I Beg to Diffract
RF Field Programming With Edges

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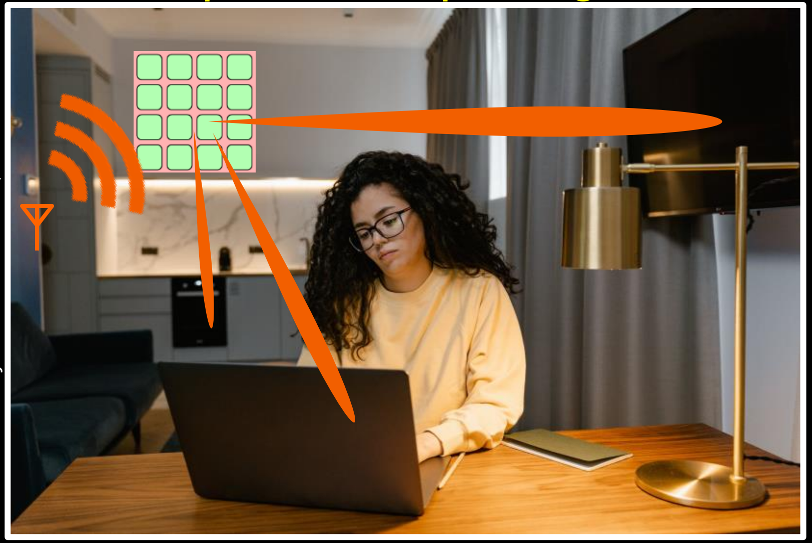
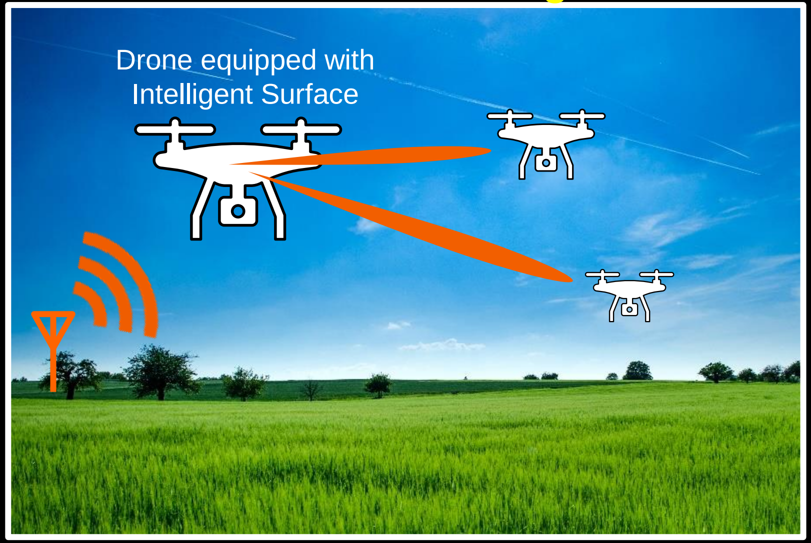
RF Field Programming

Spatial Multiplexing



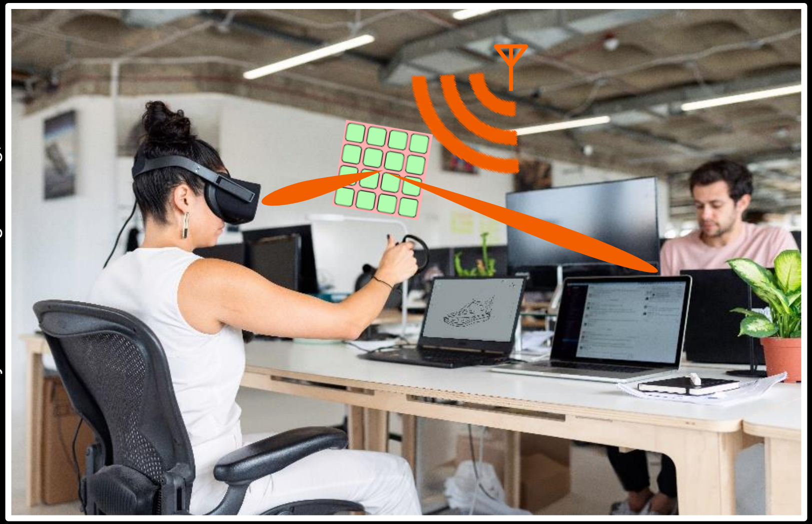
Courtesy of Mart Production, Pexels

Drone Swarm Navigation



Courtesy of Akos Szabo, Pexels

Link Privacy



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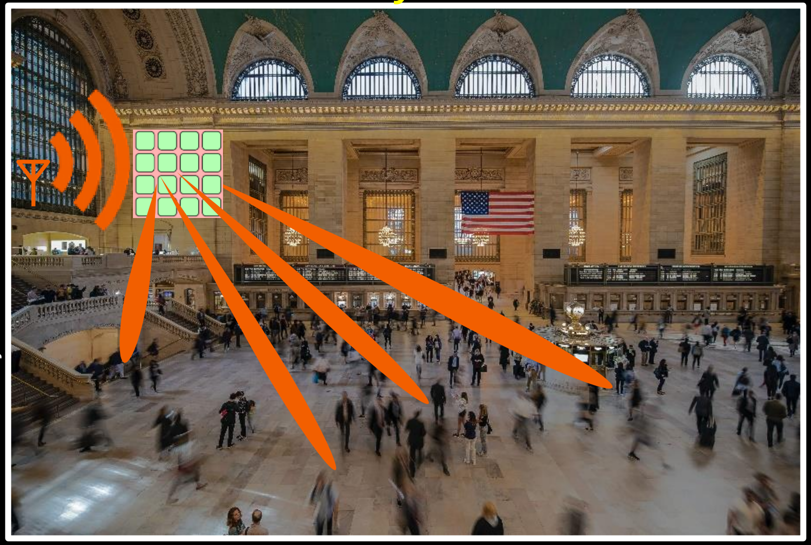
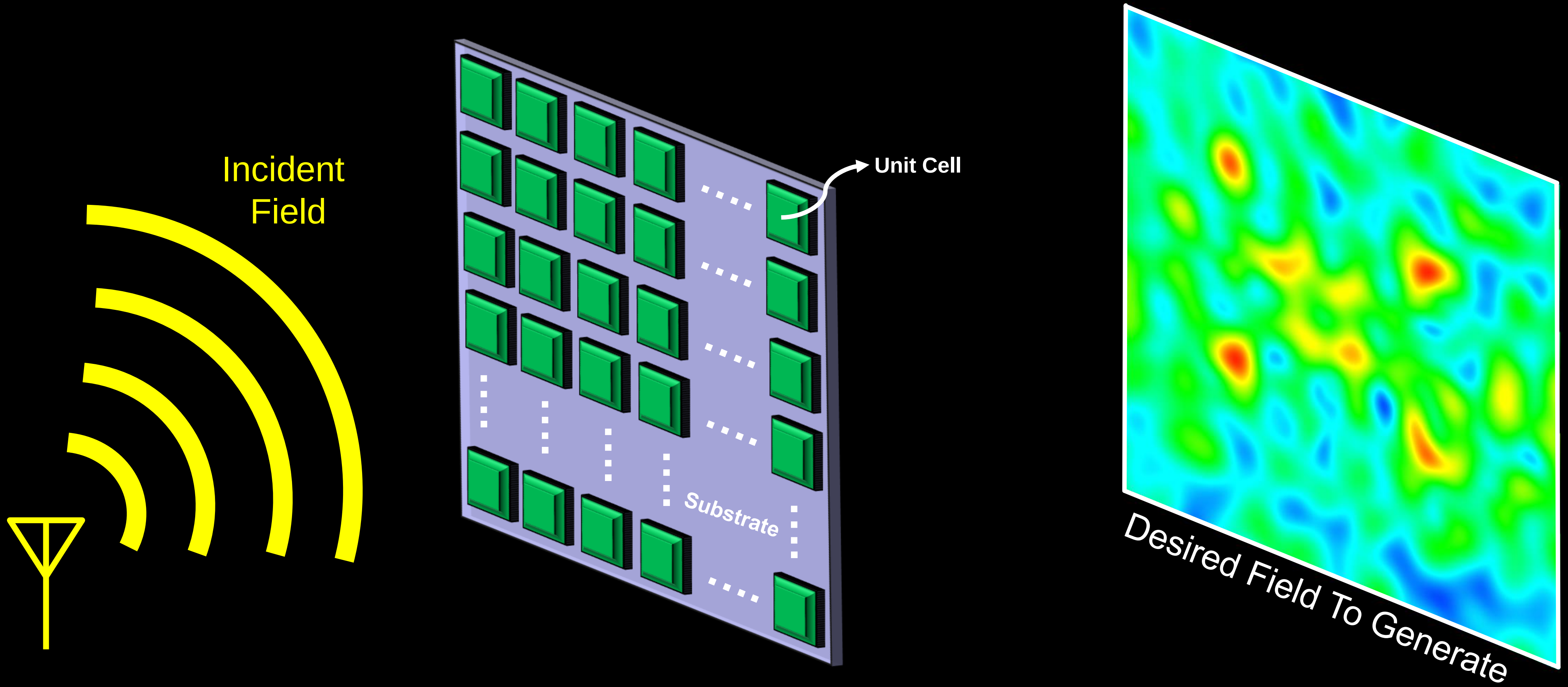
6G Systems



