Compressive tracking in mm wave picocells

Upamanyu Madhow
ECE Department
University of California, Santa Barbara

Collaborators

2012-2014

Dinesh Ramasamy
(now at Uber)

Sriram Venkateswaran
(now at Kumu)

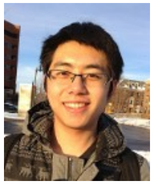
2014-present

Zhinus Marzi

Babak Mamandipoor

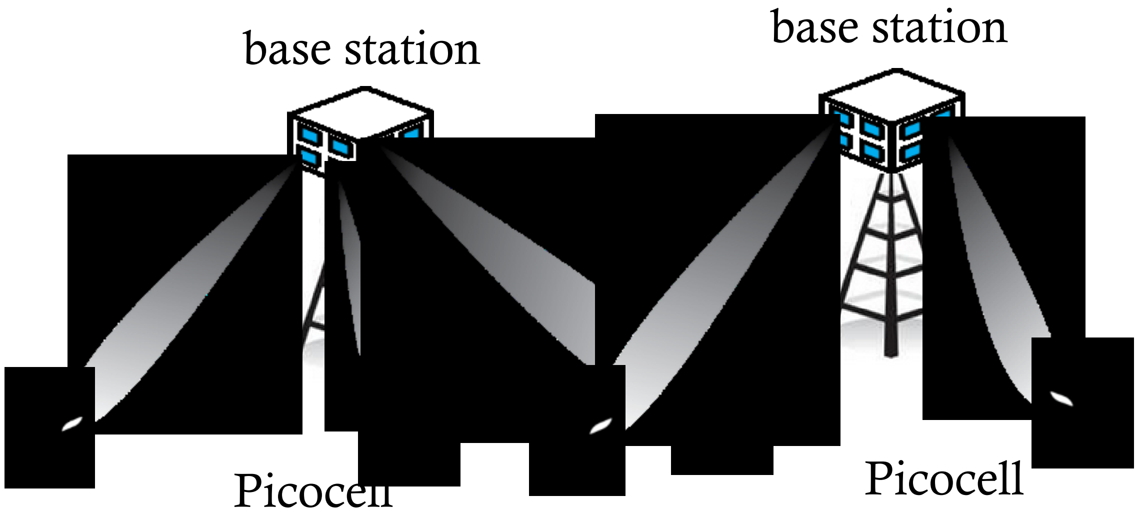
Maryam E. Rasekh

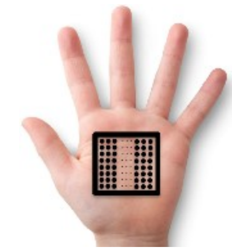
Prof. Heather Zheng (U. Chicago)



Yanzi Zhu

Network context





32x32
8cmx8cm

- Can fit very large arrays into picocell base stations
- Mobile users move → agile tracking needed
- Beams are easily blocked, so must be able to switch
  - to alternate paths
  - to alternate base stations

Each base station must maintain a path inventory for each user

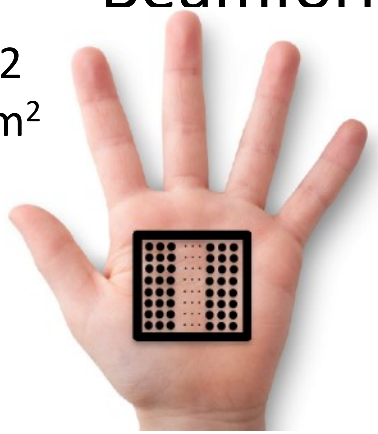
Cellular 1000X via mmwave picocells

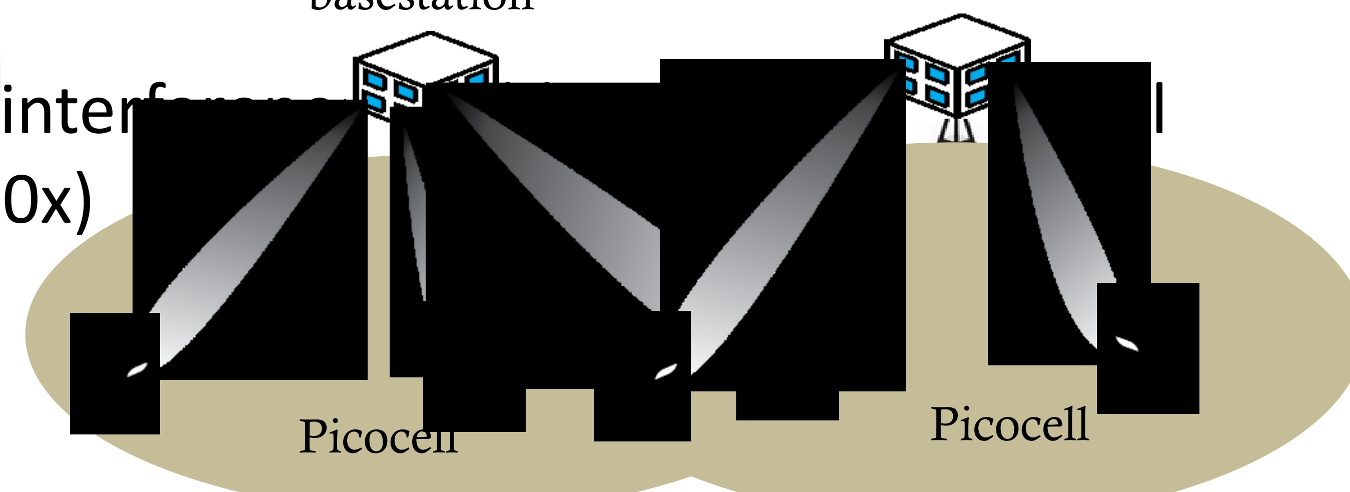
- 10-100X bandwidth (2GHz vs. 20-200 MHz)
- 100X # antennas in same form factor → pencil beams
  - Beamforming gain enables comm. over outdoor

inter l

0x)

32 x 32
8 x 8 cm^2

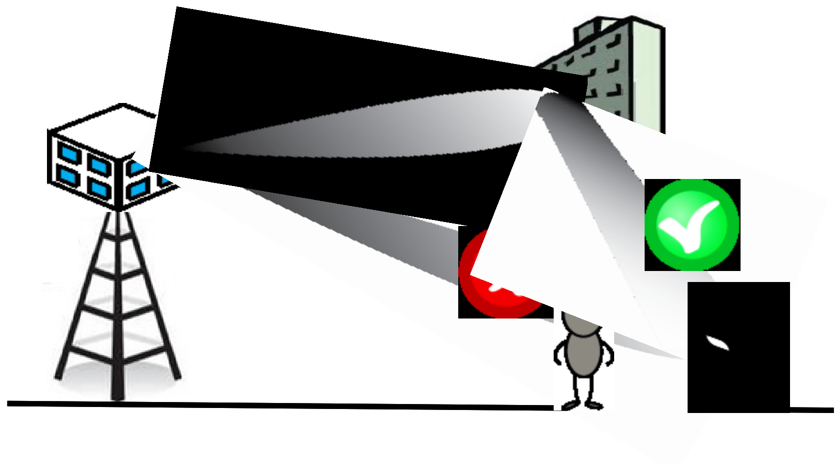




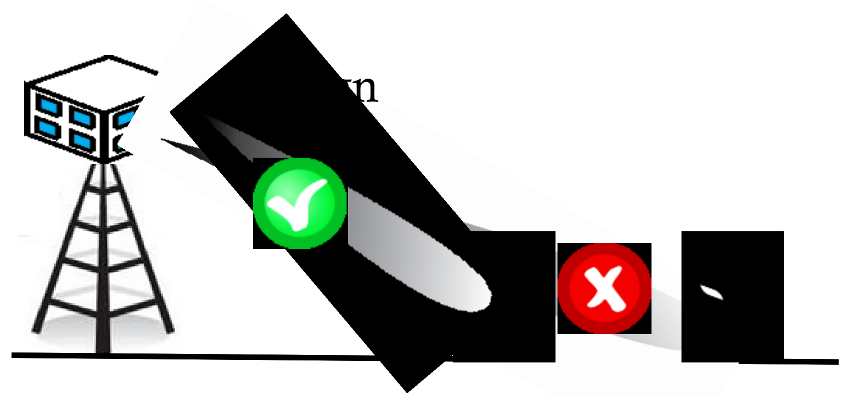
mmwave picocell architecture

Need to identify paths on the fly

- Blockage

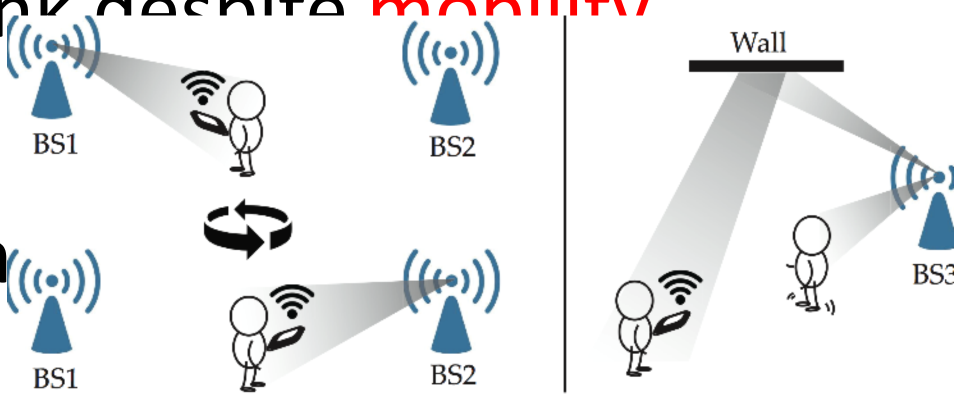


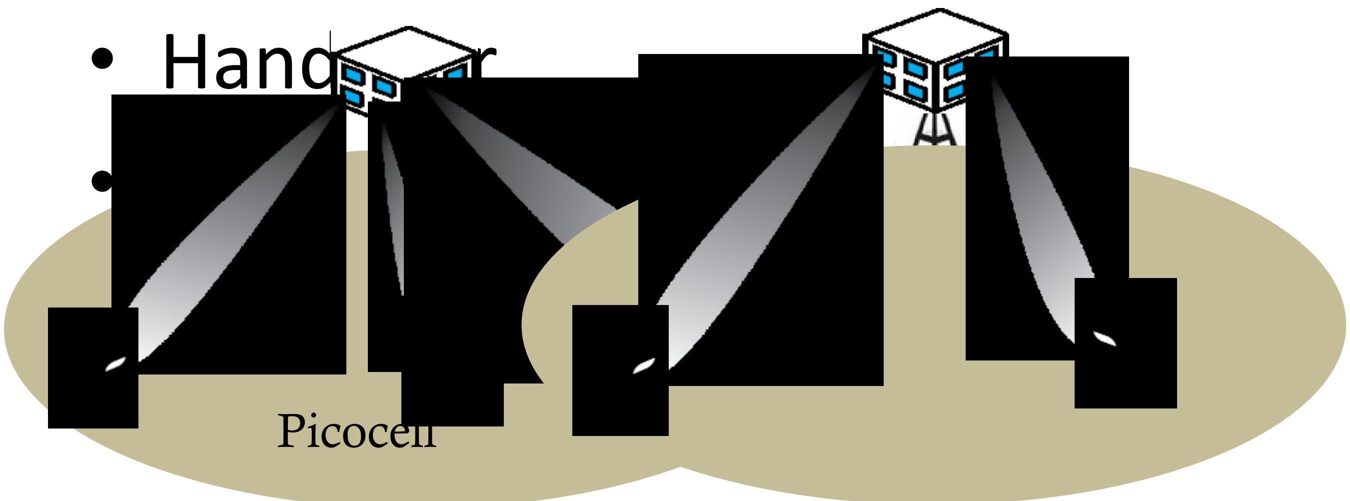
- Motion tracking



Need hyper-efficient channel tracking

- To maintain a robust link despite mobility
- Overcome blockage
- Interference managem reuse
- Hand r
-

