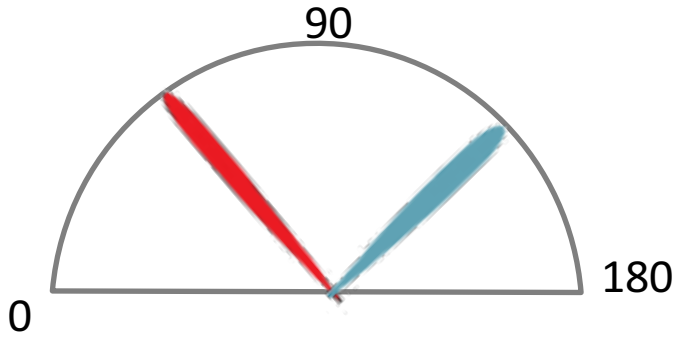



**For an Antenna Array:**

$\vec{h} = F'\vec{x}$, $F'$ **is Inverse Fourier Matrix**

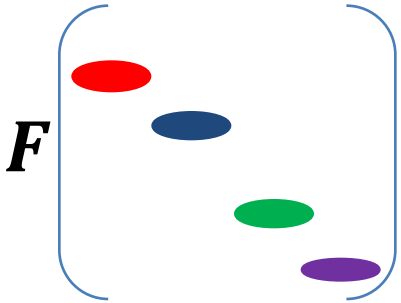
$y^i = |\vec{a^i}\,\vec{h}| = |\vec{a^i}\,F'\vec{x}|$