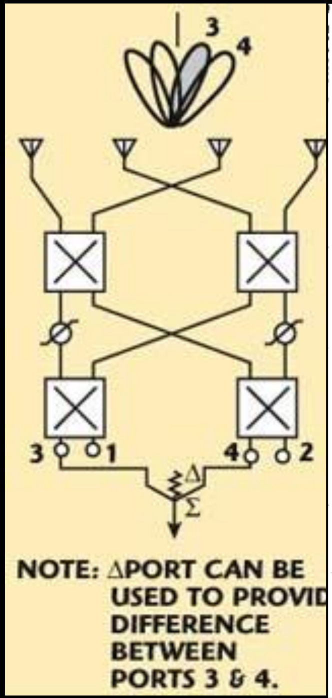
Courtesy of Peter Olexa, Pexels

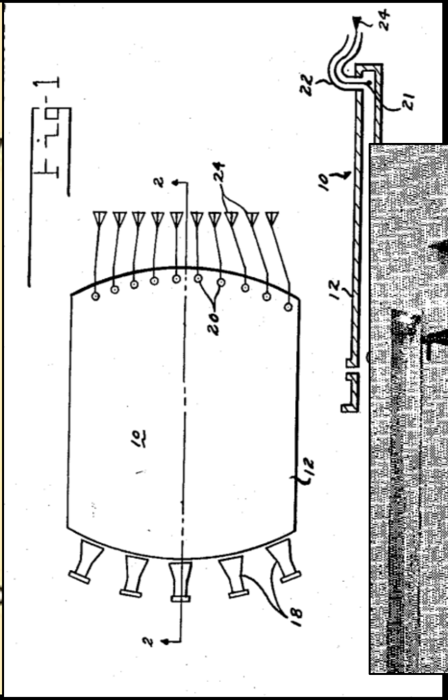
Intelligent Electromagnetic Surfaces

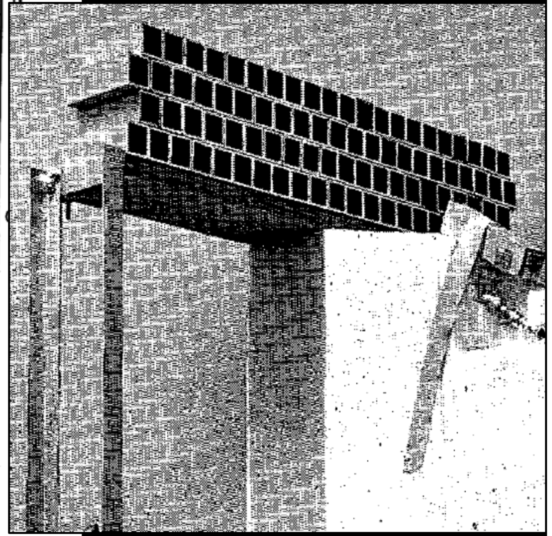
- Lattice of (semi-)passive radiating elements with sub-λ dimensions
- Smartly manipulate and program the incident electromagnetic field

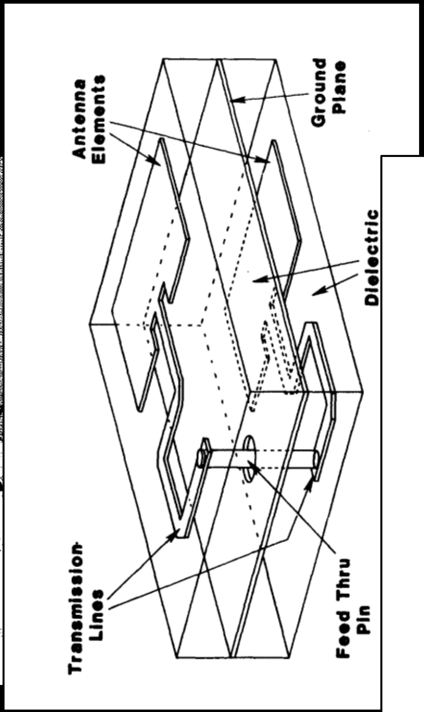


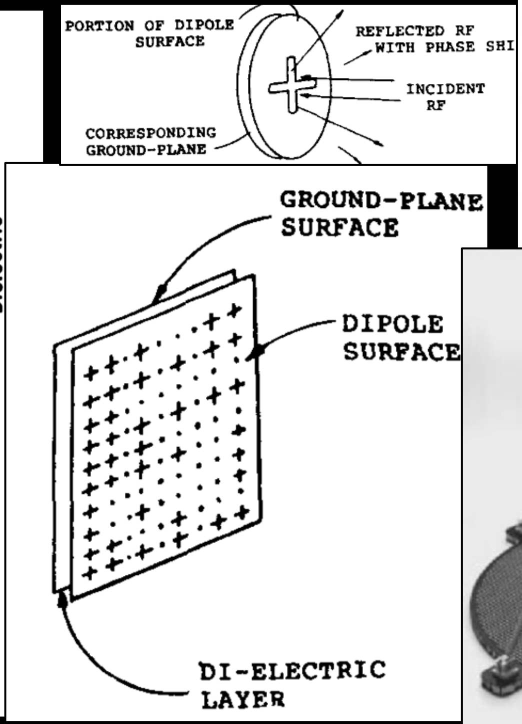
Origins of RF Field Programming











<u>April 1961</u>
Butler Matrix
J. Butler et al.,
Electronic Design

<u>November 1963</u>
Rotman Lens
W. Rotman et al.,
IEEE TAP

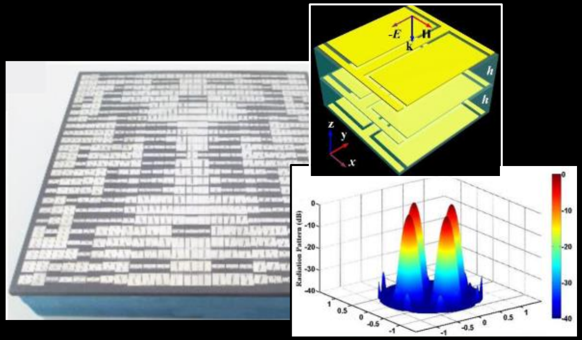
<u>November 1963</u>
Reflectarray
D. Berry et al.,
IEEE TAP

<u>September 1987</u>
Microstrip Lens
D. McGrath,
USAF

<u>March 1991</u>
FLAPS
A. Kelkar,
IEEE RadarConf

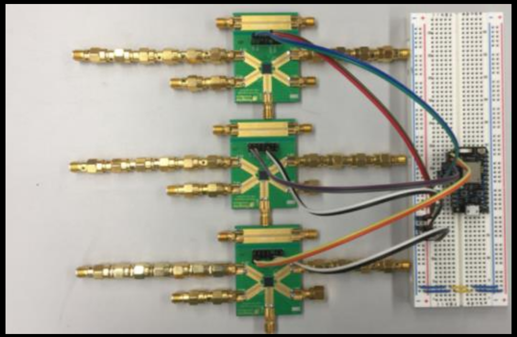
<u>May 1998</u>
Microstrip Reflectarray
J. Huang et al.,
IEEE TAP

RF Field Programming Today

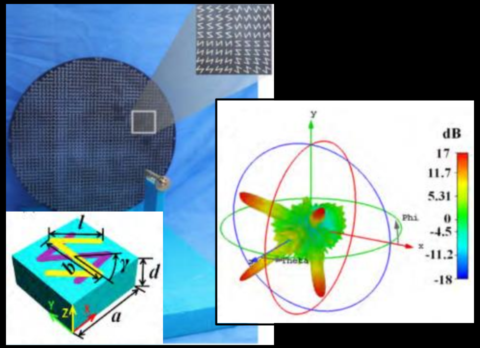


Xu et al.,
IEEE TAP, April 2017

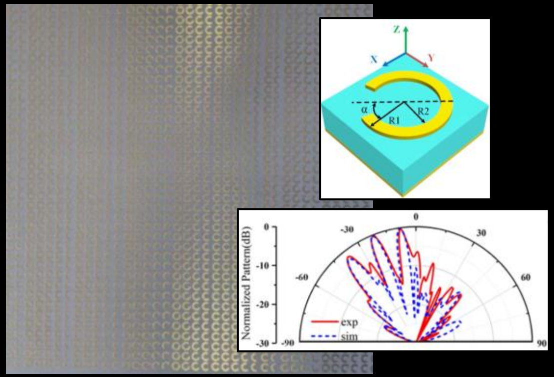
Xiong et al.,
ACM BuildSys, Nov 2017



PRESS, Welkie et al.,
ACM HotNets, November 2017

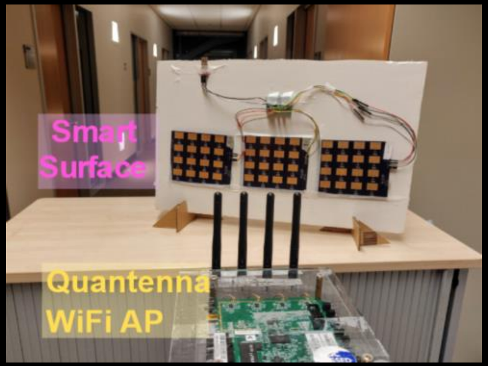


Wang et al.,
IEEE Access, April 2019

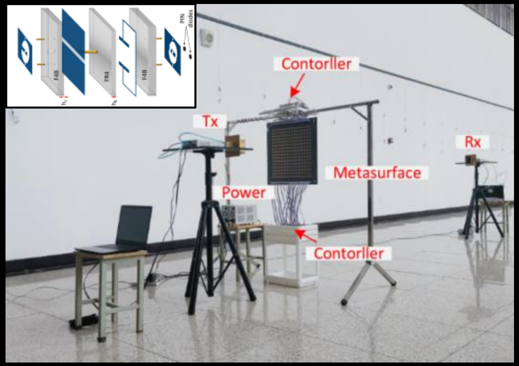


Bao et al.,
IEEE TAP, October 2019

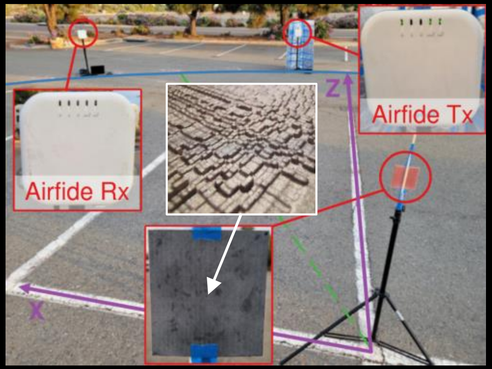
RFocus, Arun et al.,
USENIX NSDI, February 2020