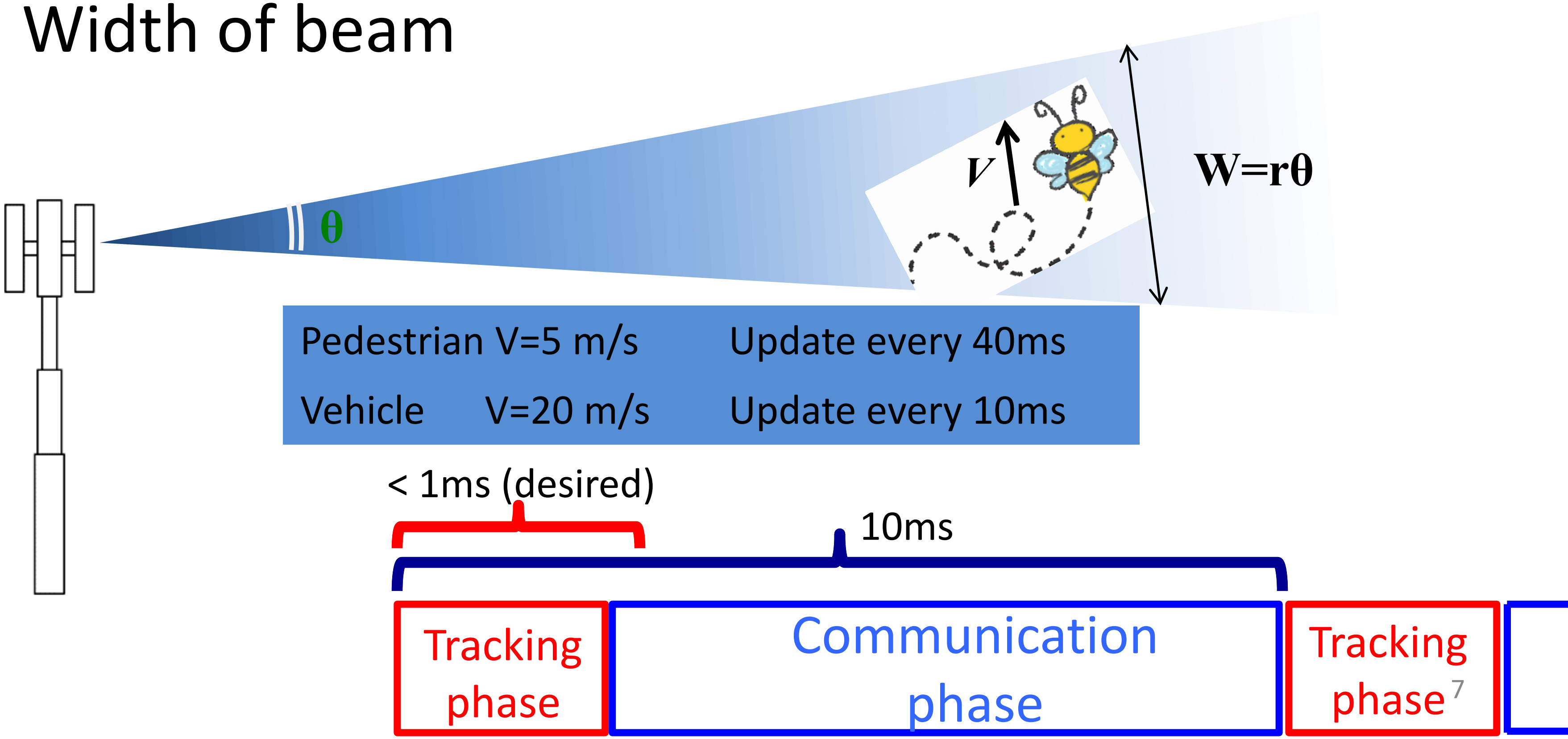




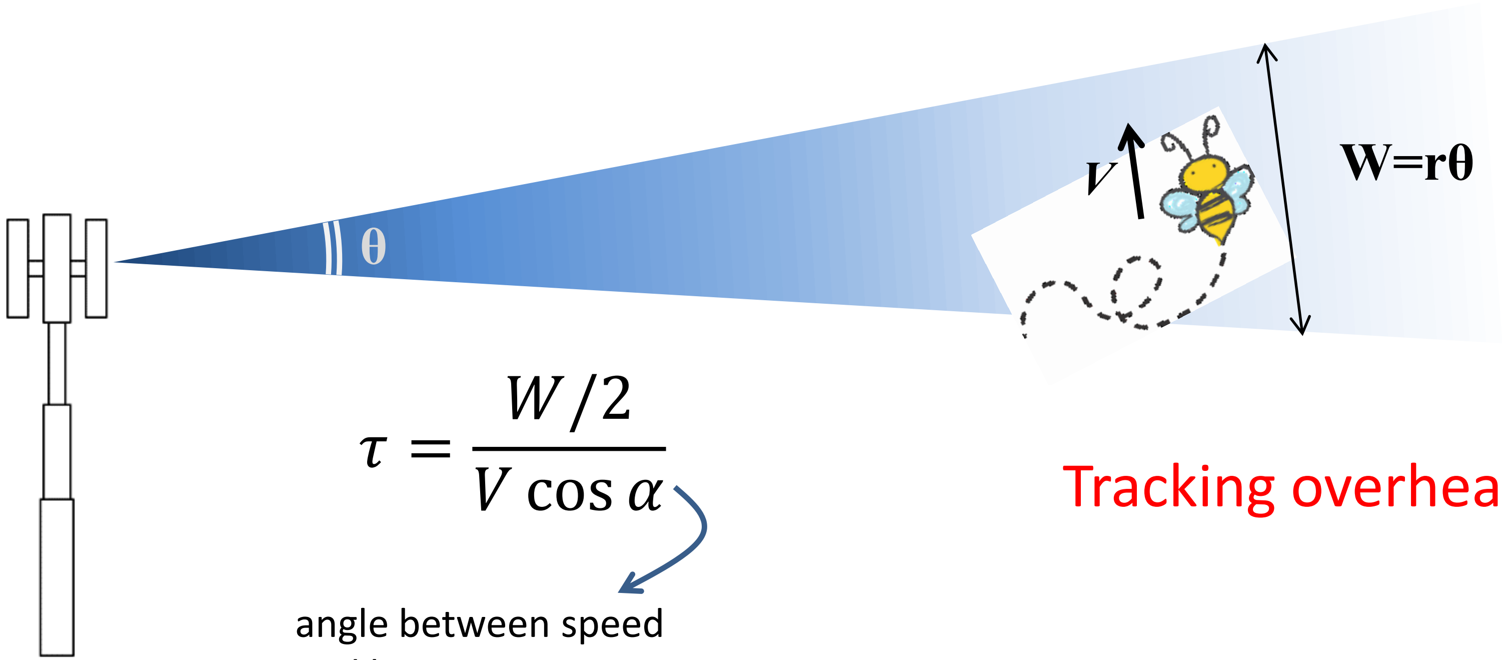
How rapidly must we track?

How long before direction information expires?

- Speed of mobile user
- Width of beam



Basic calculations



$$\tau = \frac{W/2}{V\cos\alpha}$$

angle between speed
and beam cross section

Tracking overhead?

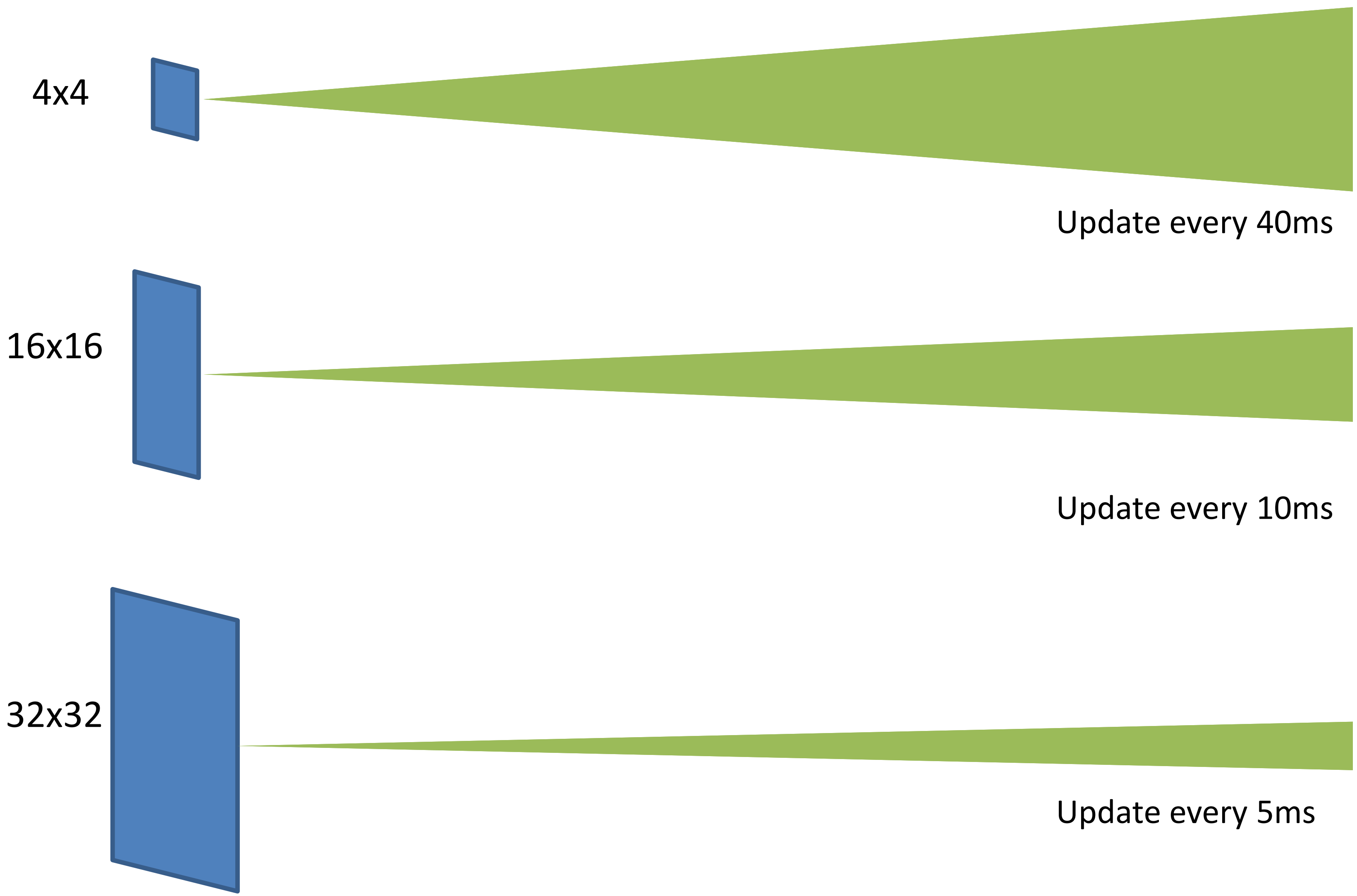
Approximation under worst-case settings for N x N array $\tau \approx \dfrac{0.888r}{Nv}$

Need to update more frequently for larger arrays

Example: urban picocellular base station tracking a vehicle

$$r = 5 \text{ m},\ v = 20 \text{ m/s},\ N = 16 \ \rightarrow \ \tau = 13.8 \text{ ms}$$

Example designs

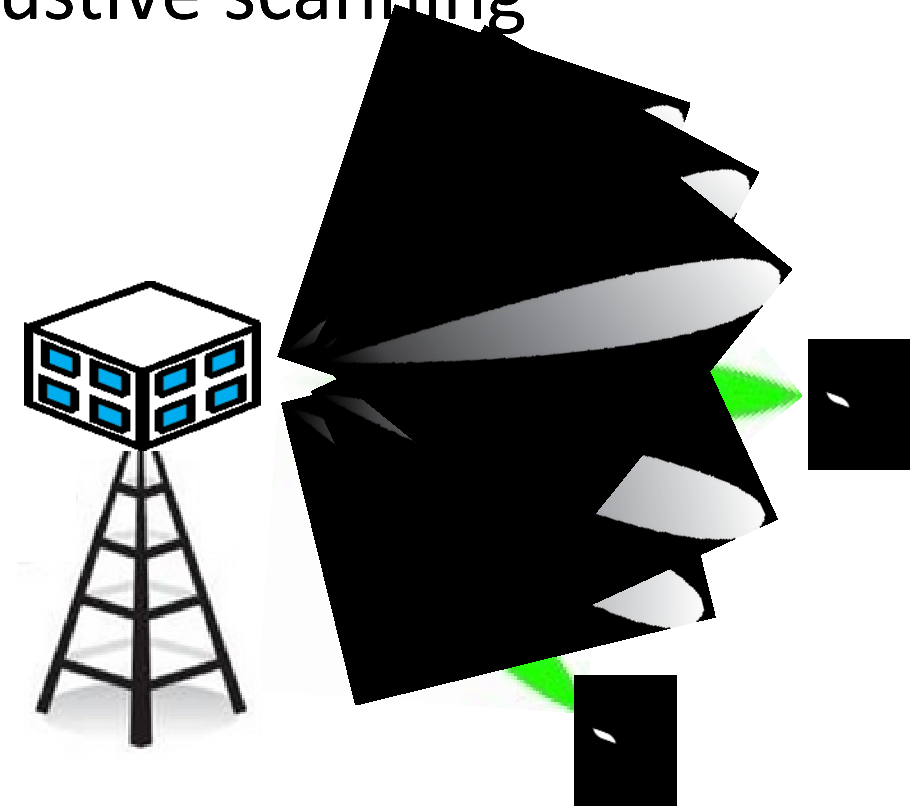


Outline

- Motivation and Background
  - There is a huge capacity at mmwave band
- Path tracking is the key bottleneck
  - Shortcomings of conventional approaches
  - Compressive estimation a promising alternative
- Noncoherent compressive estimation
  - Works with off-the-shelf hardware
- Evaluation on 60 GHz testbed and simulations

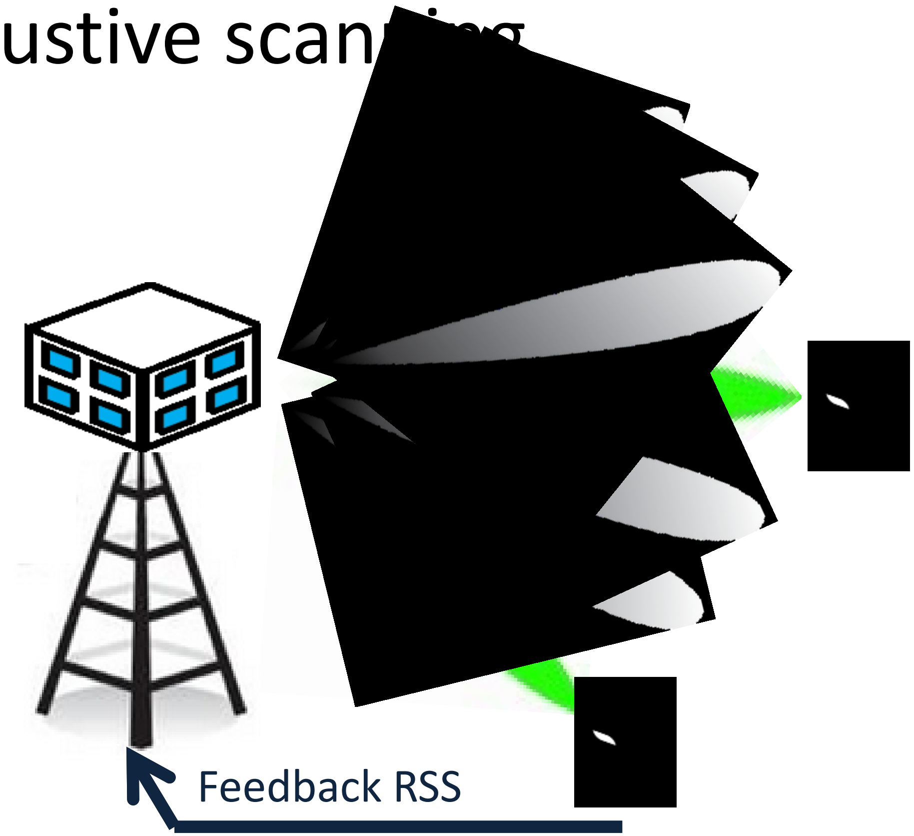
Conventional direction finding techniques