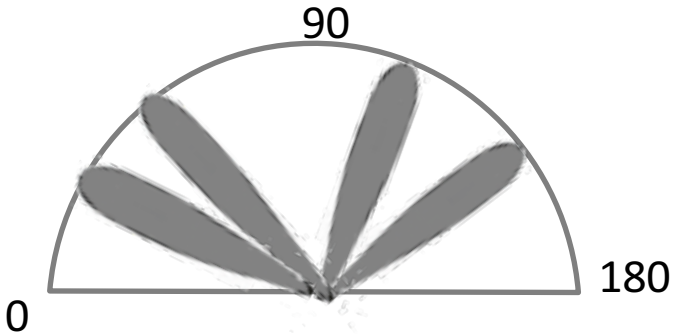



Divide $\vec{a^i}$ into segments

$\vec{a_i} =$ 

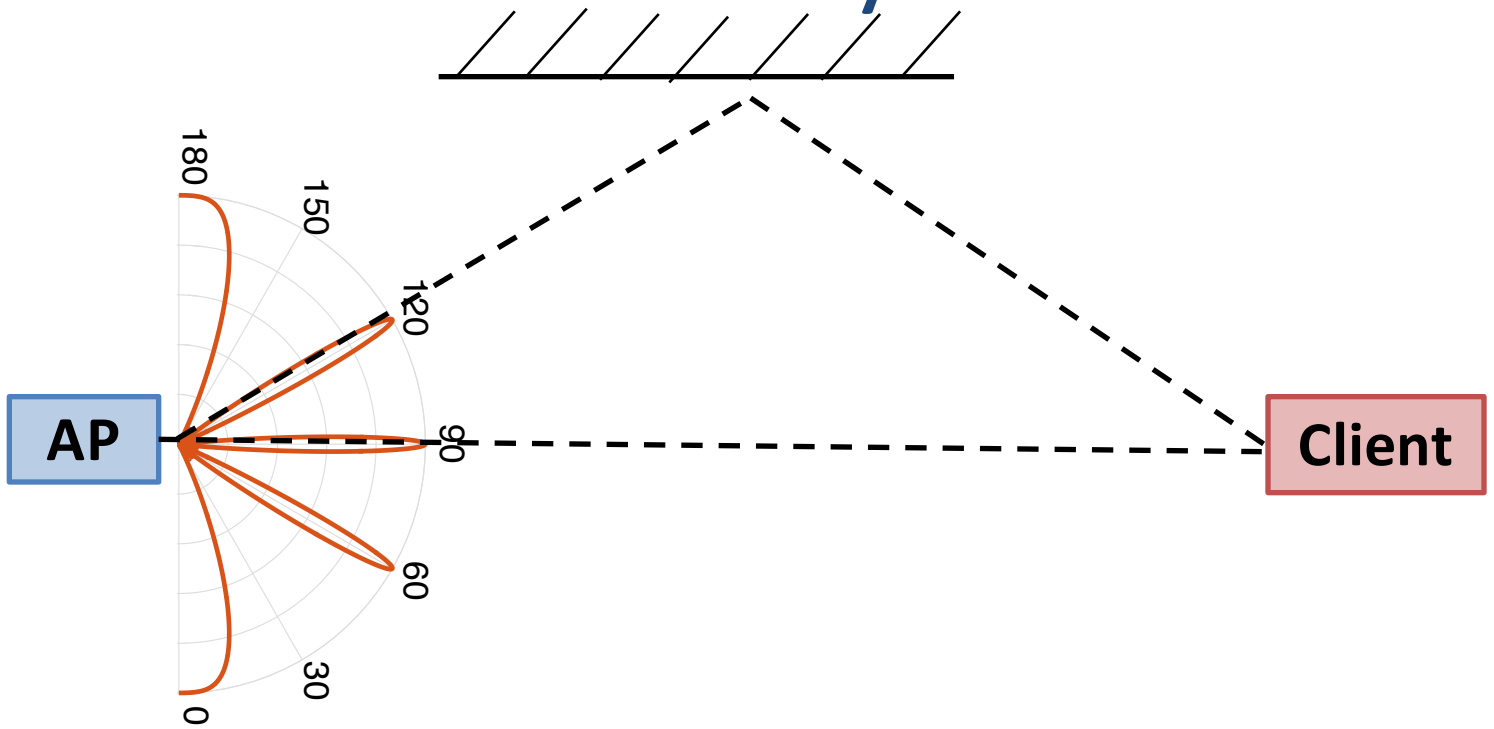


1. How do we create multi-armed beams?

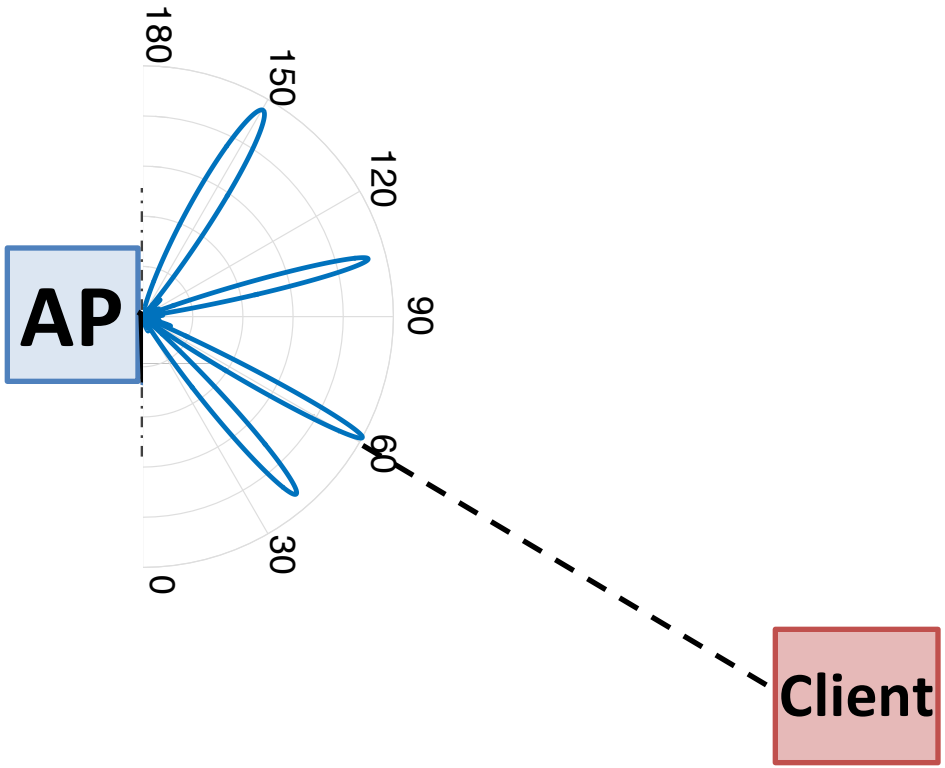
2. What is the best choice of multi-armed beams to minimize the number of measurements?