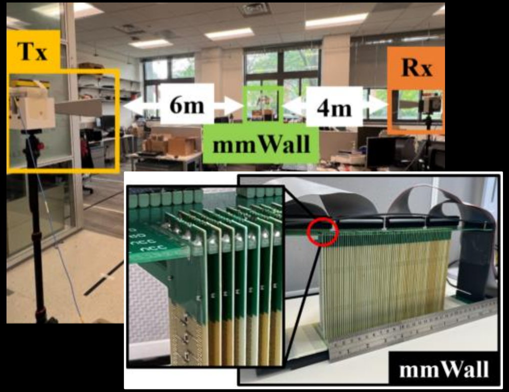
ScatterMIMO, Dunna et al.,
ACM MobiCom, September 2020



RFLens, Feng et al.,
ACM MobiCom, October 2021



MilliMirror, Qian et al.,
ACM MobiCom, October 2022

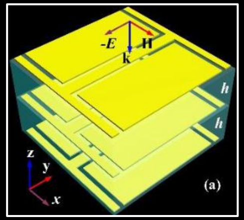


mmWall, Cho et al.,
USENIX NSDI, April 2023

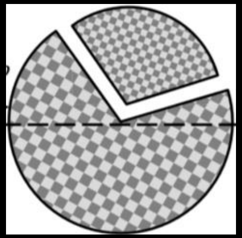
State of the Art

- Achieving high number of simultaneous focal points is challenging
  - State of the art mainly achieves 1-2 focal points
    - with maximum of 4 focal points
  - Use highly specialized element designs
    - Large number of elements
    - Mainly tested in anechoic chambers
- This paper: new paradigm for field programming and multi-point focusing

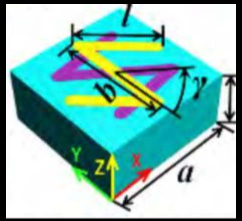
Four-Point Focusing



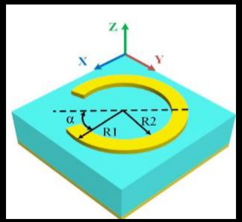
H.-X. Xu, et al.,
IEEE TAP, 2017.



I. Iliopoulos, et al.,
IEEE TAP, 2019.



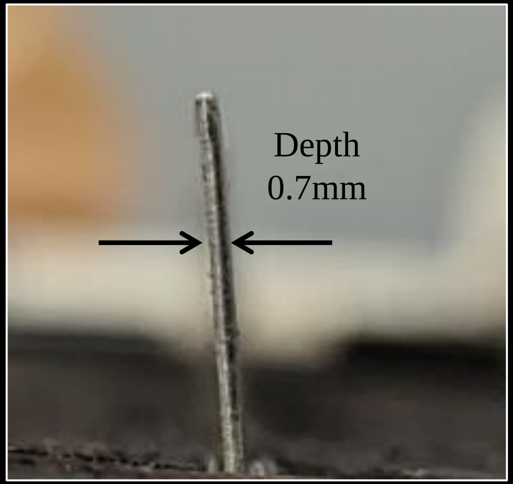
H. Wang, et al.,
IEEE Access, 2019.



L. Bao, et al.,
IEEE TAP, 2019.

RF Field Programming With Edges

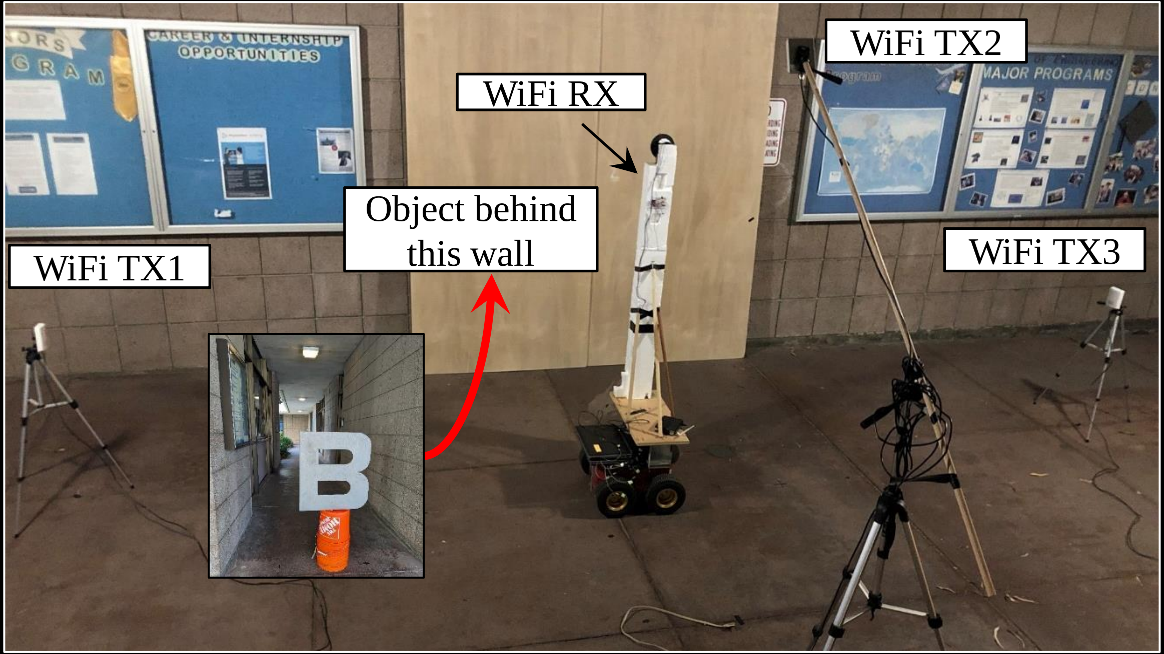
- A new perspective using edges
- What can cheap thin metal plates do here?
- Rich set of “knobs” for RF field programming
- Exploiting Geometrical Theory of Diffraction (GTD) and the corresponding Keller cones
- Several real-world experiments, using only WiFi



7¢ Steel Plate from Home Depot

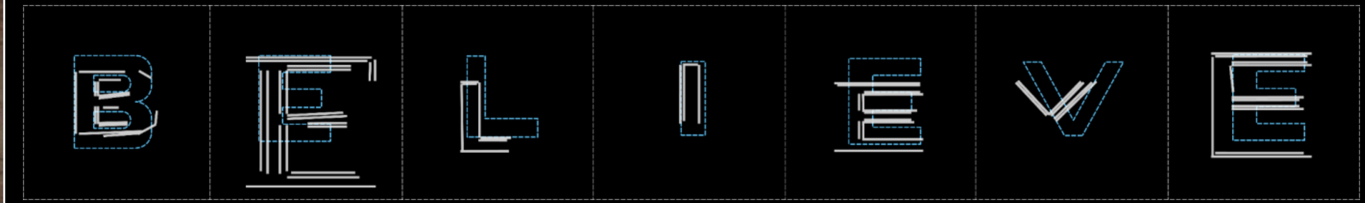
Recap: Edge Tracing with Wiffract

- Inspired by Wiffract (our MobiCom 2022 paper)
- Exploited edges for imaging still objects via edge tracing