- Exhaustive scanning



Conventional direction finding techniques

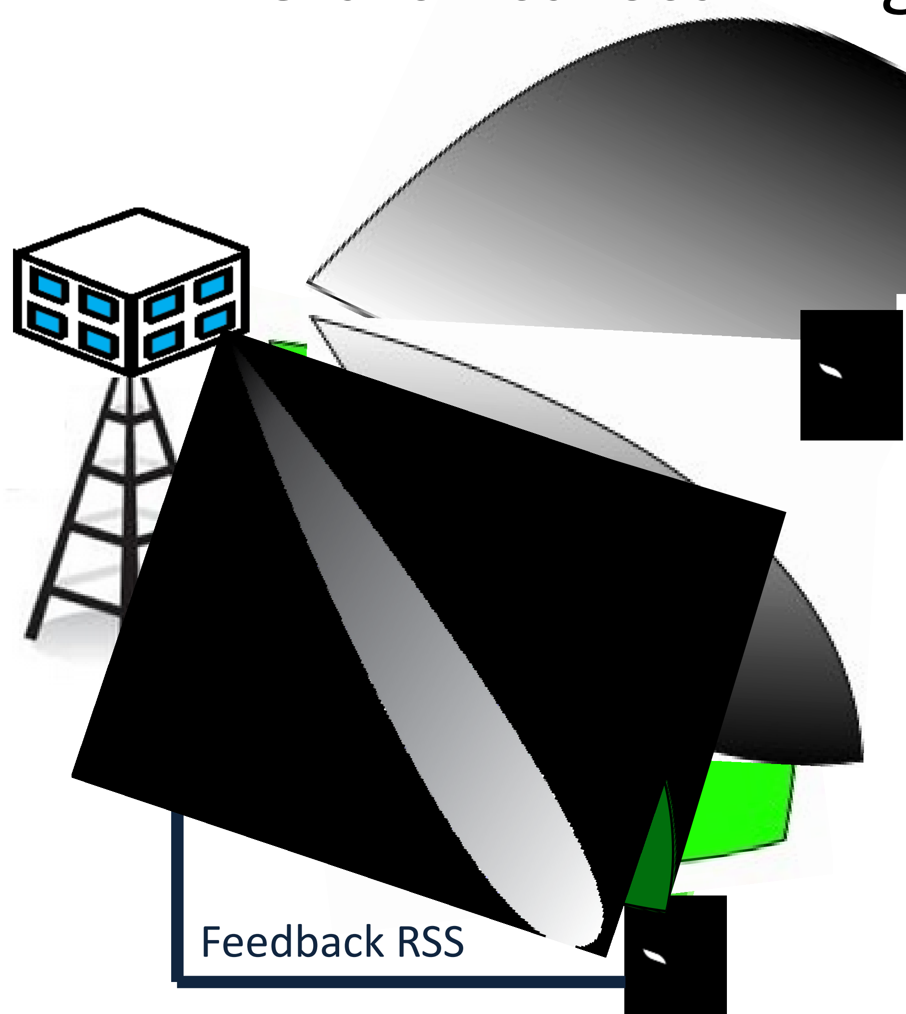
- Exhaustive scanning



Does not scale well with # of antennas (N)

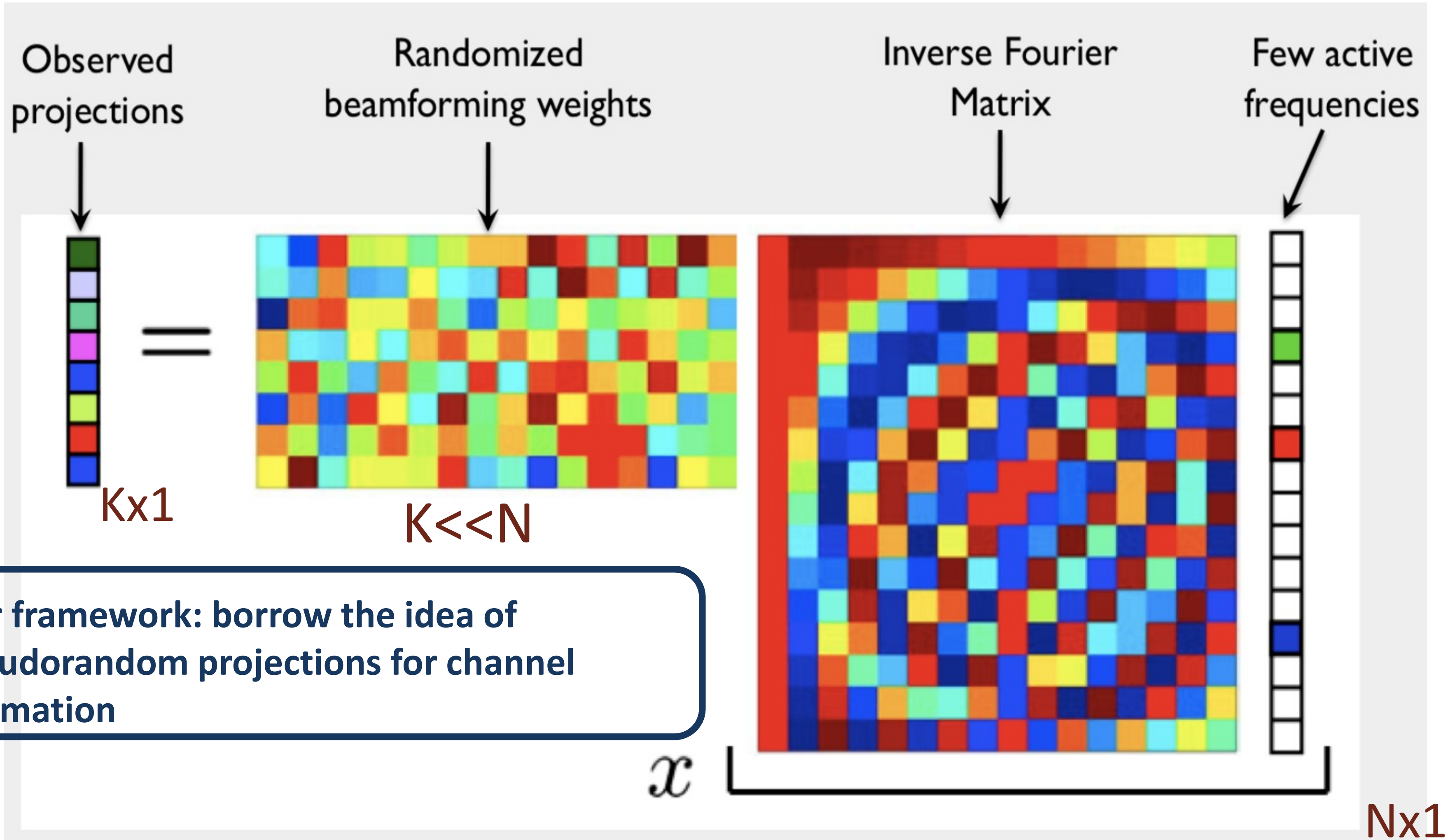
Conventional direction finding techniques

- Hierarchical scanning:



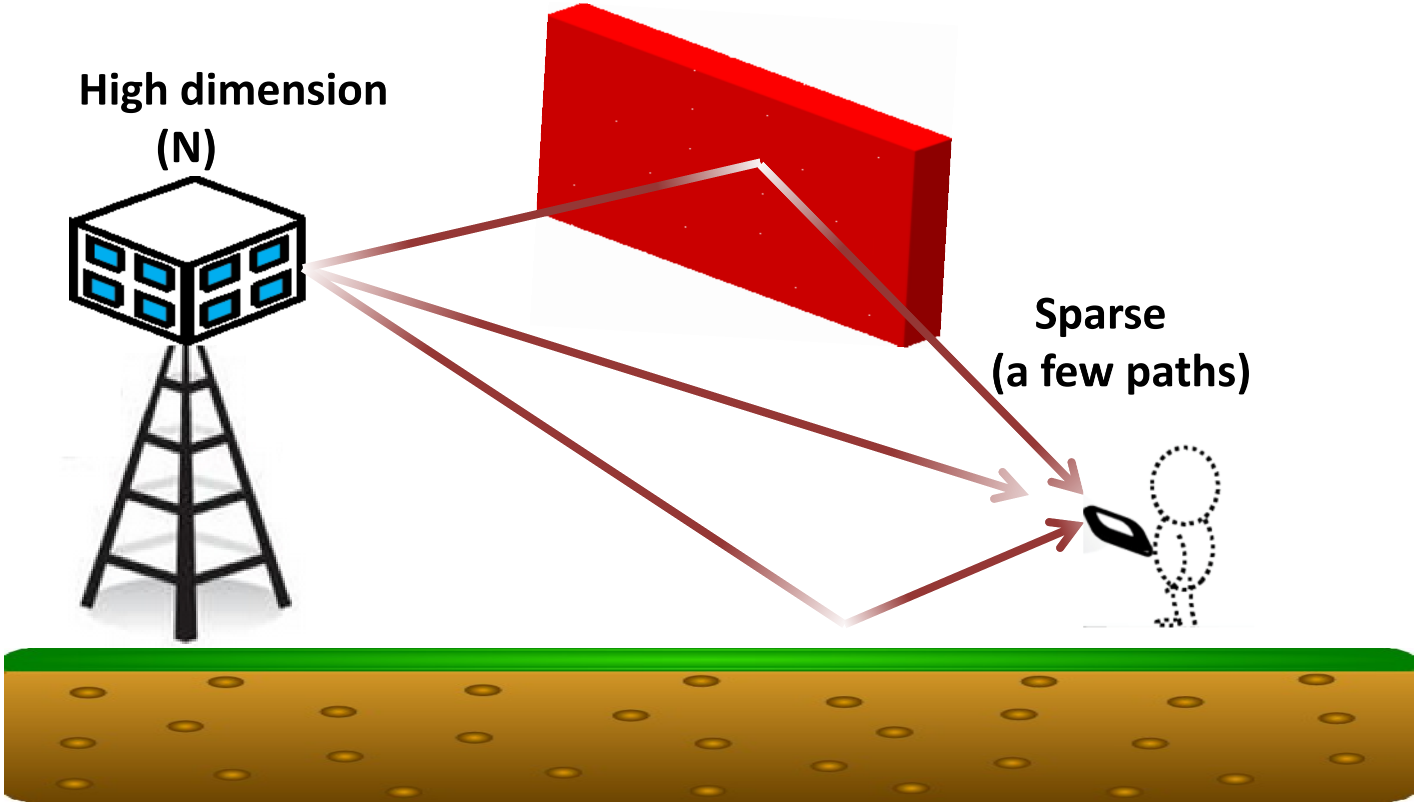
- Scales well with # of antenna (log(N))
- Too much feedback overhead and delay
- Does not scale well with # of users
- Compromise on range and reliability

Compressive sensing: basic concept

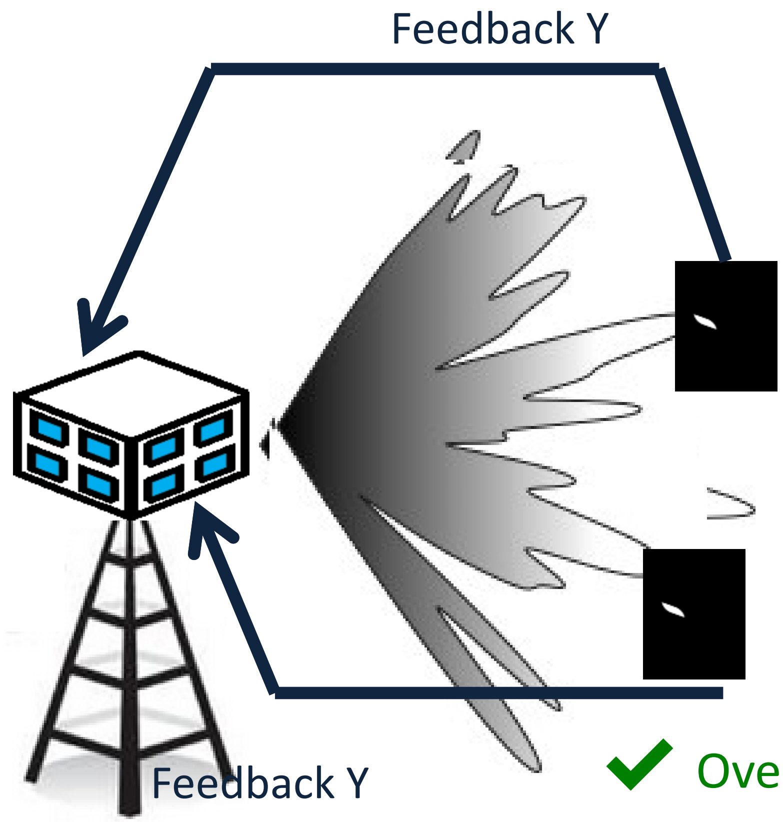


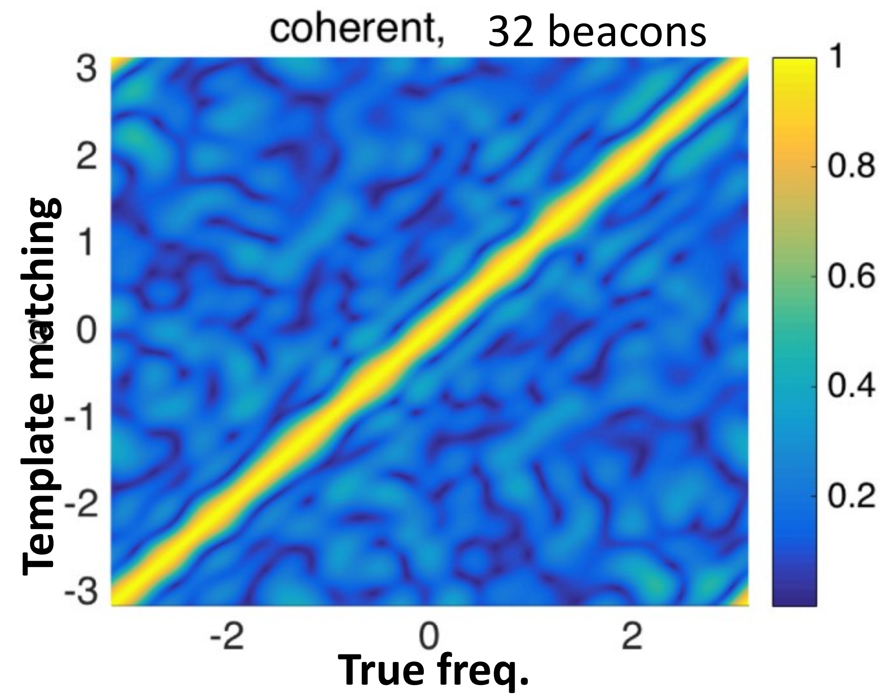
Our framework: borrow the idea of pseudorandom projections for channel estimation

Mmwave channel model



Compressive estimation





$$\boxed{y_i = h_0 \mathbf{b}_i^T \mathbf{a}(\omega_0) + v_0}$$

- ✔ Overhead (# of beacons) scales as Log(N)
- ✔ scalable with # of users
- ✔ Each user sends only one feedback packet
- ✔ Support coarse phase control (e.g. 2bit)