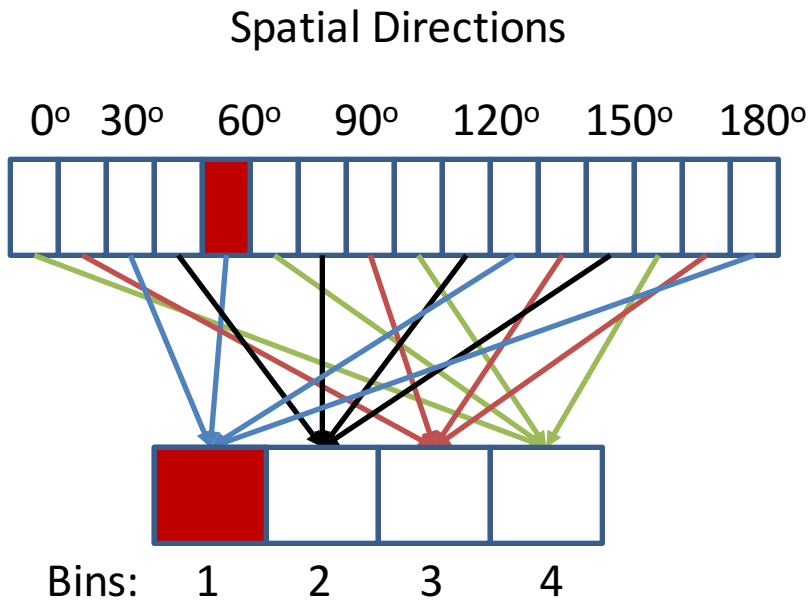
# Why do we need to choose the beams carefully?




Signals traveling along different paths can cancel each other

# Best Choice of Multi-Armed Beams




## Hashing

- Pick multi-armed beams to create random hash functions

## Voting

- Estimate the true direction using voting

# Theorem

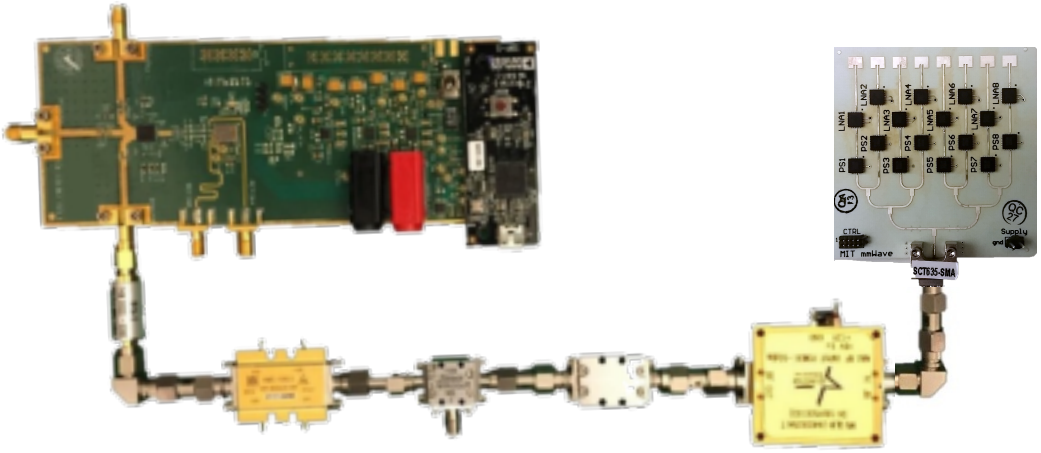
(Informal)

- Assuming:
  - N possible directions
  - K signal paths
- Our algorithm finds the optimal beam alignment in $O(K \log N)$ measurements.