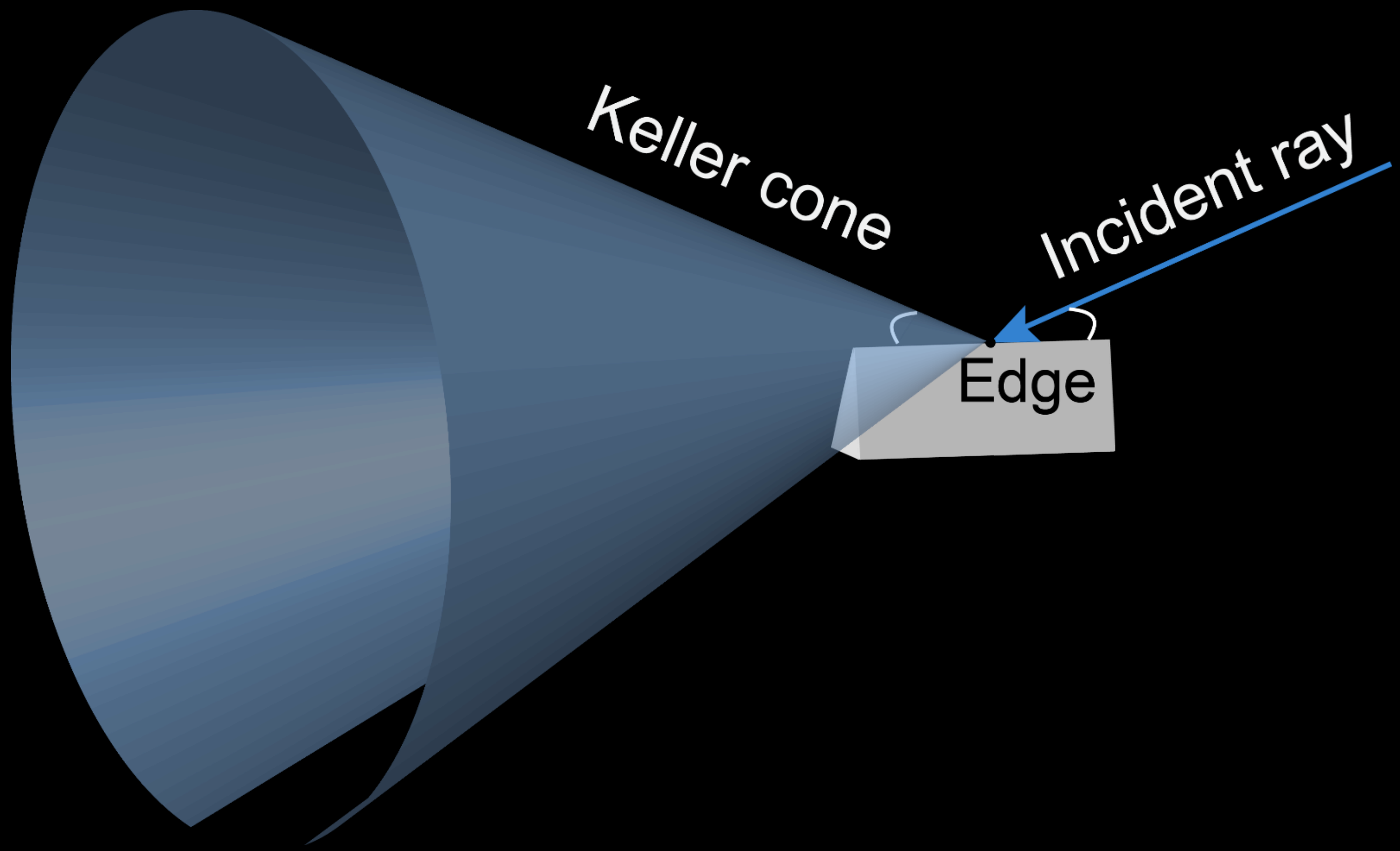


Letters behind the wall

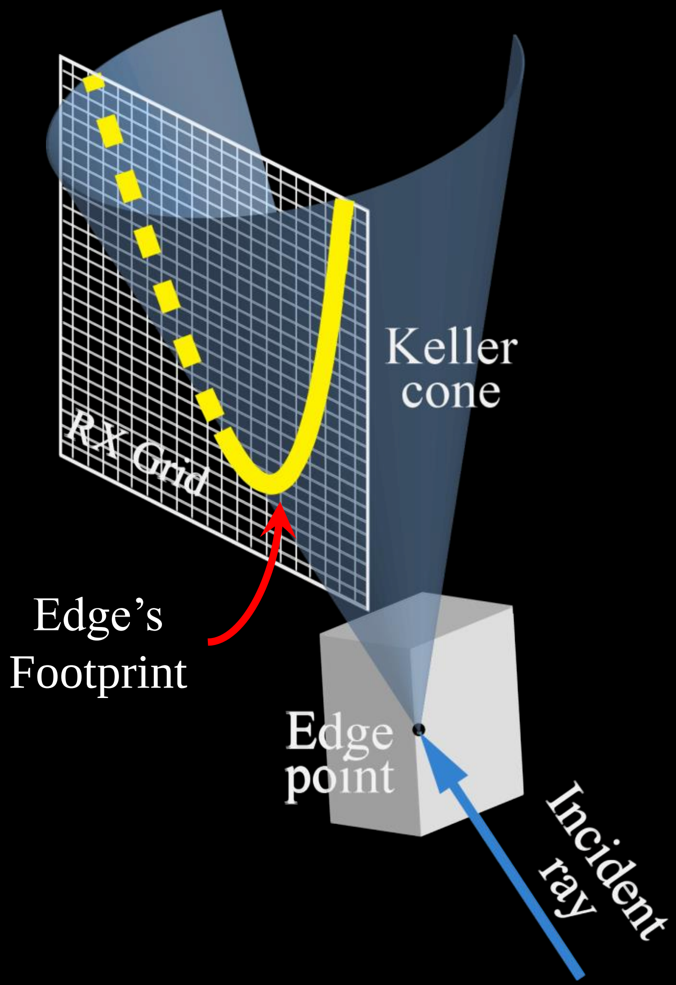
Our Imaging Results

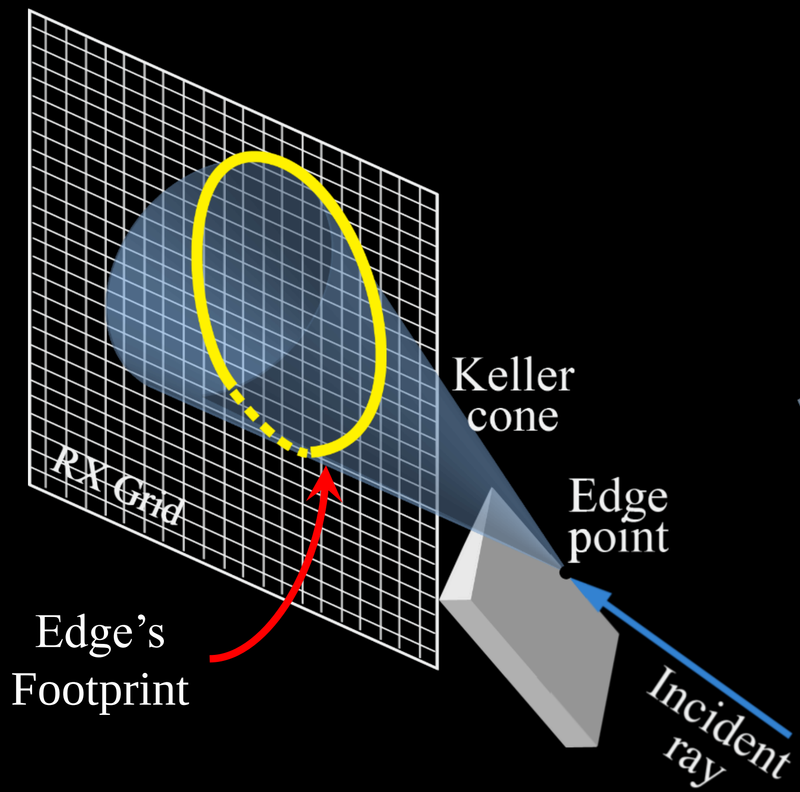


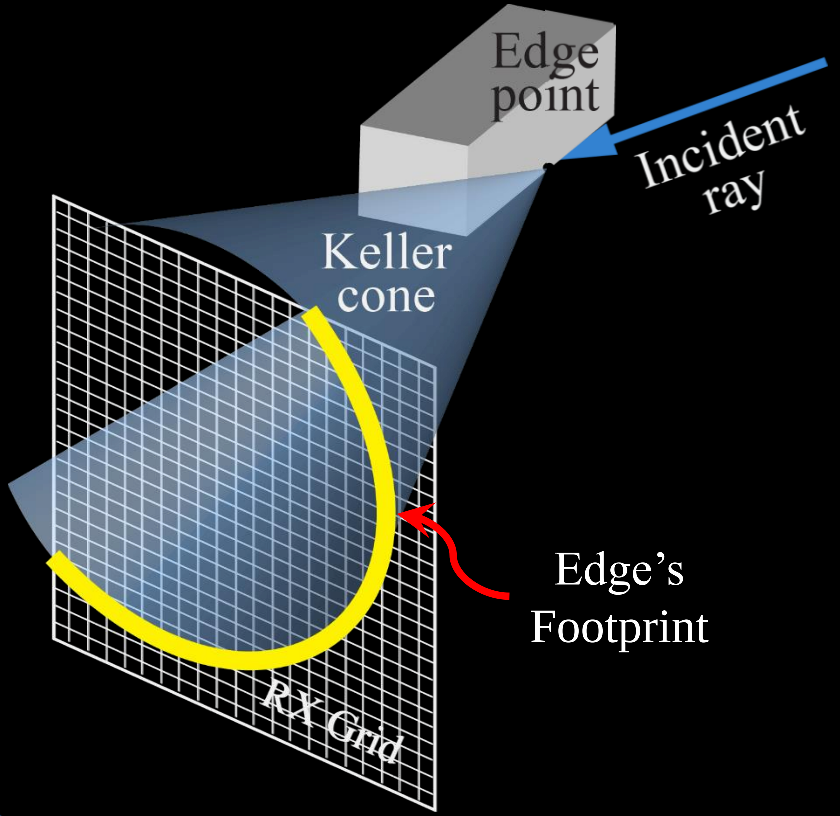
1. A. Pallaprolu, B. Korany, Y. Mostofi, "Wiffract: A New Foundation for RF Imaging via Edge Tracing", ACM MobiCom 2022
2. A. Pallaprolu, B. Korany, Y. Mostofi, "Analysis of Keller Cones for RF Imaging", IEEE RadarConf 2023