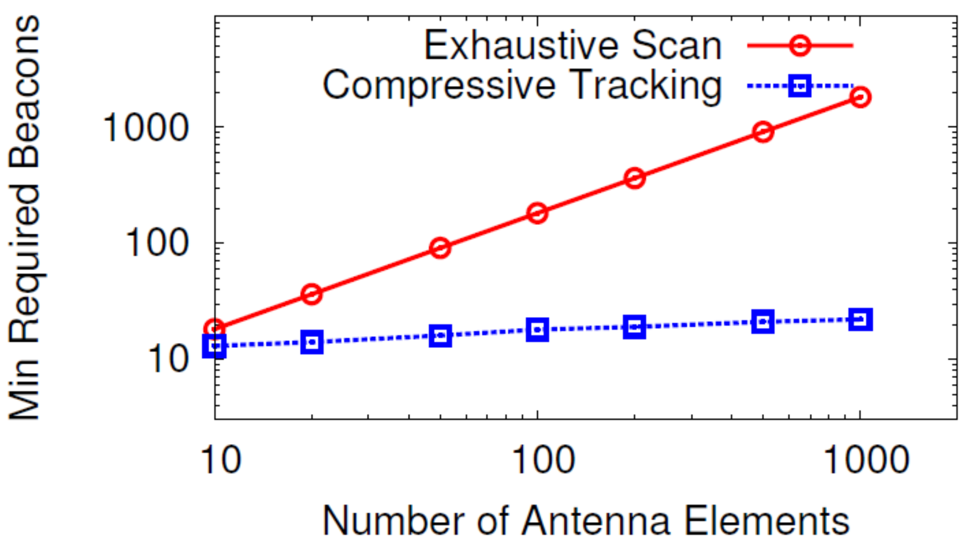
Z. Marzi, D. Ramasamy and U. Madhow, "Compressive Channel Estimation and Tracking for Large Arrays in mm-Wave Picocells," IEEE Journal of Selected Topics in Signal Processing

#beacons scale logarithmically with #elements

- 1000 element array can be trained with only 24 beacons
- 5 µs per beacon

training time < 120 µs

overhead < 1.2 % (once every 10 ms for fast car)

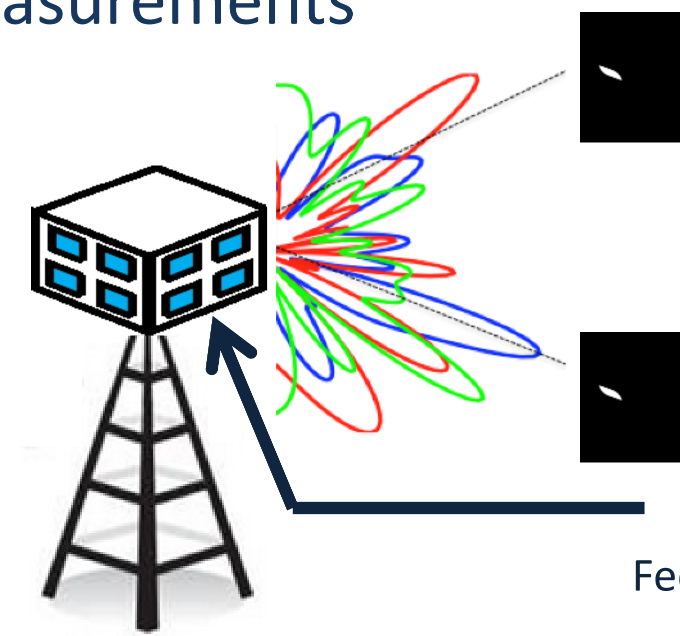


But todays's transceivers can only do *Noncoherent* measurements

- Frequency offset between local oscillators at TX and RX
- Random phase offset in measurements

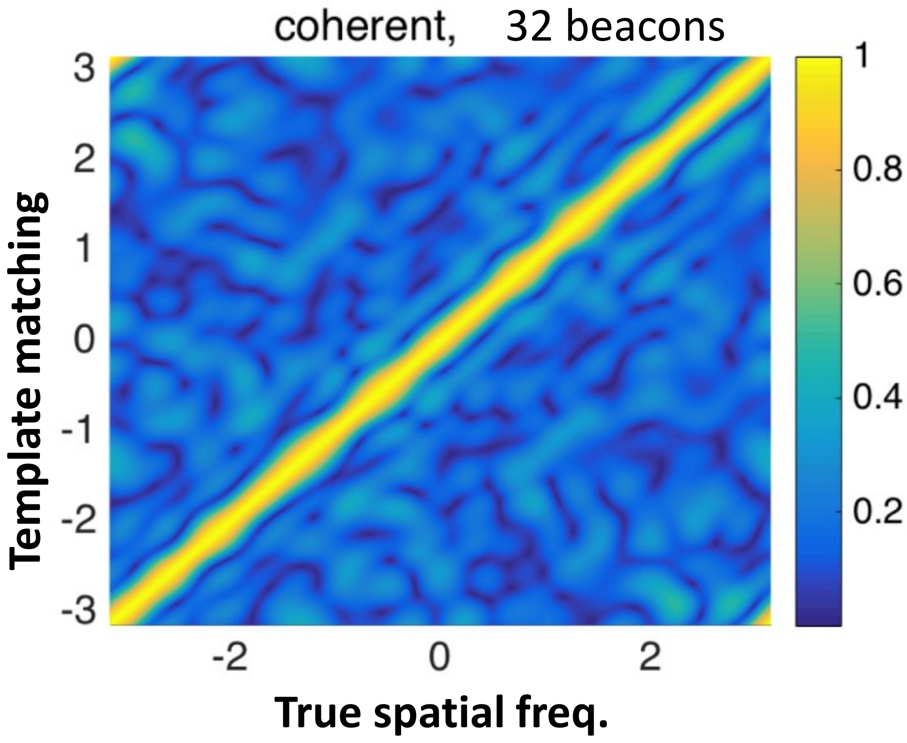
➔ Phase of measurements cannot be used!

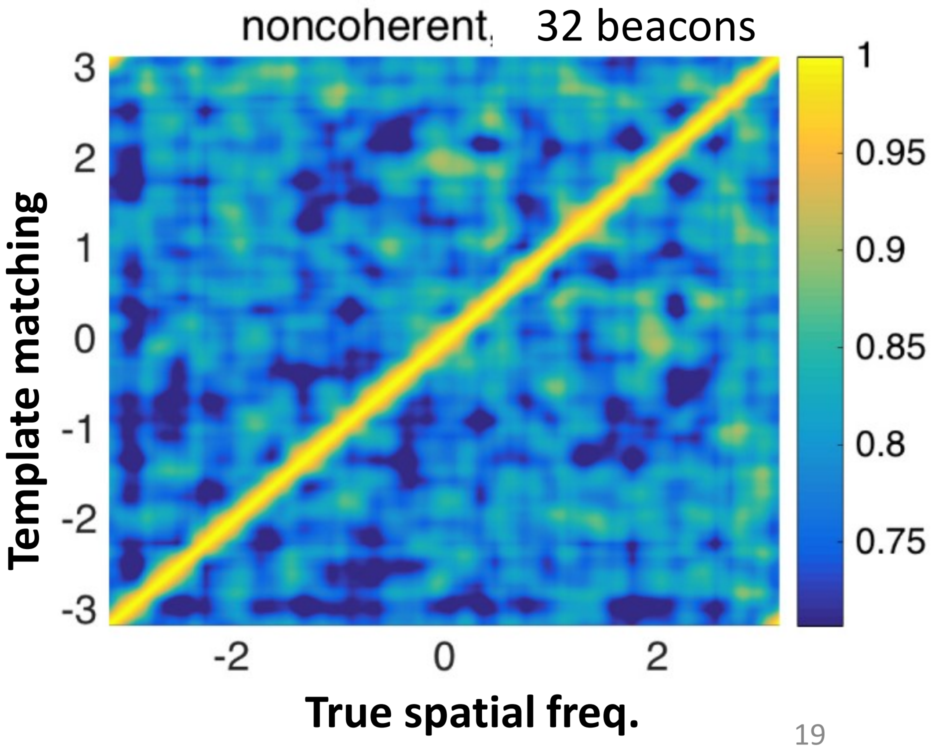
➔ RSS-only measurements



Noncoherent compressive sensing

--Match (normalized) RSS measurements against expected RSS measurements across "spatial frequencies"

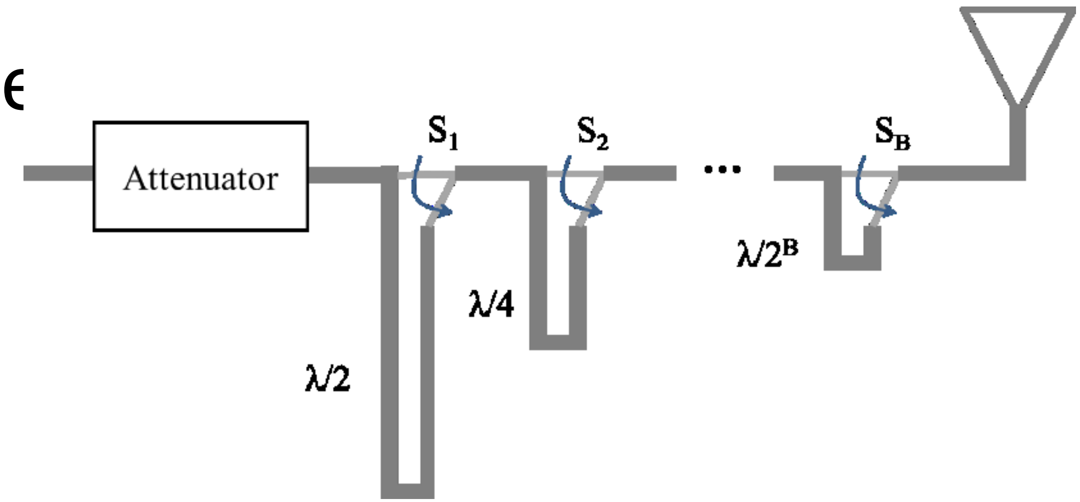




Hardware scalability: coarse phase control

- Large arrays, limited number of RF chains
- Simple RF phase control, for example via delay lines

➔ severe



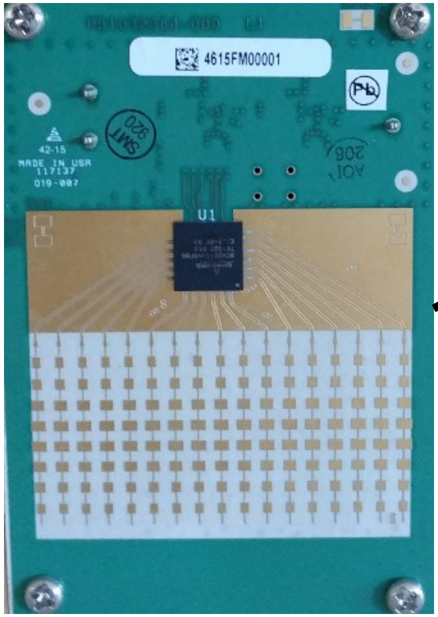
phases

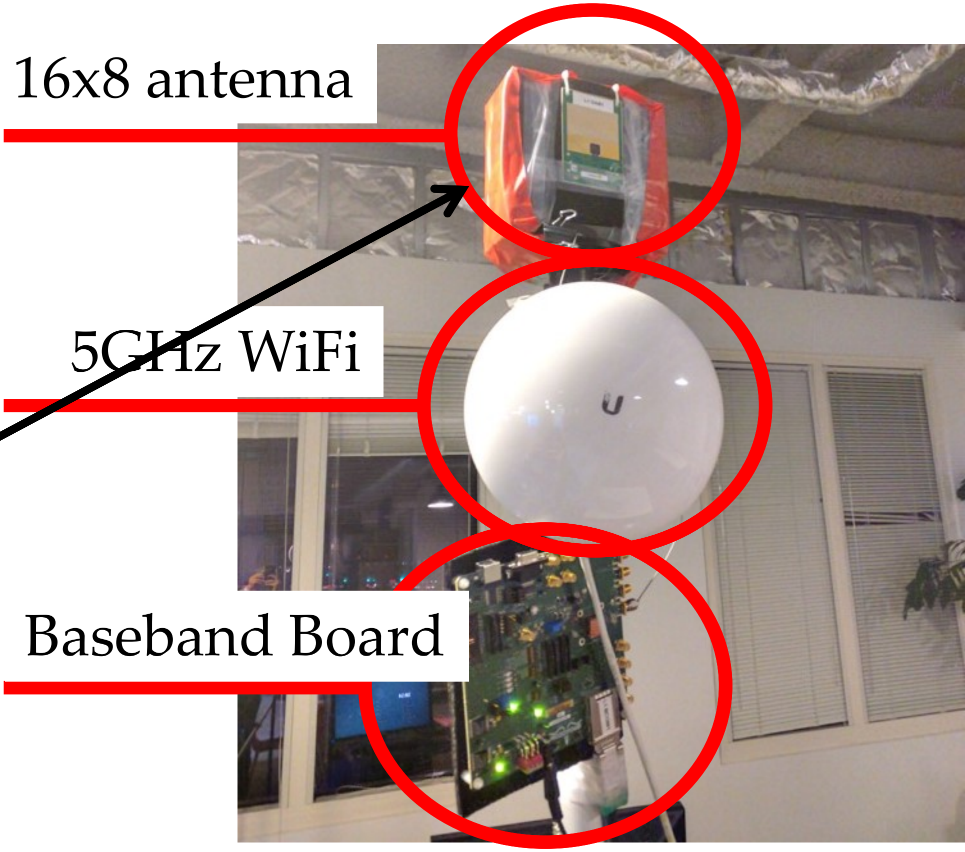
Scanning requires fine-grained control
Compressive approaches works fine with severe phase quantization