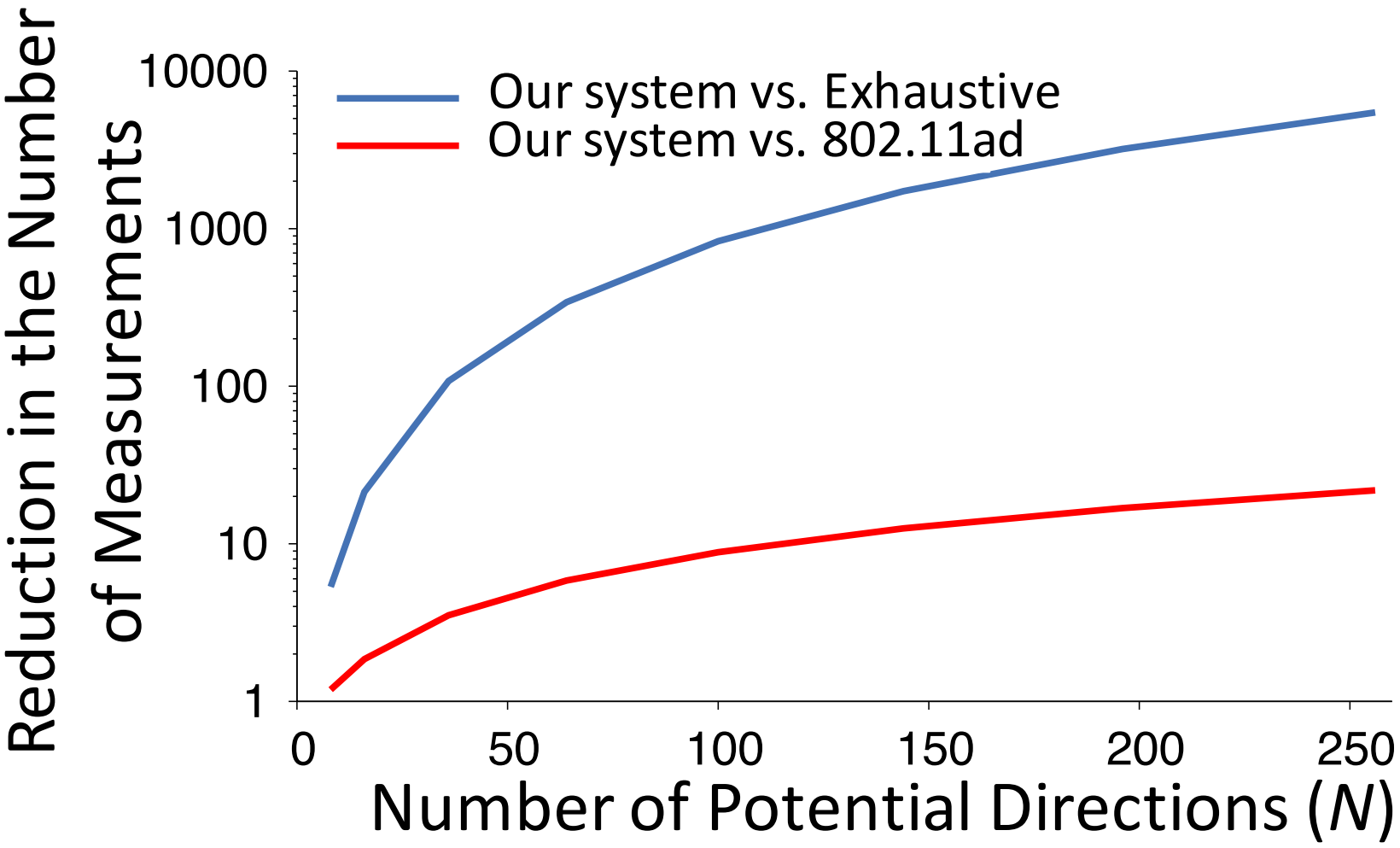
# Experimental Results

# Implementation and Evaluation

Built a Millimeter Wave Radio with a Phased Array.