Keller's Geometrical Theory of Diffraction (GTD), 1962

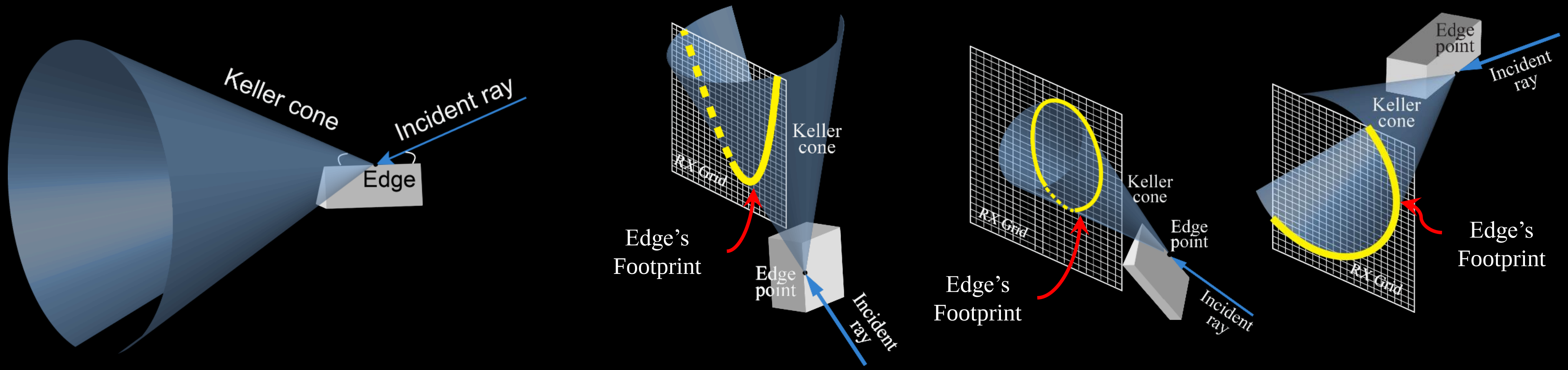






- Different edge orientations leave different signatures on RX grid
- Rich knobs for RF field programming

Geometrical Theory of Diffraction



RX Location

3D Edge Orientation

$$F_{\text{cone}}(\mathbf{x}, \mathbf{p}, \mathbf{e}) = I(\mathbf{x}, \mathbf{p}, \mathbf{e}) \times \frac{D e^{-j2\pi ||\mathbf{x}-\mathbf{p}||/\lambda}}{\sqrt{||\mathbf{x}-\mathbf{p}||}} \times F_{\text{inc}}(\mathbf{p}, \mathbf{x}_{\text{src}})$$

Edge Point Location

Edge Footprint Indicator

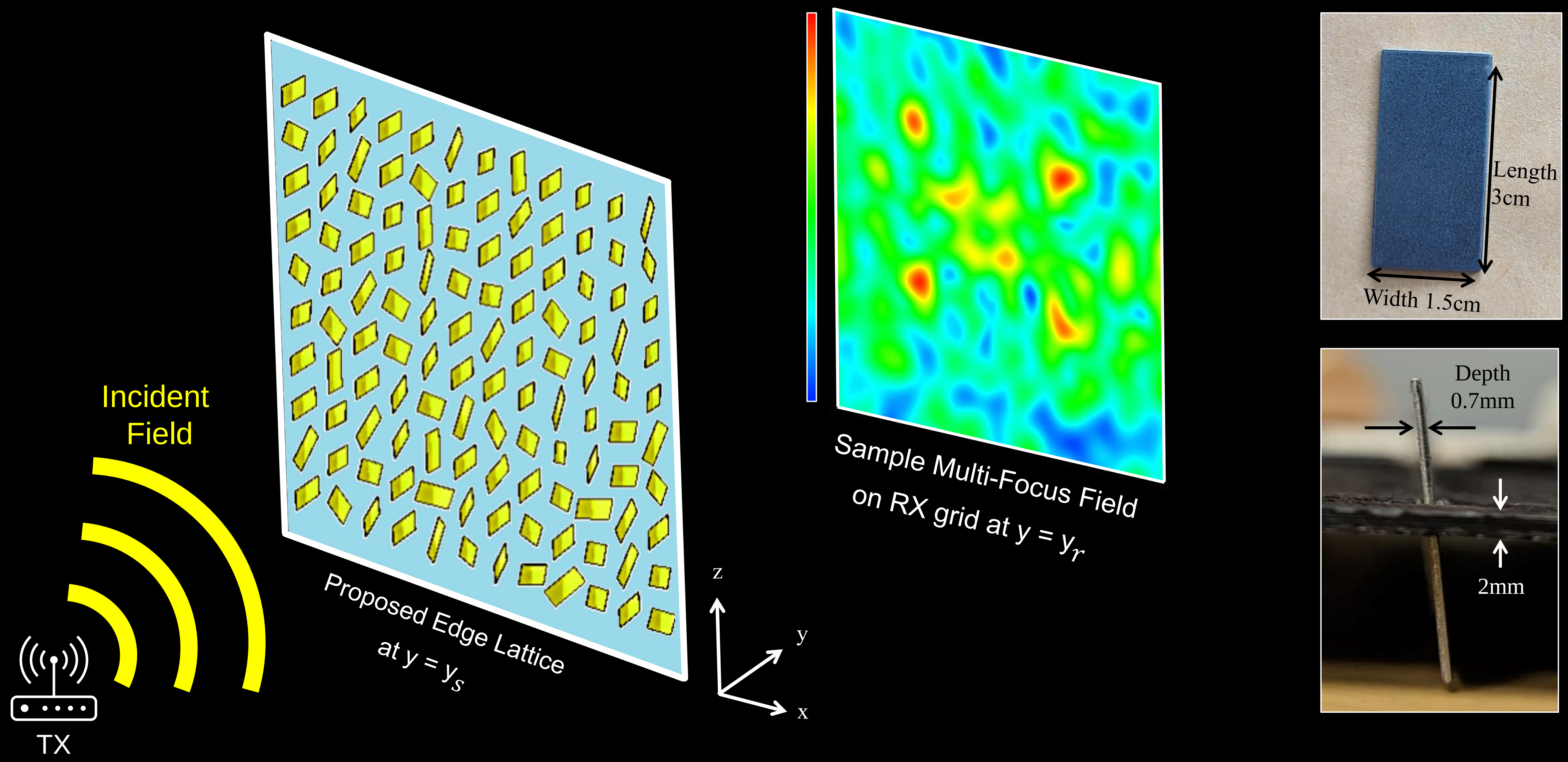
Scattered Field On Keller Cone

Incident Field On Edge Point

$$I(\mathbf{x}, \mathbf{p}, \mathbf{e}) = \begin{cases} 1 & \text{If } \arccos\left\{\frac{<(\mathbf{x}-\mathbf{p}),\mathbf{e}>}{||\mathbf{x}-\mathbf{p}||\,||\mathbf{e}||}\right\} = \psi_{\text{inc}} \\ 0 & \text{Otherwise} \end{cases}$$

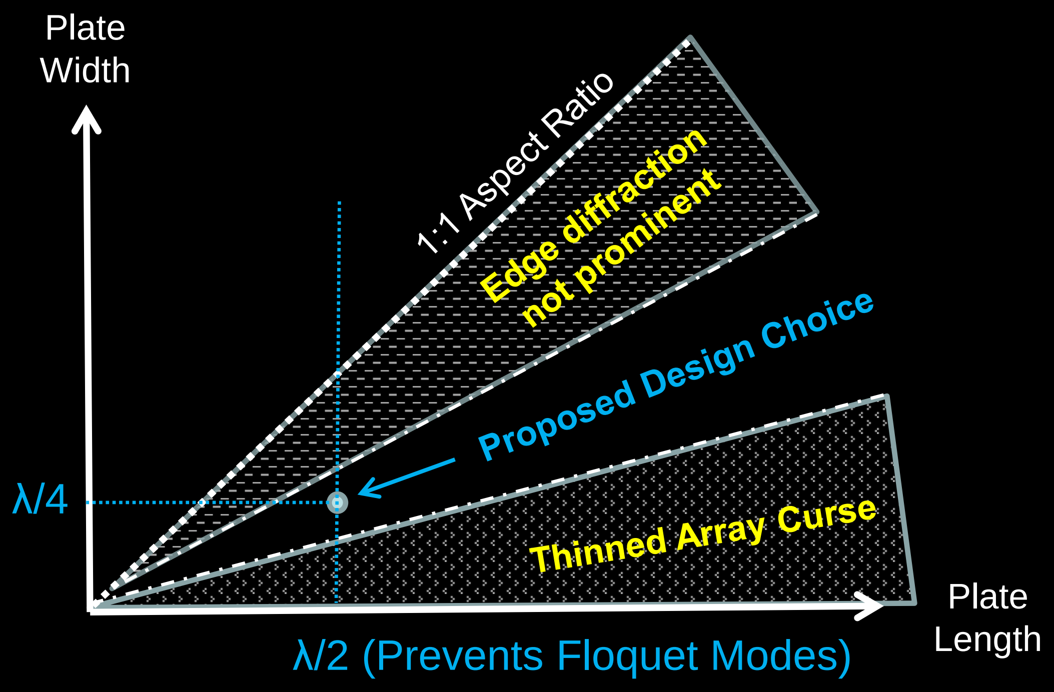
$$\psi_{\text{inc}} = \arccos\left\{\frac{<\mathbf{p}-\mathbf{x}_{\text{src}}, \mathbf{e}>}{||\mathbf{p}-\mathbf{x}_{\text{src}}||\,||\mathbf{e}||}\right\}$$

Electromagnetic Edge Lattice



Design of an Edge Element

- Element dimensions for efficient edge diffraction
- Square plate *i.e.*, 1:1
  - No dominant long edge [1]
- Very long (or wide) plates
  - Need large inter-element spacing for free rotation, increases sidelobe leakage [2]
- 2:1 strikes a good balance
  - Spacing of λ/2 to avoid grating lobes [3]



1. C. A. Balanis, “Advanced Engineering Electromagnetics”, 2nd ed., Wiley, 2012
2. R. L. Forward, “Roundtrip interstellar travel using laser-pushed light-sails”, in Journal of Spacecraft and Rockets, 1984
3. F. Liu, D.-H. Kwon, and S. A. Tretyakov, “Reflectarrays and metasurface reflectors as diffraction gratings”, on arXiv:2202.09029, 2022

How to orient the edge element directions to achieve a desired RF field?