EXPERIMENTS

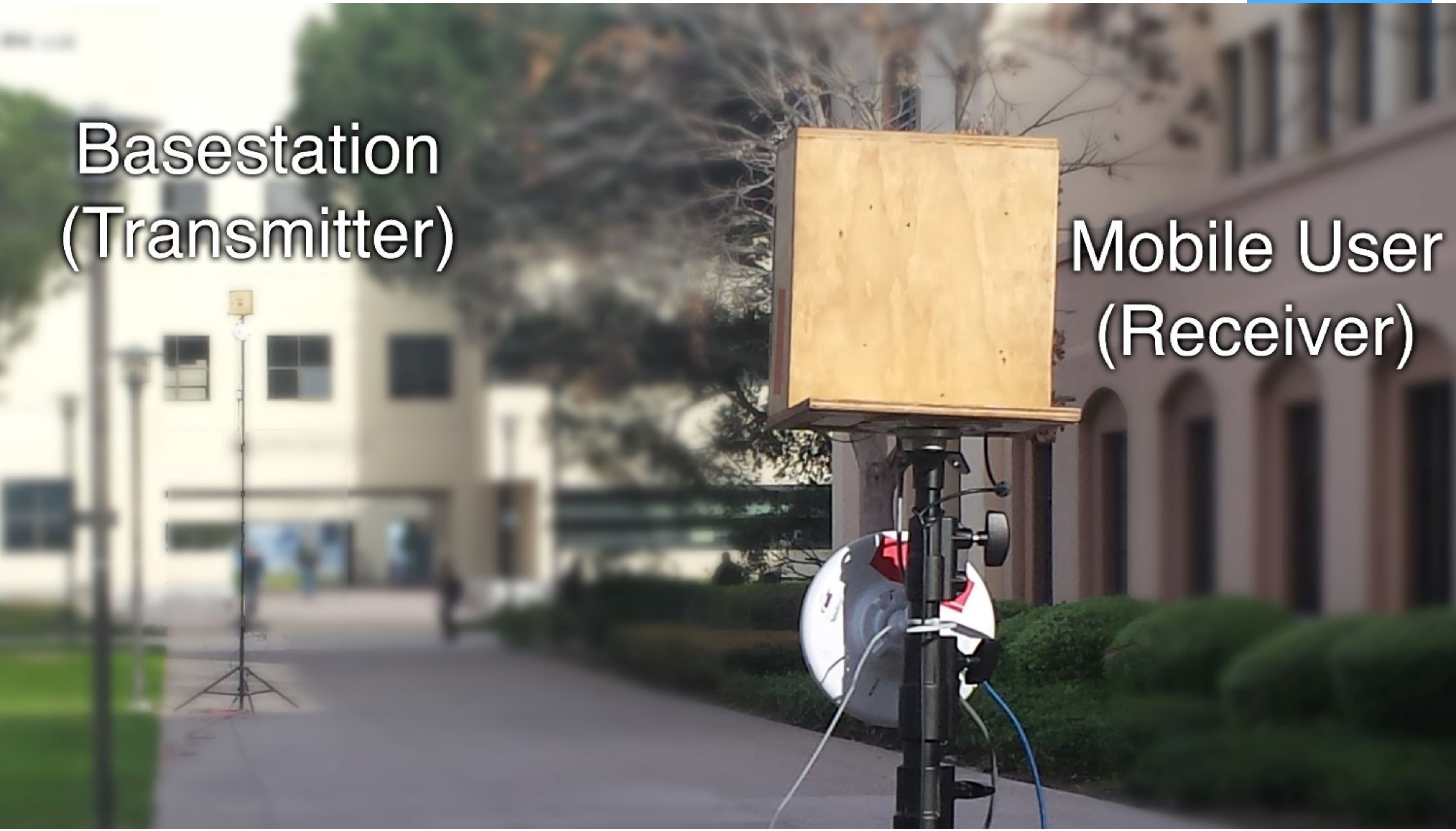
Hardware: 60GHz testbed

- A pair of
  - 16x8 antenna array

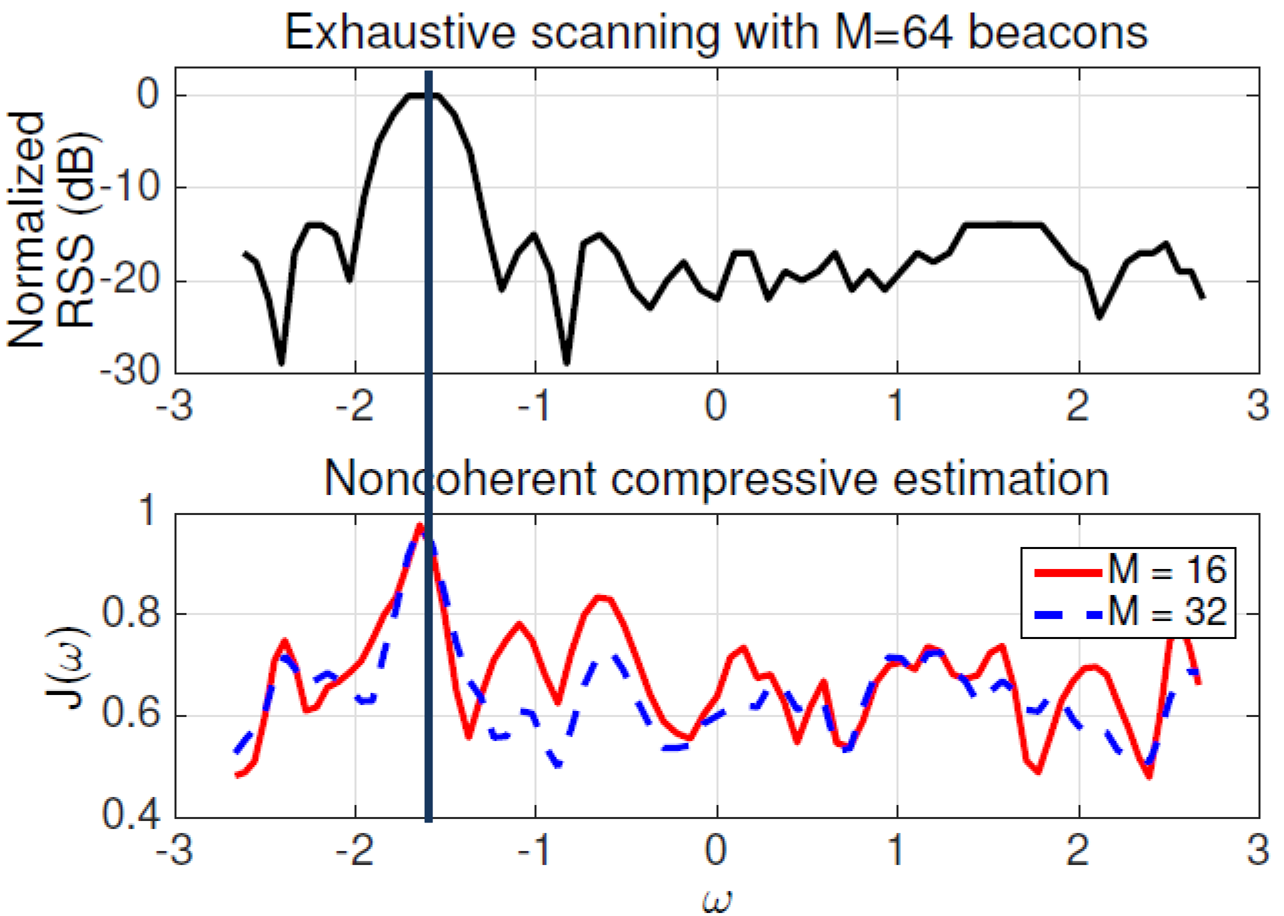




Thanks: Facebook Terragraph team

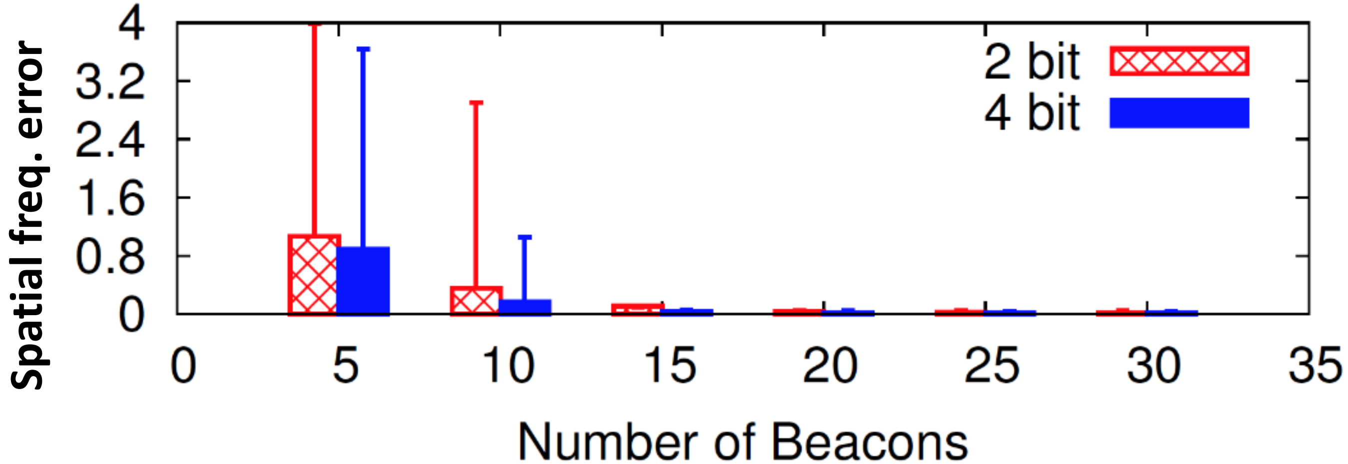

Basestation
(Transmitter)
Mobile User
(Receiver)

Noncoherent cost function follows the same pattern as exhaustive scan

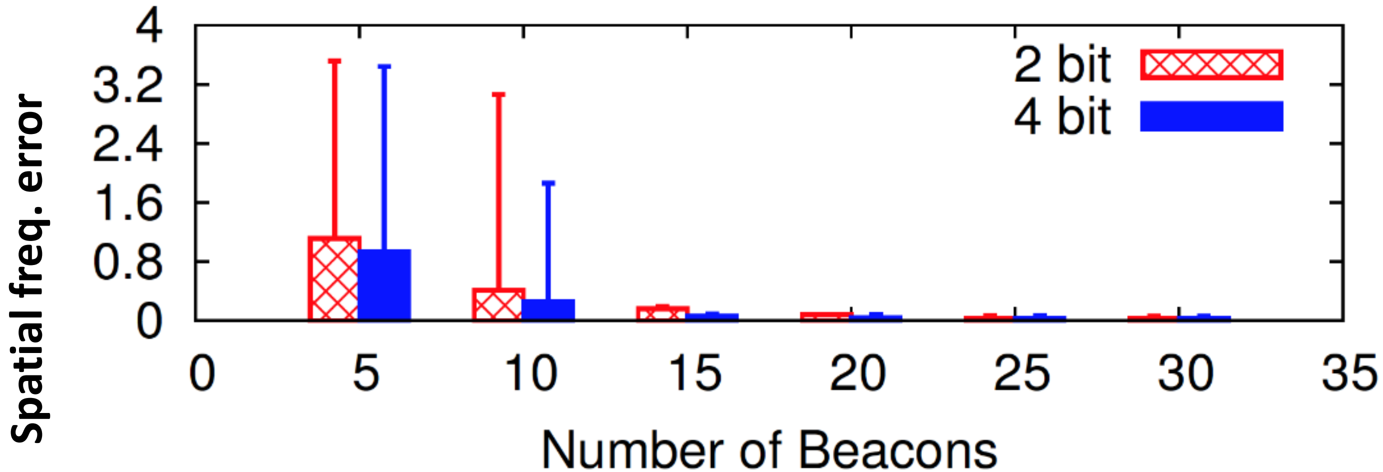


Dominant path identified effectively

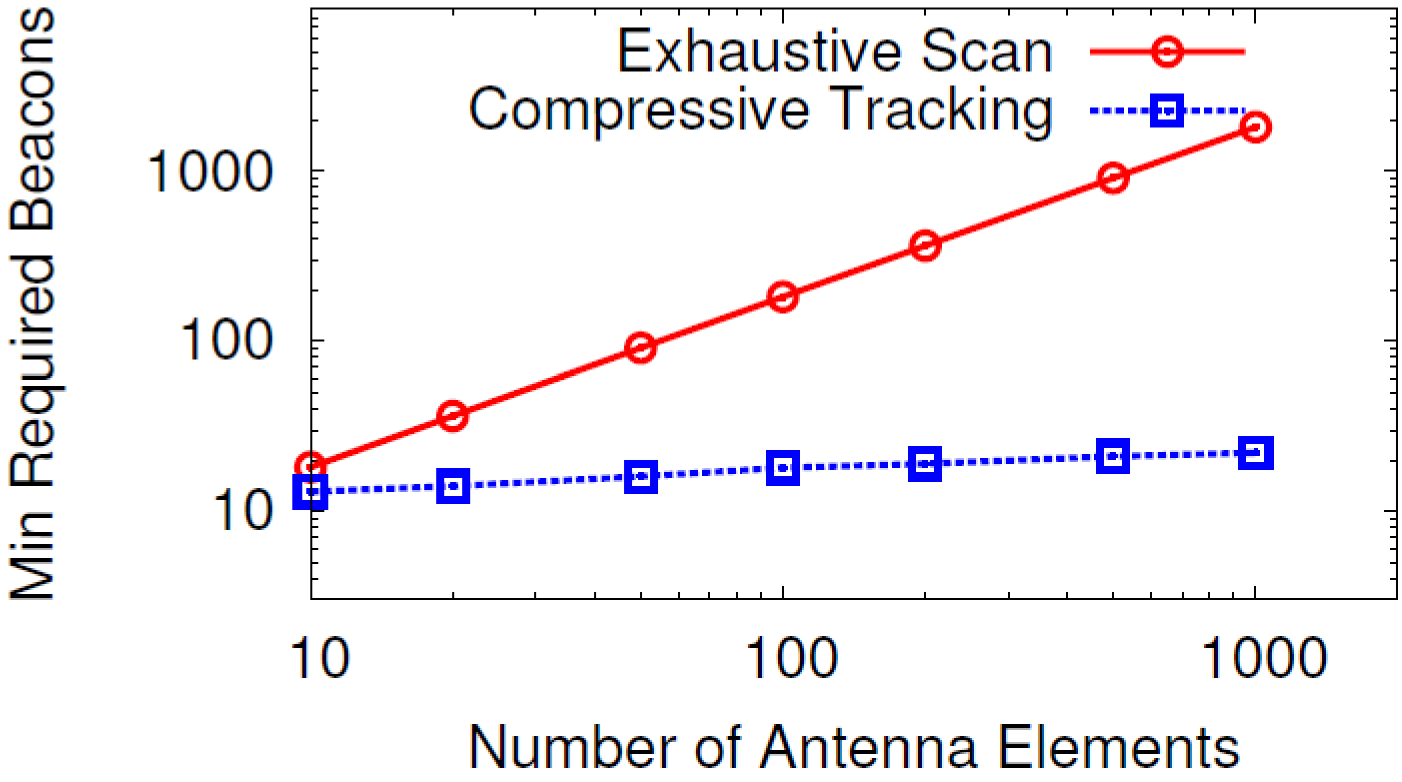
- **Single path**



- **Two path** (one dominant path 8 dB stronger)



Sims show effective scaling with array size



Compressive tracking take-aways

- Compressive channel tracking eliminates a key bottleneck to Cellular 1000X (and other mm-wave systems)
  - Low overhead
  - Scalable with # of users and # of antenna elements
  - Compatible with simplified hardware (heavily quantized phases)
- Noncoherent compressive estimation works with today's hardware
  - Effective solution demonstrated when there is a single dominant path
- Recent result: noncoherent algorithms for multipath channels

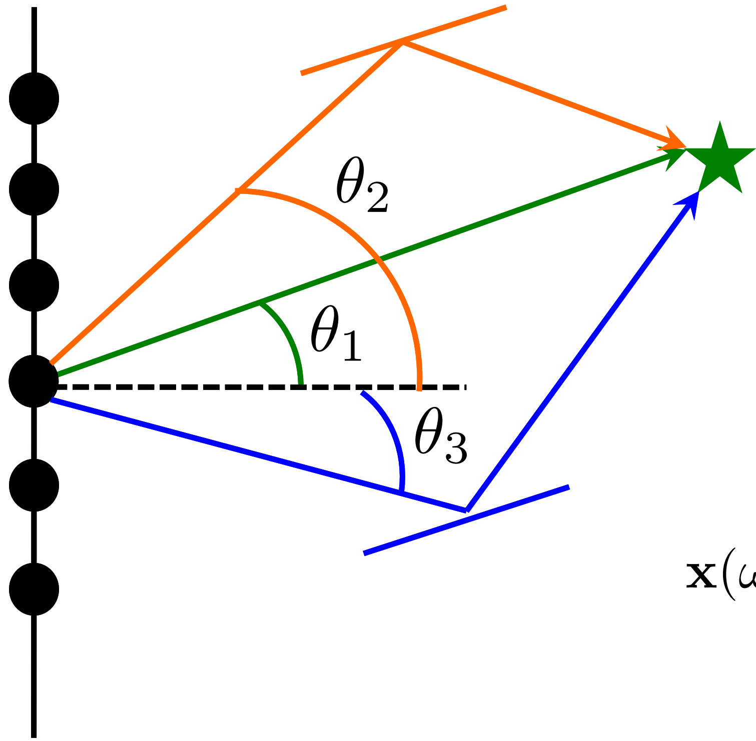
Opens up new system design challenges

- Assuming each base station maintains path inventory for nearby mobile users
  - How do the base stations coordinate to provide robust connectivity?
  - How do the base stations coordinate to provide high throughput and manage interference?
  - How do we manage the transport layer?
  - What are the implications for backhaul requirements?