# Number of Measurements



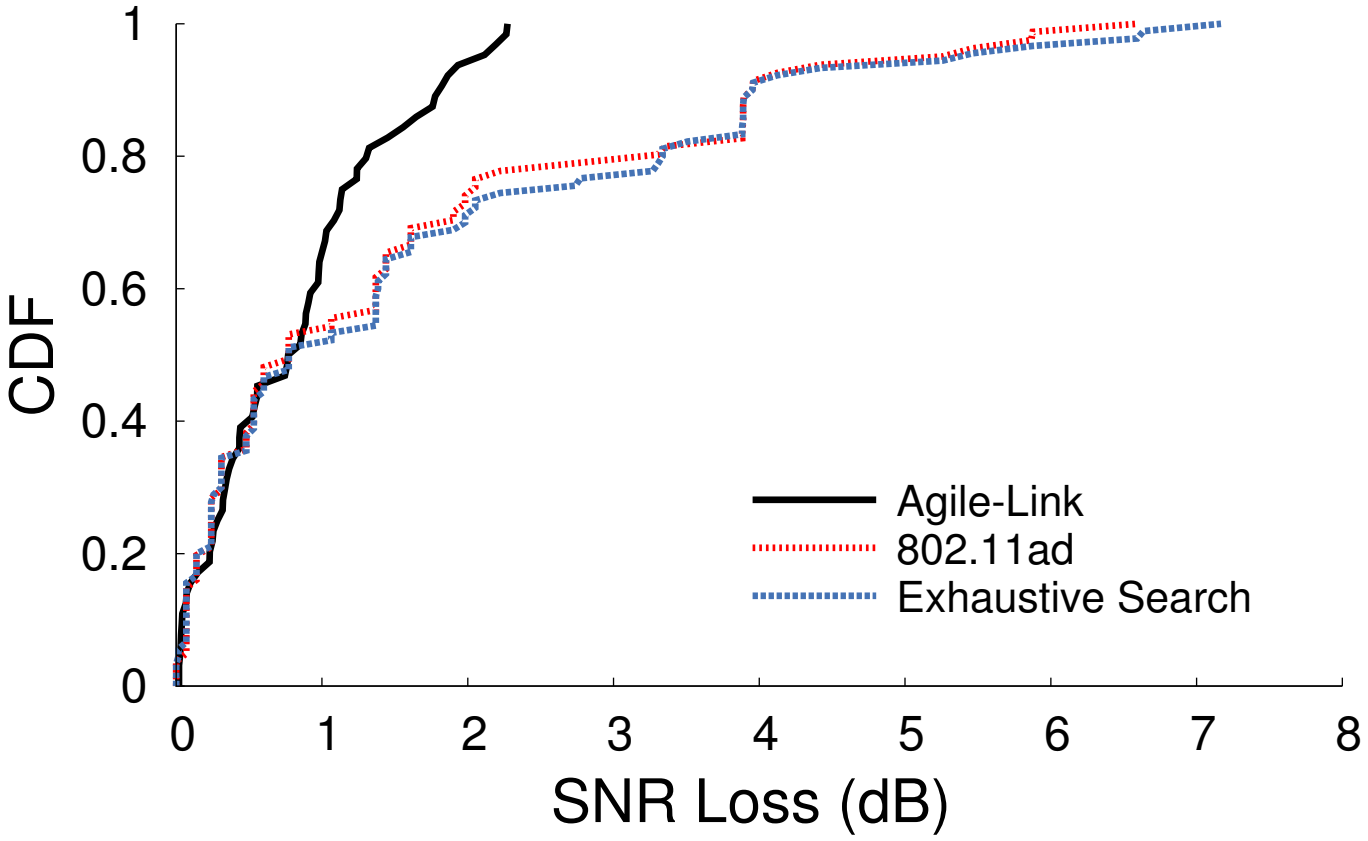

Our system requires orders of magnitude fewer measurements

# Beam Alignment Latency

| Number of Directions | 802.11ad | 802.11ad with our algorithm |
|---|---|---|
| 16 | 1ms | 0.5ms |
| 64 | 4ms | 0.8ms |
| 128 | 106ms | 0.9ms |
| 256 | 310ms | 1.0ms |

**Achieved fast beam alignment (less than 1ms)**

# Beam Alignment Accuracy




Agile-Link performs much better than Exhaustive search and 802.11ad

# Related Work

- **Past Work on Beam Alignment:**

[D. Araujo EUSIPCO'14, J. Kim Jour. Communications'14, B. Li Trans. Wireless'13, Y. M. Tsang Globecom'11, J. Wang Communications'09, W. Yuan PIMR'15, L. Zhou PIMRC'12, D. Ramasamy Allerton'12, A. Alkhateeb IEEESP'14, B. Gao. IET'14, B.Li Trans. Wireless'13, T. Nitsche ENET'15, T. Nitsche Infocom'15,etc]

- **Past Work on mmWave Channel Studies:**

[C. R. Anderson Trans. Wireless'04, S. Collonge Trans. Wireless'04, S. Rangan IEEE'14, M. Smulders Trans on Ant.'09, J. Violette NASA report, J. Comm. '02, S. Sur SIGMETRIC'15, A. Saeed VTC'16, X. Tie PAM'11, etc]

- **Past Work on using Sparsity:**

[E. Eltayeb GLOBESIP'15, A. Alkhateeb J. IEEE'14, B. Gao' IET14, D. Ramasamy, IEEE'14, etc]

# 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!

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