Single Point Focusing

- **Goal:** Orient the edge elements to maximize field intensity at a given point
- How to orient an edge such that Keller cone passes through given point?
- Only activate paths that reinforce field
- Propose Algorithm 1 to orient all edges

Theorem

Element at $\mathbf{p}_{ij}$ and TX at origin, Keller cone passes through $\mathbf{f}$ if

$$\mathbf{e}_{ij} = \frac{\mathbf{f} - \mathbf{p}_{ij}}{|\mathbf{f} - \mathbf{p}_{ij}|} + \frac{\mathbf{p}_{ij}}{|\mathbf{p}_{ij}|}$$

Algorithm 1: Single Point Focusing with a Lattice of Edges

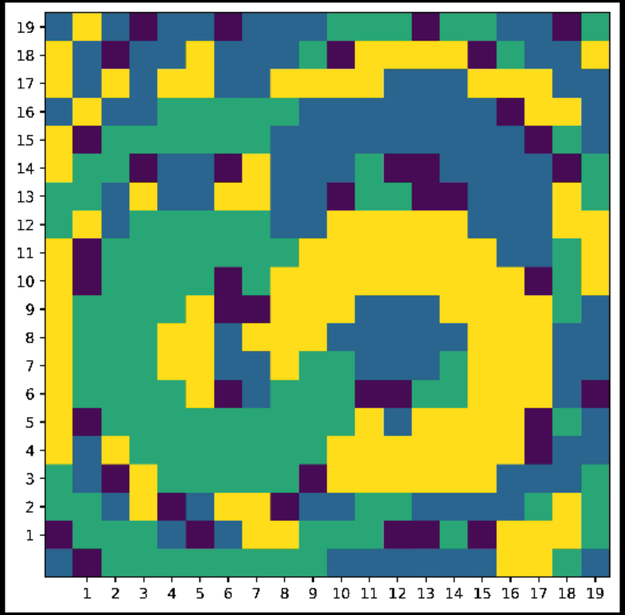
```
for edge element (i, j) ∈ M at location p_ij do
    Using above theorem, find orientation such that
    edge element's Keller cone impinges on target.
    if resulting edge diffraction path has positive projection
    on direct path from TX then
        Orient edge element's cone to impinge on target, i.e., set
        e_ij = (f − p_ij)/|f − p_ij| + p_ij/|p_ij| .
    else
        Put element in idle state, i.e., e_ij = [0, 0, 1].
    end if
end for
```

Multi-Point Focusing

- Map each edge to a single focal point
- What is the right mapping?

$$\min_{a_{ij}\in\mathcal{T}_{ij}} \left(\underbrace{\frac{1}{2}\sum_{i,j}\nu_{ij}}_{\text{Enforce Contiguity}} + \underbrace{\max_{k,l\in\{1,\ldots,K\}}(|\mu_k|-|\mu_l|)}_{\text{Fair Resource Allocation}}\right)$$

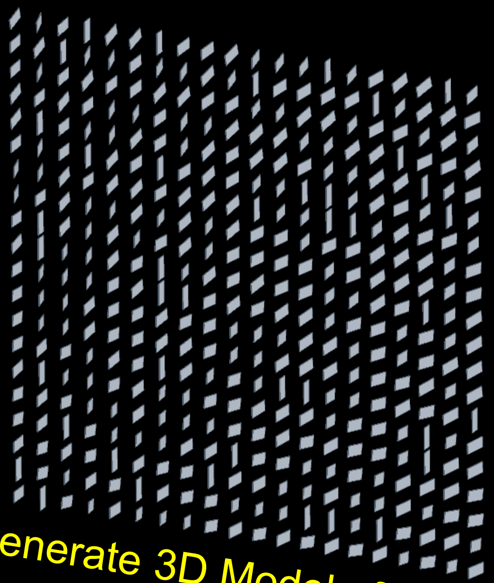
- Random Walk with Metropolis-Hastings Filter



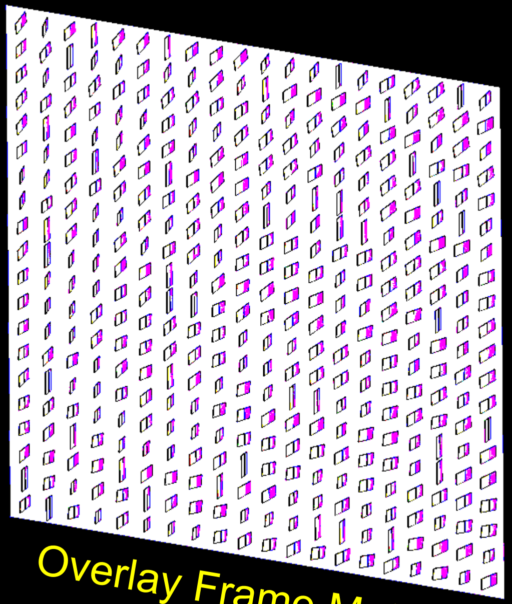
Algorithm 2: Metropolis Random Walk

Input: Maximum number of iterations, C_{iters}
Output: Partition assignment matrix $A = [a_{ij}]$
Initialize the assignment matrix A by sampling uniformly from $\mathcal{T}_{ij}\ \forall i, j$.
Initialize iteration count $c = 1$.
while $c \leq C_{\text{iters}}$ **do**
  Randomly choose an edge element (i, j).
  if $|\mathcal{T}_{ij}| > 0$ **then**
    For each possible assignment, evaluate the objective, keeping the assignments for all other elements fixed.
    Sample a_{ij} from the corresponding Boltzmann distribution with temperature $T = 10\log(c)$.
  end if
  Increment c.
end while