Appendix

Details of compressive scheme

Estimation problem



Channel is a sum of a few sinusoids

$$\mathbf{h} = g_1\mathbf{x}(\omega_1) + g_2\mathbf{x}(\omega_2) + g_3\mathbf{x}(\omega_3)$$

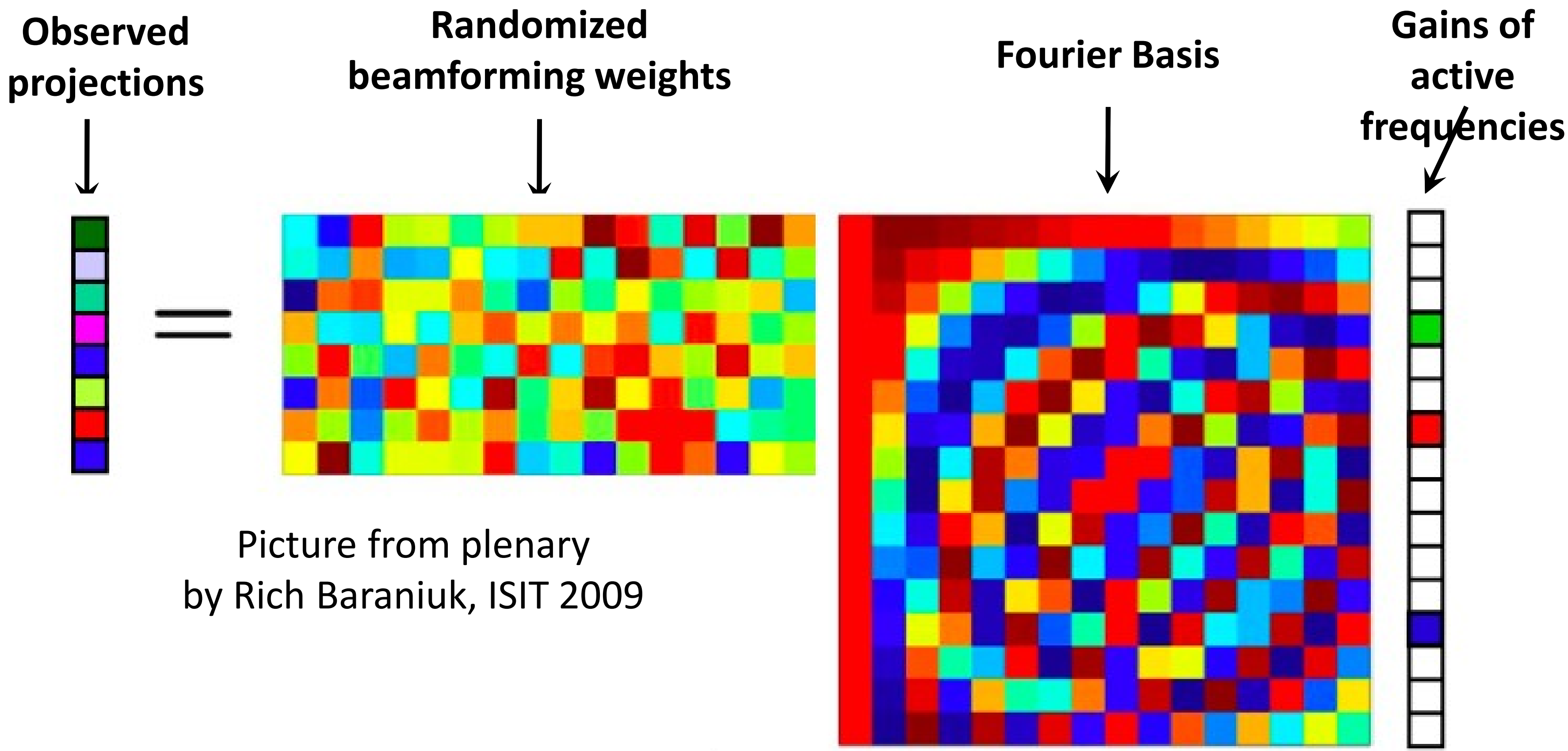
$$\mathbf{x}(\omega) = \begin{pmatrix} 1 \\ e^{j\omega} \\ e^{j2\omega} \\ \vdots \\ e^{j(N-1)\omega} \end{pmatrix} \quad \omega_i = \frac{2\pi d}{\lambda}\sin\theta_i$$

Mobile makes compressive measurements

$$y_i = \mathbf{a}_i^T\mathbf{h}, i = 1, 2, \ldots, M$$

Estimate gains and spatial frequencies from compressive measurements

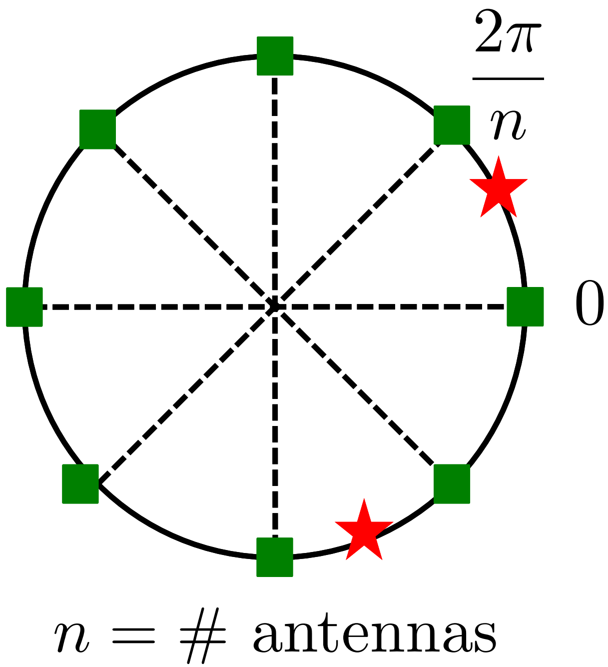
Can we use standard compressed sensing?



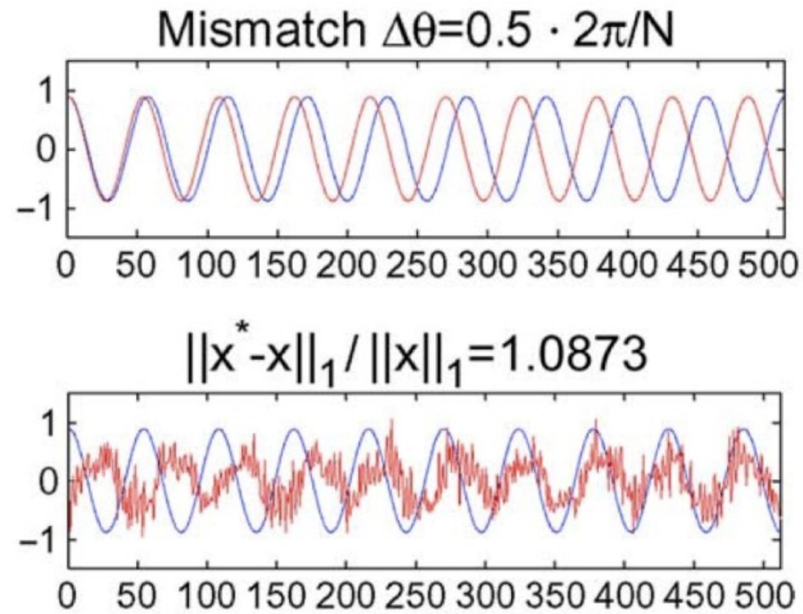
Picture from plenary
by Rich Baraniuk, ISIT 2009

$$\mathbf{y} = \sum_{k=1}^{L} g_k \mathbf{A}\mathbf{x}(\omega_k) + \mathbf{n}$$

Basis mismatch is the problem



Frequencies come from a continuum, not a grid



With standard CS, off-grid frequencies can have large estimation errors

Sensitivity to Basis Mismatch in Compressed Sensing,
Y. Chi, L. Scharf, A. Pezeshki, R. Calderbank

Need compressive estimation in a continuum

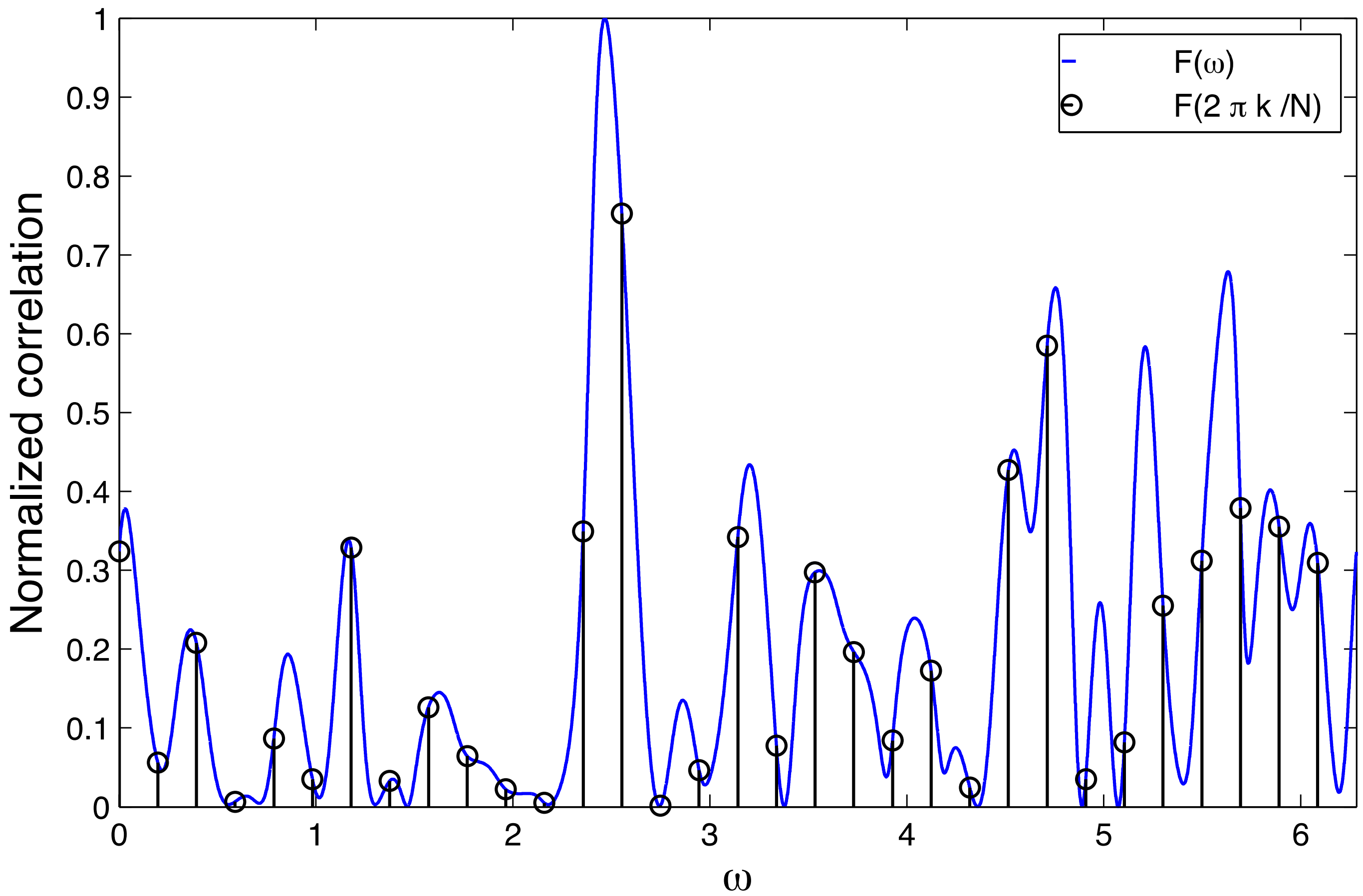
Algorithm

- Acquisition
  - No knowledge of spatial frequencies whatsoever
- Tracking
  - Leverage frequency estimate from previous round
  - Refine based on new measurements