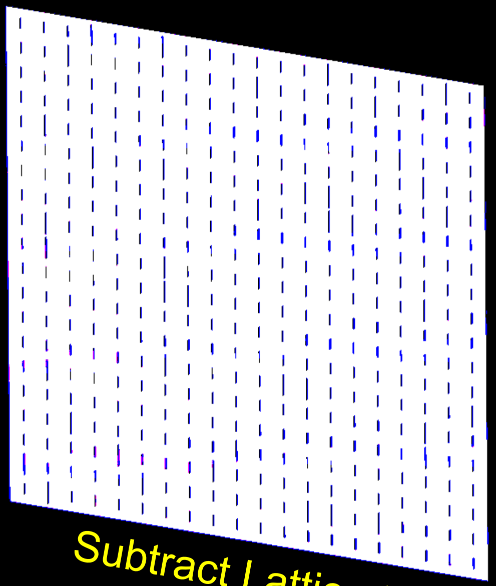
Edge Lattice Manufacturing Pipeline



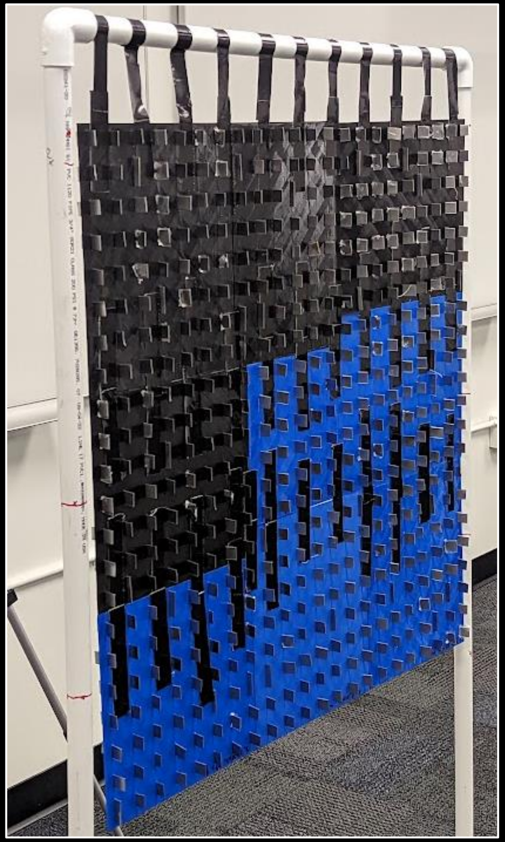
Generate 3D Model of Lattice



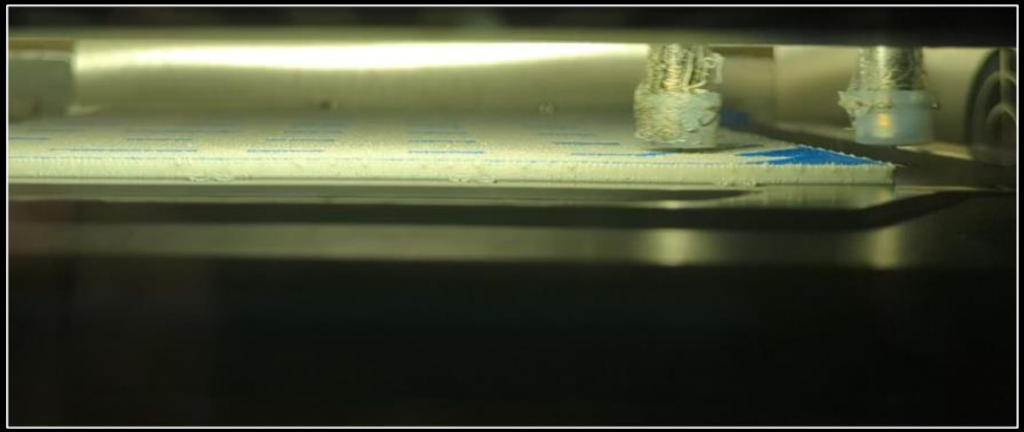
Overlay Frame Material



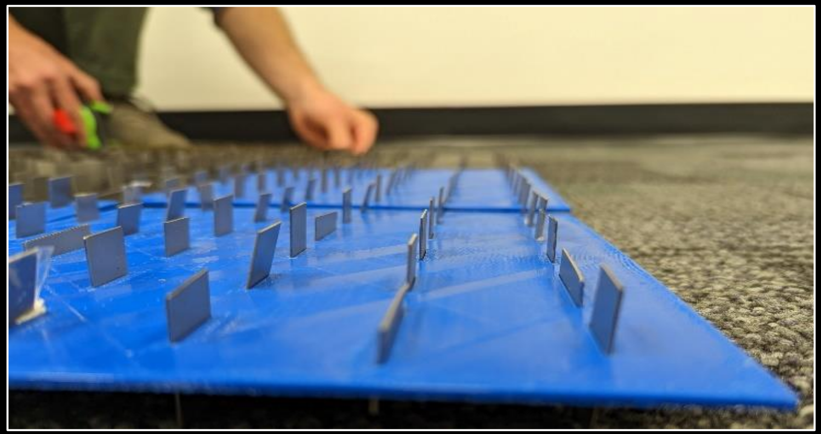
Subtract Lattice to create angled slots



Complete Edge Lattice



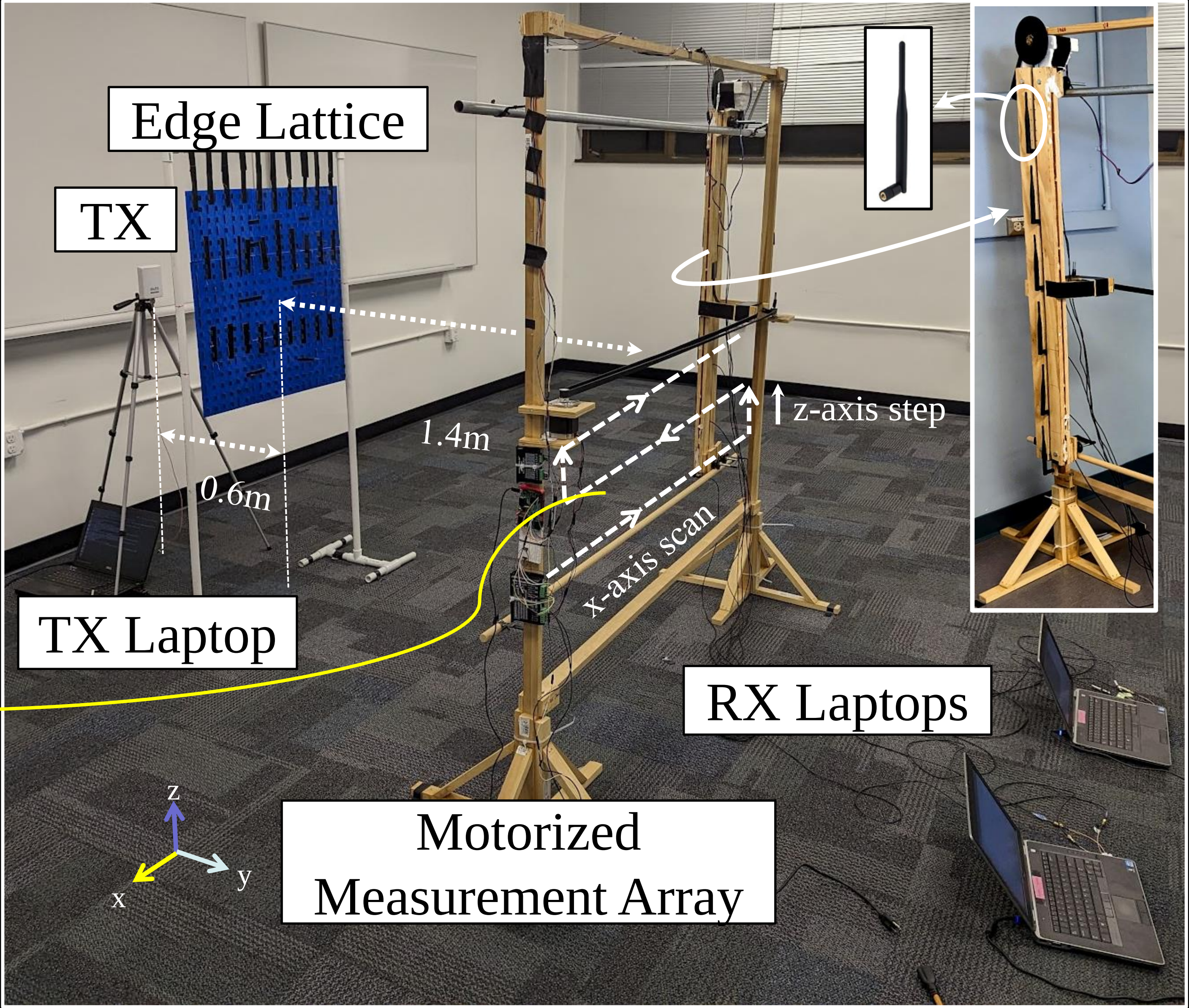
3D print the frame with slots



Insert edge elements into printed frame