Acquisition: Coarse Estimate

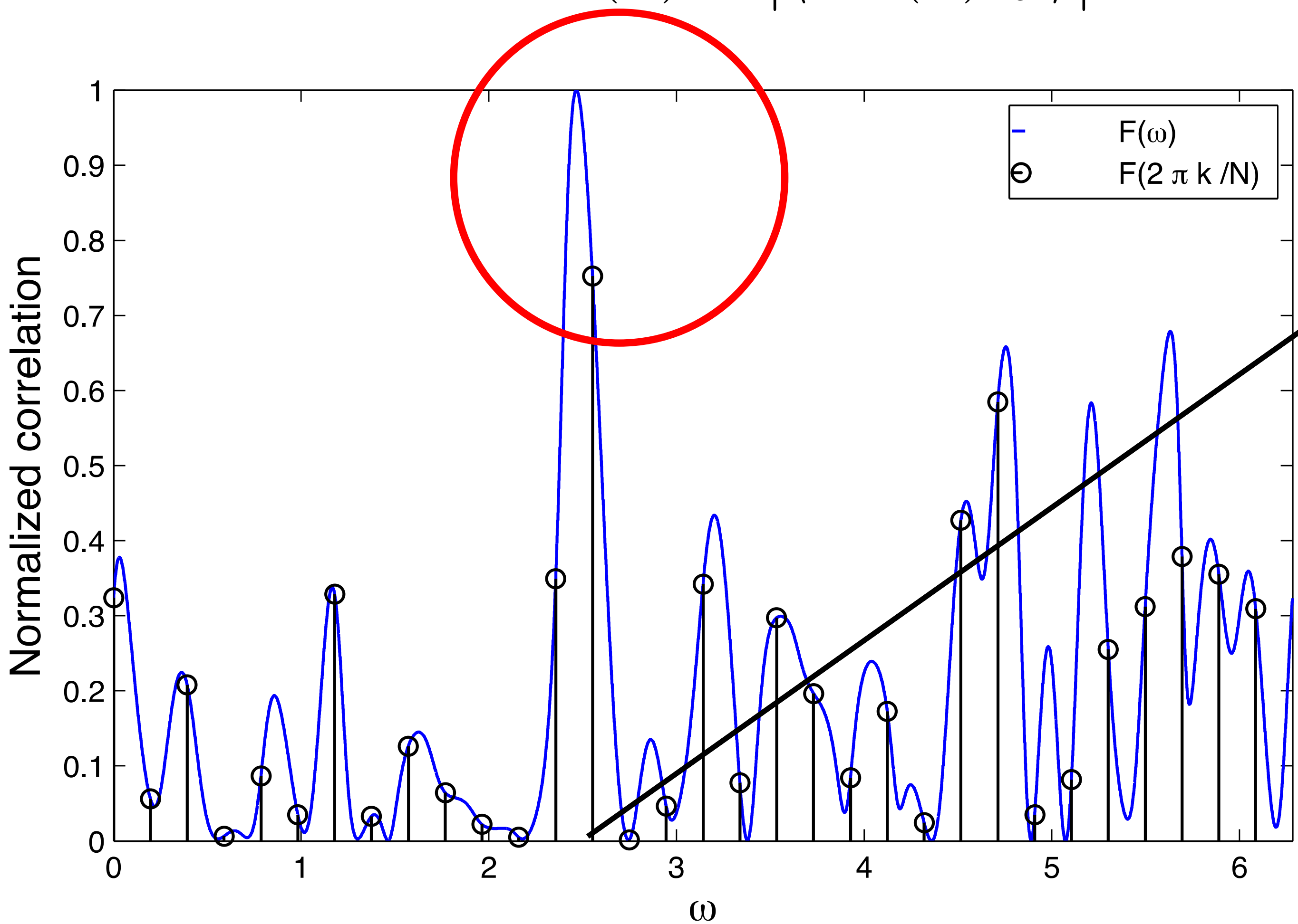
$$\text{maximize } F(\omega) = \left|\langle \mathbf{A}\mathbf{x}(\omega), \mathbf{y}\rangle\right|^2$$

$$\omega = 0, \frac{2\pi}{2N}, 2\left(\frac{2\pi}{2N}\right), \ldots, (2N-1)\left(\frac{2\pi}{2N}\right)$$



Acquisition: Coarse Estimate

$$\text{maximize } F(\omega) = \left|\langle \mathbf{Ax}(\omega), \mathbf{y}\rangle\right|^2$$



$$\hat{\omega}_1$$

$$\hat{g}_1 = \frac{\langle \mathbf{Ax}(\hat{\omega}_1), \mathbf{y}\rangle}{\|\mathbf{Ax}(\hat{\omega}_1)\|^2}$$

Iterative refinements

Given

Gains: $\hat{g}_1, \hat{g}_2, \ldots, \hat{g}_K$

Freqs: $\hat{\omega}_1, \hat{\omega}_2, \ldots, \hat{\omega}_K$

Project out contributions from these frequencies

$$\mathcal{S} = \mathbf{A}\left[\mathbf{x}(\hat{\omega}_1)\ \mathbf{x}(\hat{\omega}_2) \ldots \mathbf{x}(\hat{\omega}_K)\right]$$

$$\mathbf{y}_r = \mathcal{S}^{\perp}\mathbf{y}$$

Coarsely estimate (K+1)th freq

$$\max_{\omega = 0, \frac{2\pi}{2N}, 2\left(\frac{2\pi}{2N}\right), \ldots, (2N-1)\left(\frac{2\pi}{2N}\right)} |\langle \mathbf{A}\mathbf{x}(\omega), \mathbf{y}_r \rangle|^2$$

$\hat{\omega}_{K+1}, \hat{g}_{K+1}$

Fix gains: $\hat{g}_1, \hat{g}_2, \ldots, \hat{g}_K, \hat{g}_{K+1}$

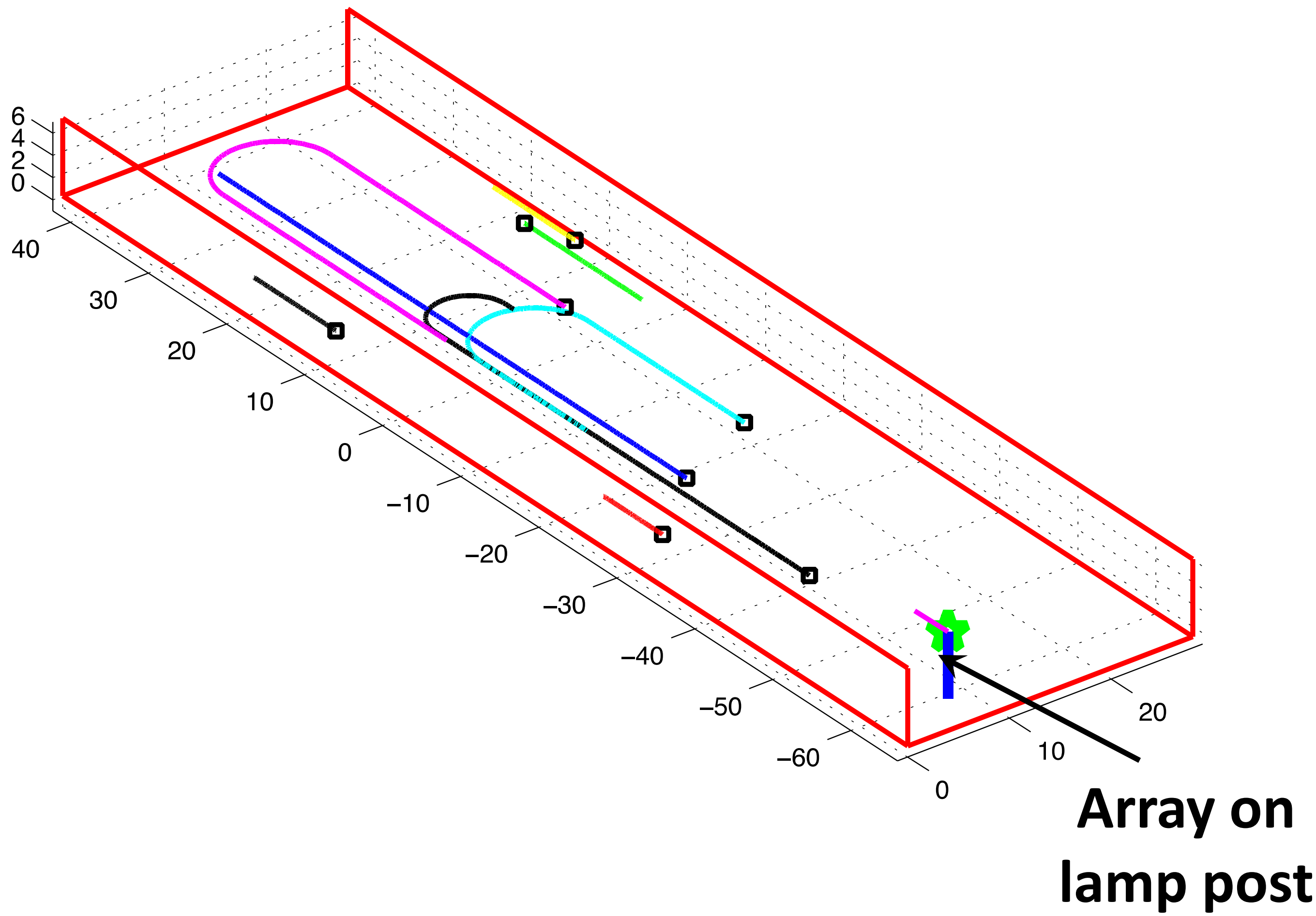
Refine freqs: $\Delta_1, \Delta_2, \ldots, \Delta_{K+1}$

Fix freqs: $\hat{\omega}_1, \hat{\omega}_2, \ldots, \hat{\omega}_{K+1}$

Estimate g's: $\hat{g}_1, \hat{g}_2, \ldots, \hat{g}_K, \hat{g}_{K+1}$

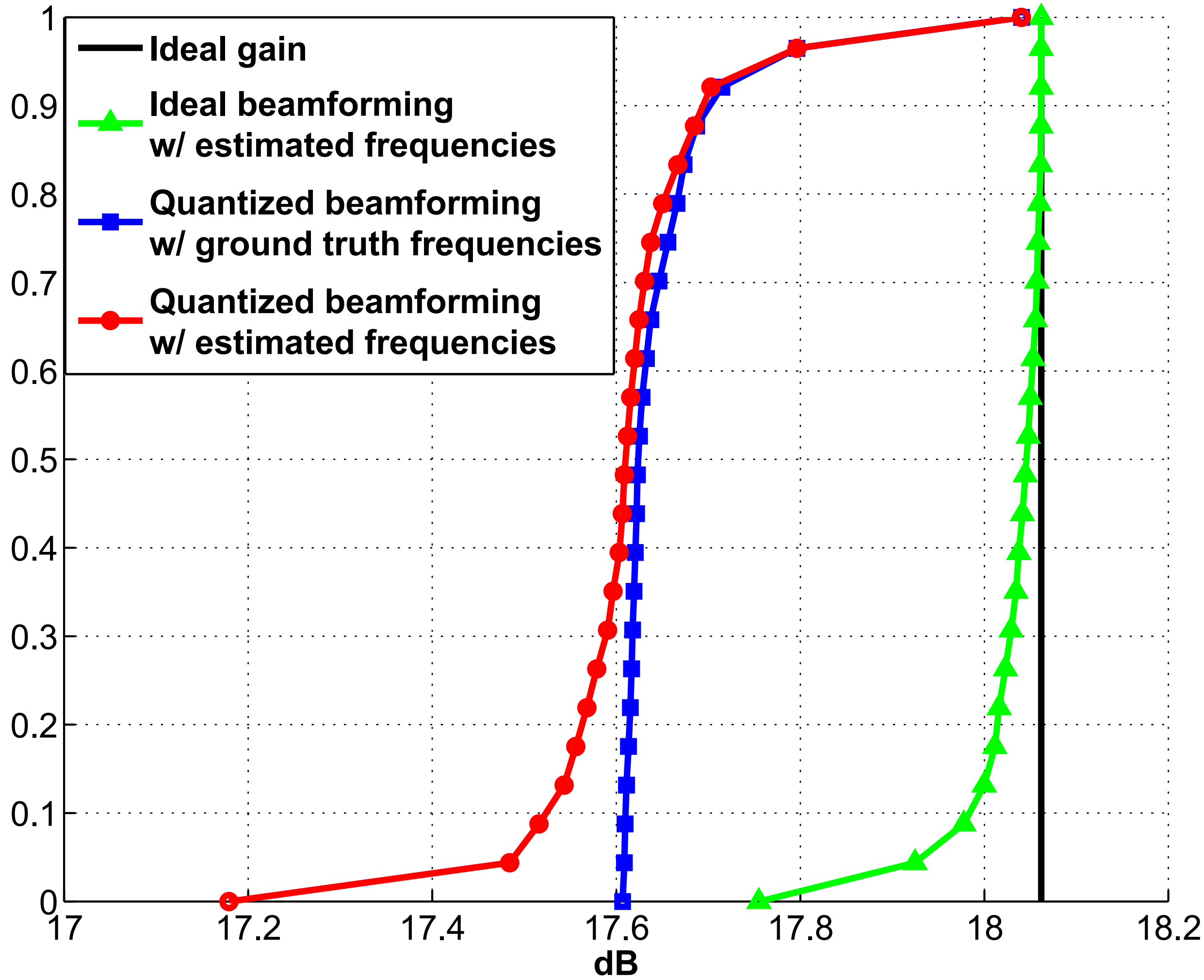
Stop when residual energy can be explained by noise: CFAR criterion

Simulation Setup



Within a dB of ideal beamforming

$$8 \times 8$$



The need for noncoherent tracking

- Phase synchronization not maintained between packets
  - Relative phase of measurements is corrupted
  - **Coherent compressive estimation does not work**
- Effective measurement model (high SNR approximation)

$$
\begin{aligned}
y_i &= |h_0 \mathbf{b}_i^T x(\omega) + v_i|, \quad v_i \sim \mathcal{CN}(0, 2\sigma^2) \\
&\approx |h_0 \mathbf{b}_i^T x(\omega)| + v_i, \quad v_i \sim \mathcal{N}(0, \sigma^2)
\end{aligned}
$$

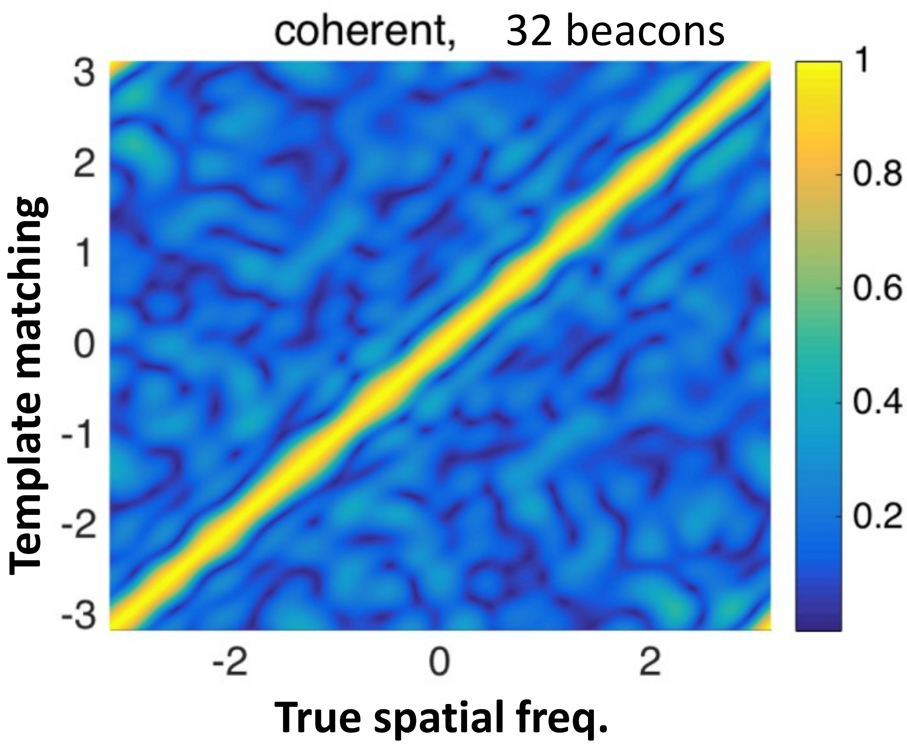
Noncoherent compressive tracking (single path)

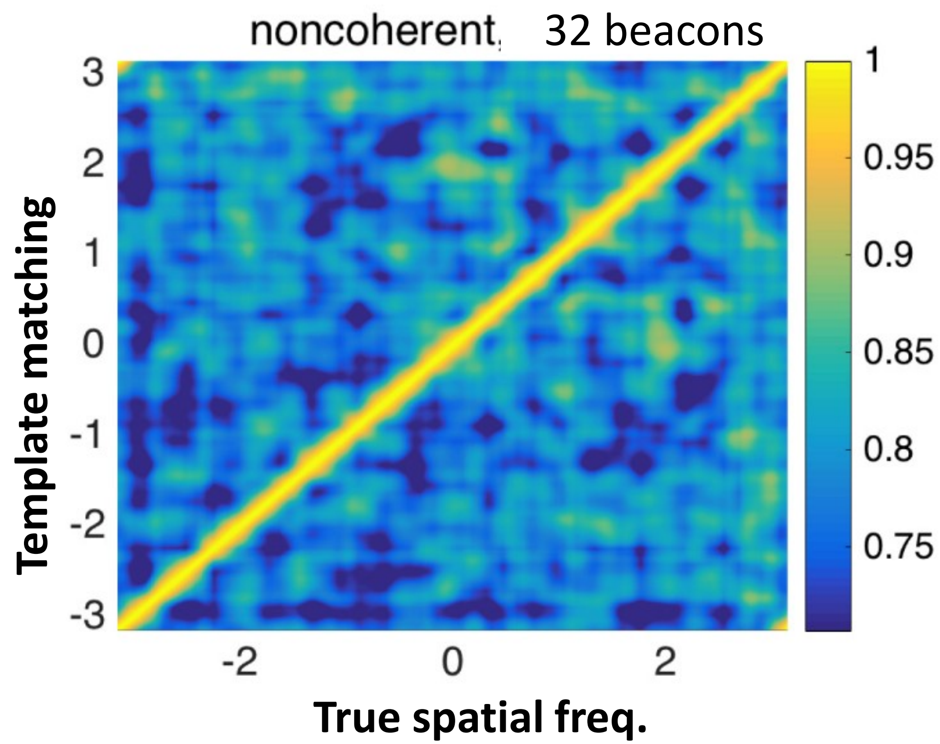
- Noncoherent template matching gives ML estimate under high SNR approximation

$$\hat{\omega}_0 = \underset{\omega}{\operatorname{argmax}} \, J(\omega)$$

$$J(\omega) = \langle \frac{\mathbf{y}}{||\mathbf{y}||}, \frac{|\mathbf{f}(\omega)|}{||\mathbf{f}(\omega)||} \rangle^2$$

Noncoherent compressive tracking (single path)



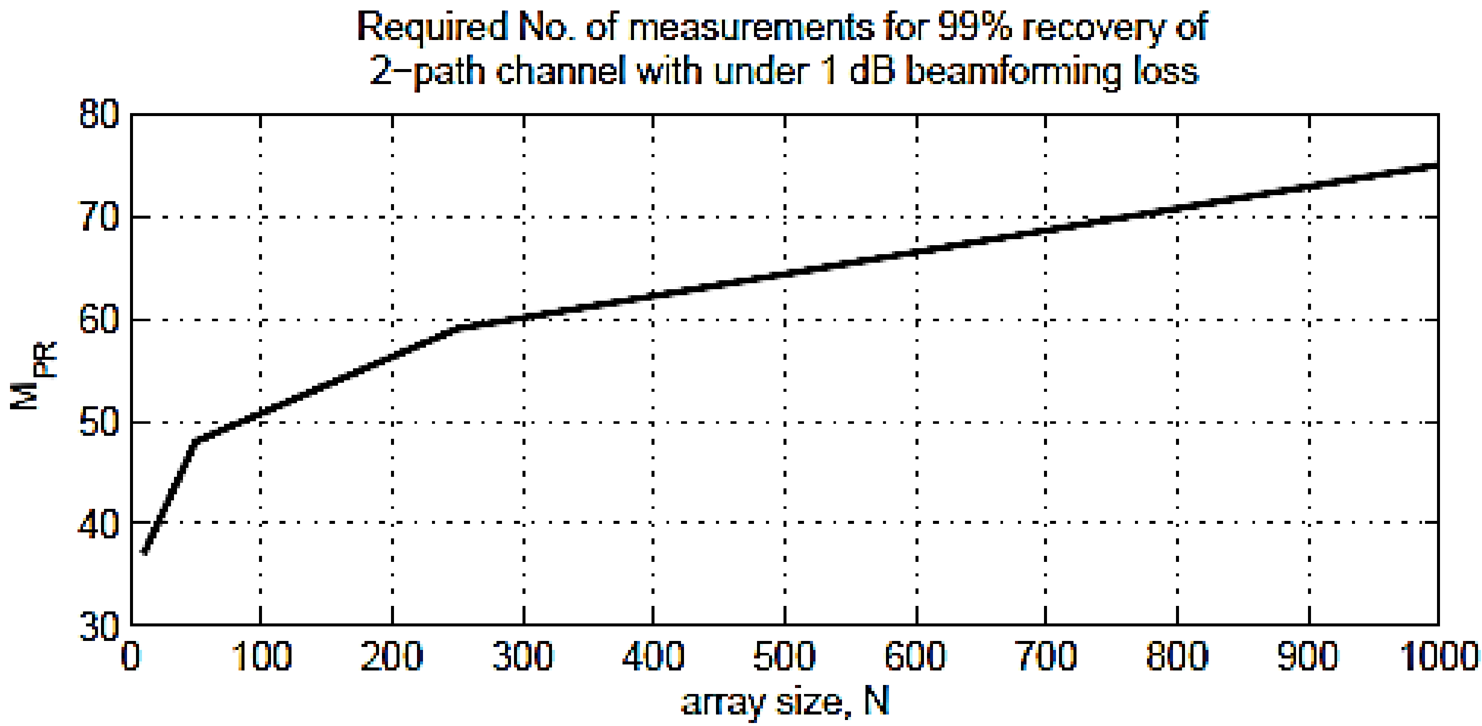


What about multiple strong paths?

How do we sort out interference across paths?

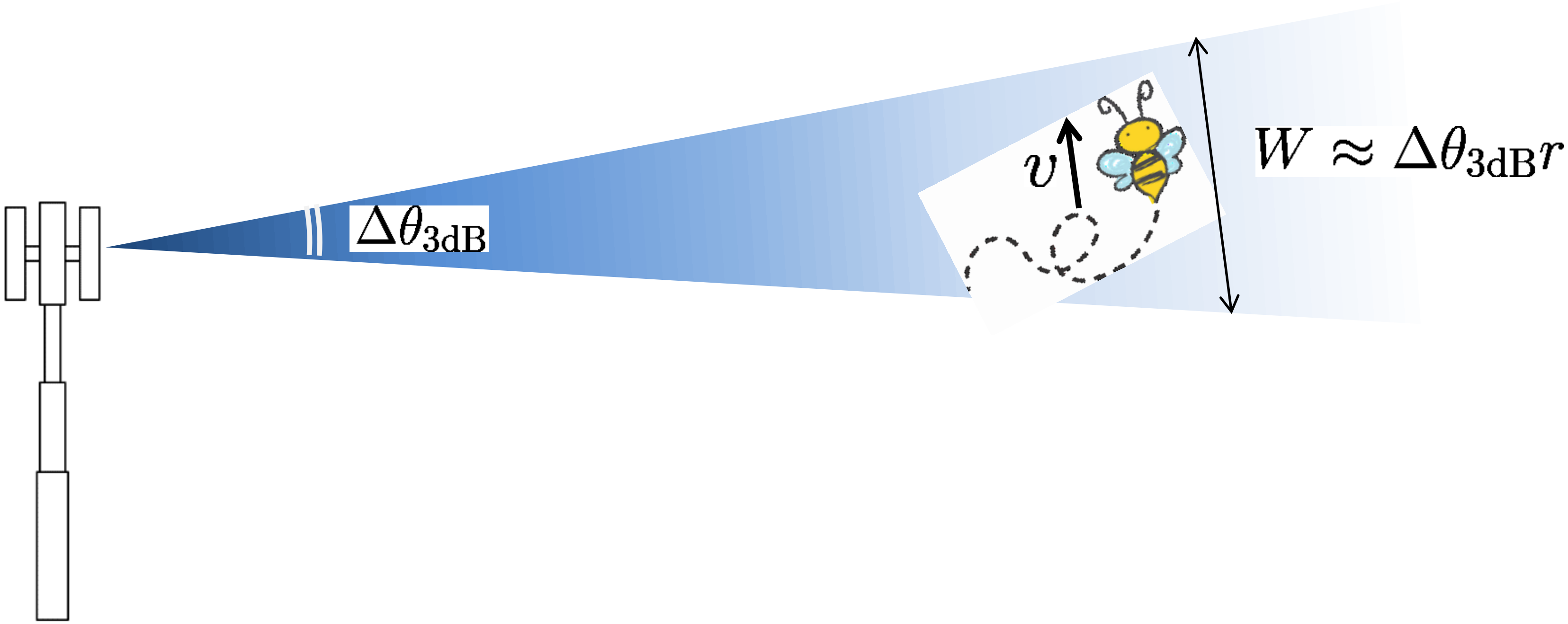
$$y_i \approx |\sum_{k=1}^{K} h_k \mathbf{b}_i^T x(\omega_k)| + v_i, \quad v_i \sim \mathcal{N}(0, \sigma^2)$$

Recent result: Noncoherent can be made almost as efficient as coherent



Details omitted until publication
Experimental results not yet obtained

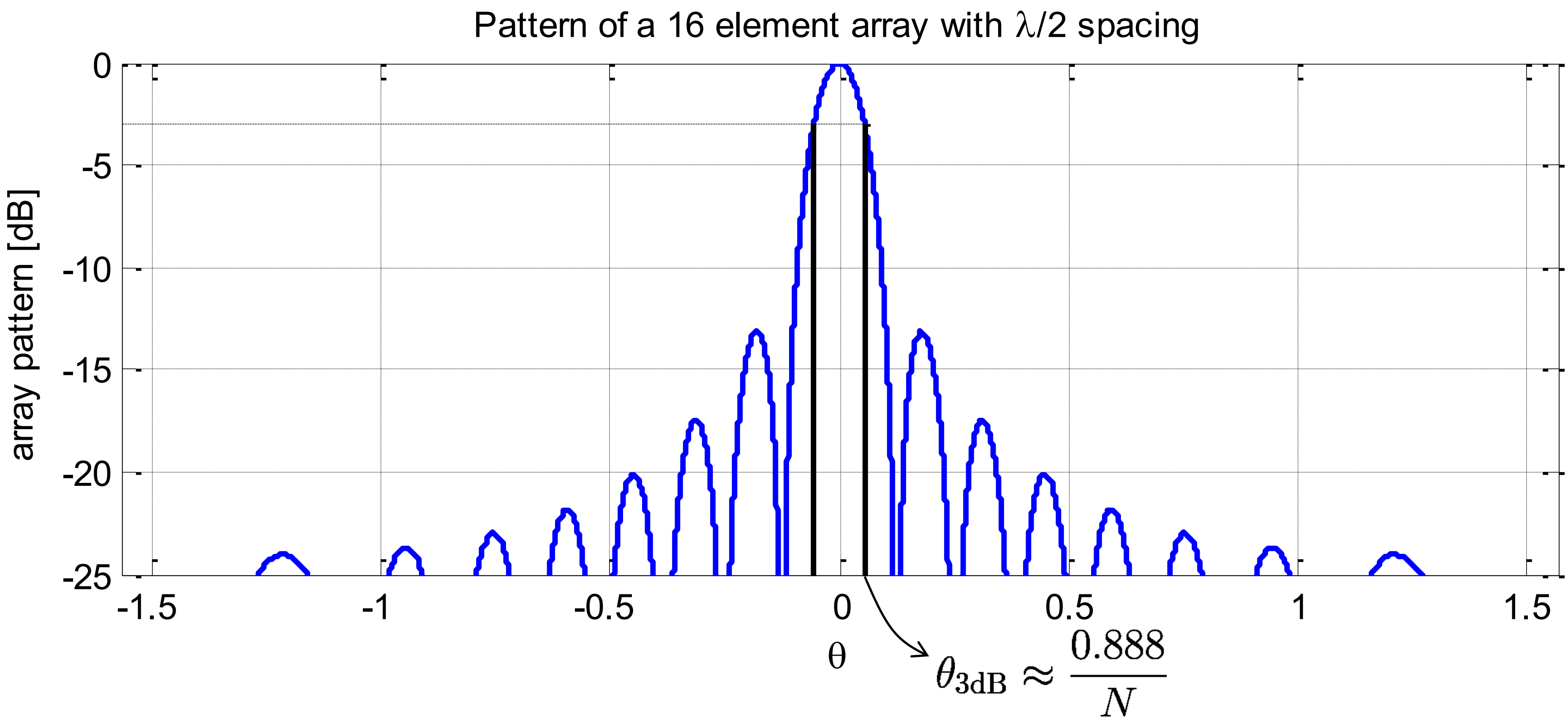
Time scale of tracking mobile user



$$\tau = \frac{\Delta\theta_{3\mathrm{dB}} r}{2v}$$

Time scale of tracking mobile user

3-dB beamwidth of N element array:



Time scale of tracking mobile user

3-dB beamwidth of N element array:

$$\text{array response} = \left.\frac{\sin(N\pi/2\sin\theta)}{N\sin(\pi/2\sin\theta)}\right|_{\theta_{3\mathrm{dB}}} = \frac{1}{\sqrt{2}}$$

$$\theta_{3\mathrm{dB}} \approx \sin\theta_{3\mathrm{dB}} = \alpha/N \Rightarrow \frac{\sin(\alpha\pi/2)}{\underbrace{N\sin(\alpha\pi/2N)}_{\approx\alpha\pi/2}} = \frac{1}{\sqrt{2}}$$

$$\Rightarrow\ \alpha = 0.888, \quad \theta_{3\mathrm{dB}} \approx \frac{0.888}{N} \qquad \left(\Delta\theta_{3\mathrm{dB}} \approx \frac{1.776}{N}\right)$$

$$\boxed{\tau = \frac{\Delta\theta_{3\mathrm{dB}} r}{2v} \approx \frac{0.888r}{Nv}}$$