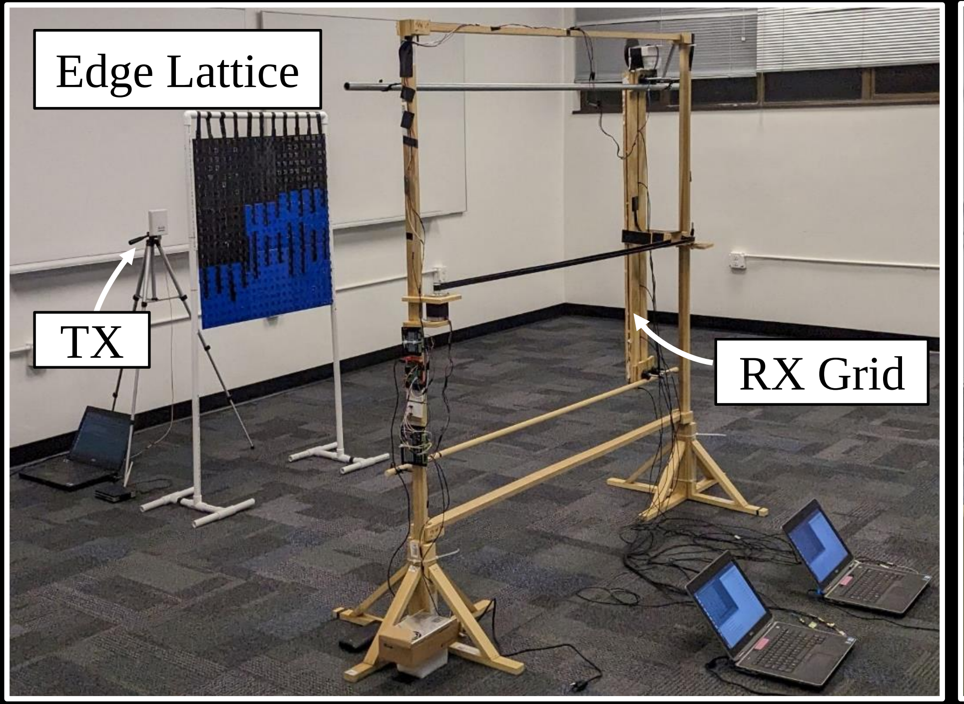
Measurement Setup

*Video sped up for demonstration purposes

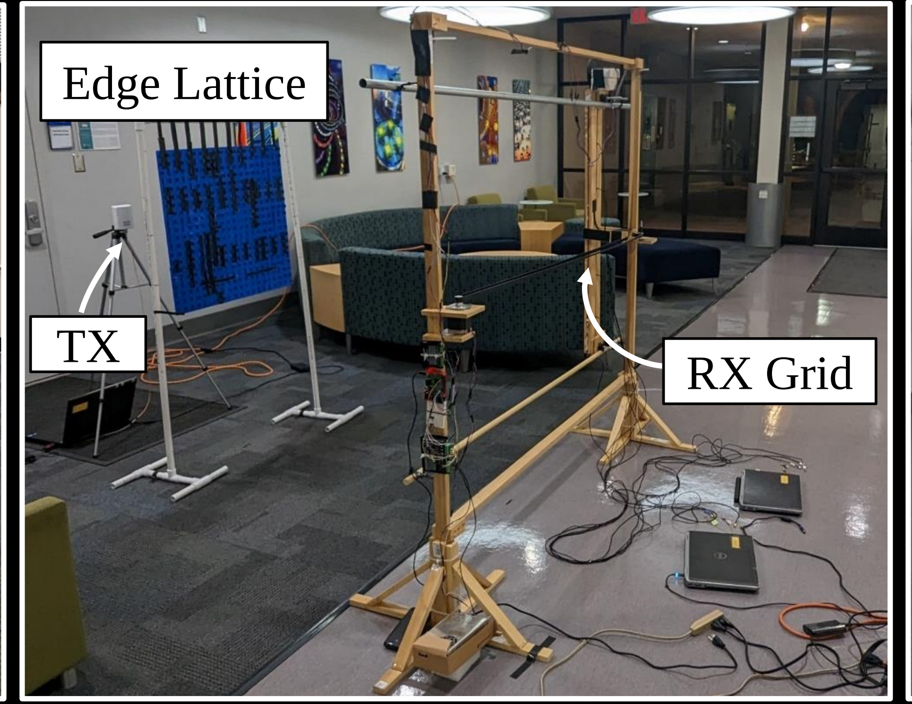


Experimental Areas

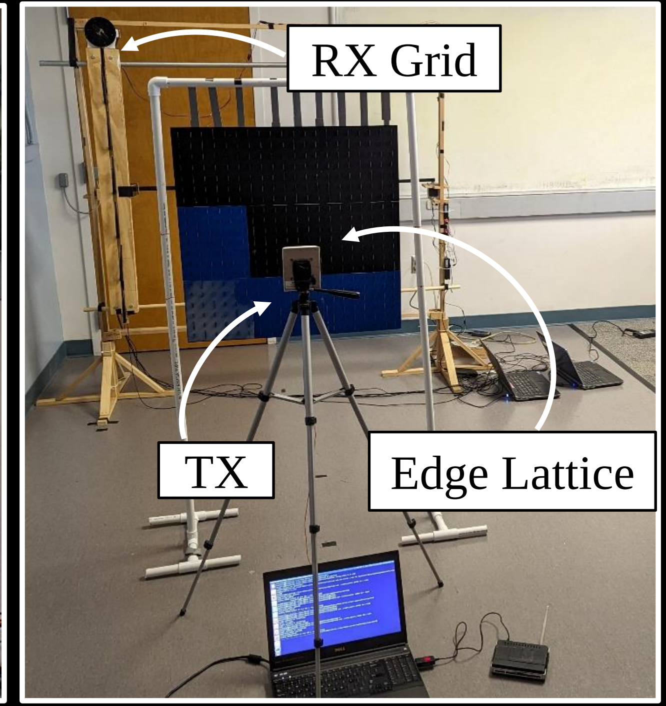
Conference Room



Building Lobby

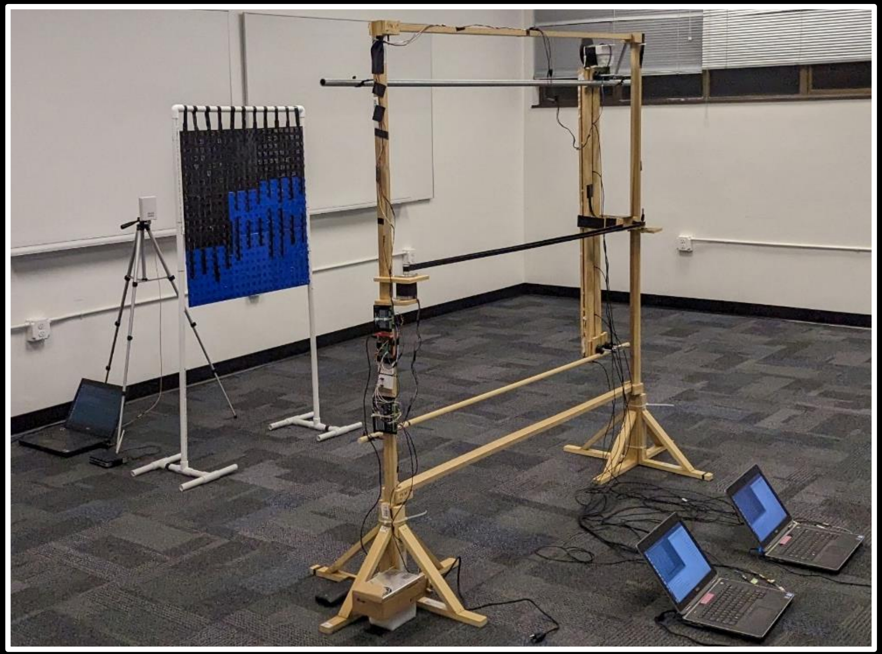


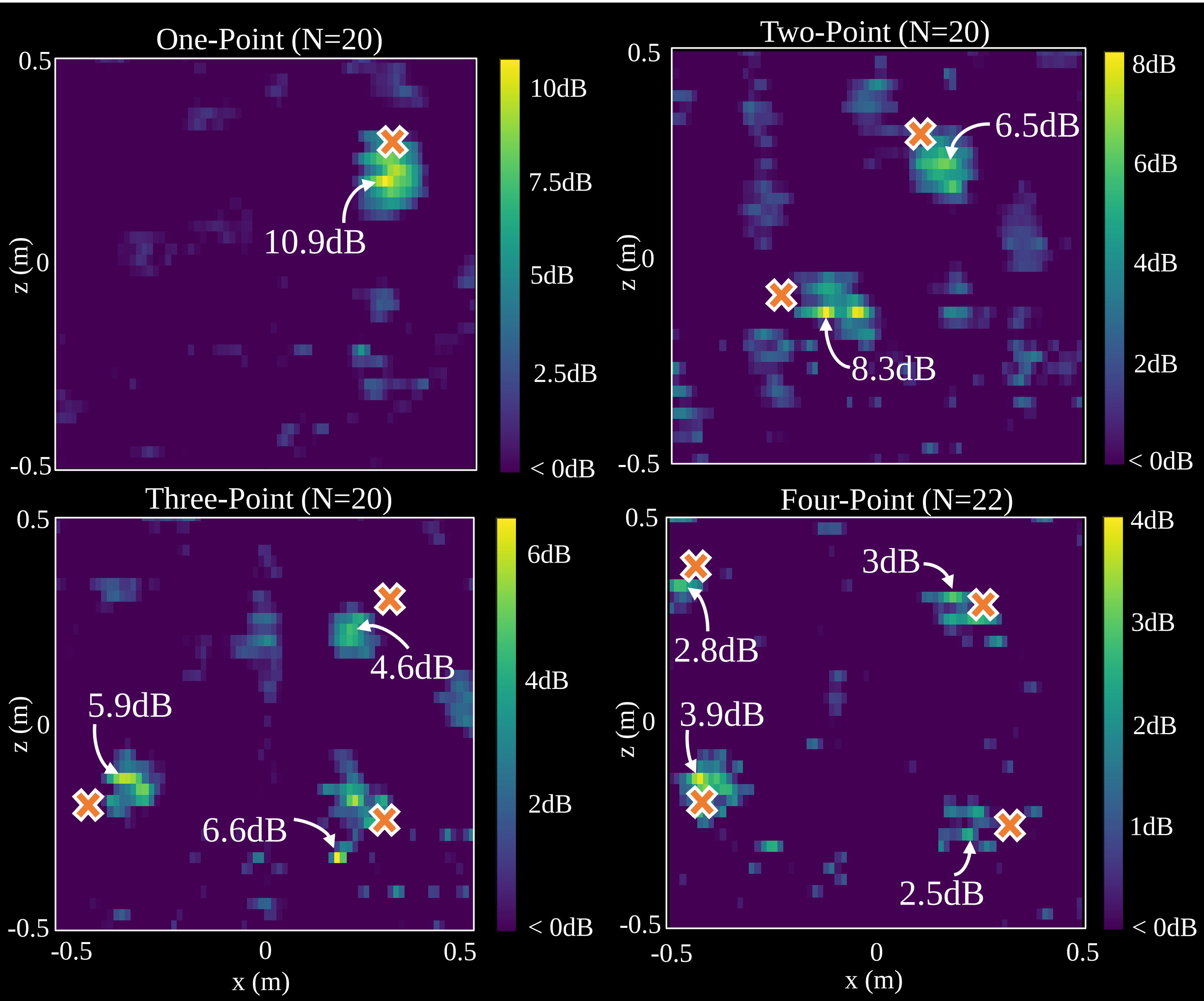
Laboratory



Sample Focusing Results

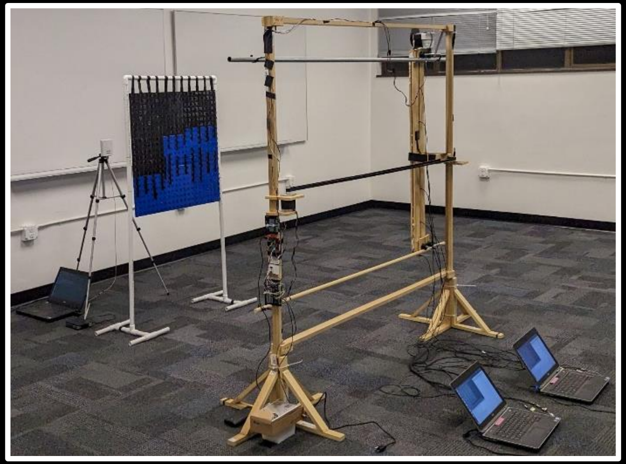
Conference Room



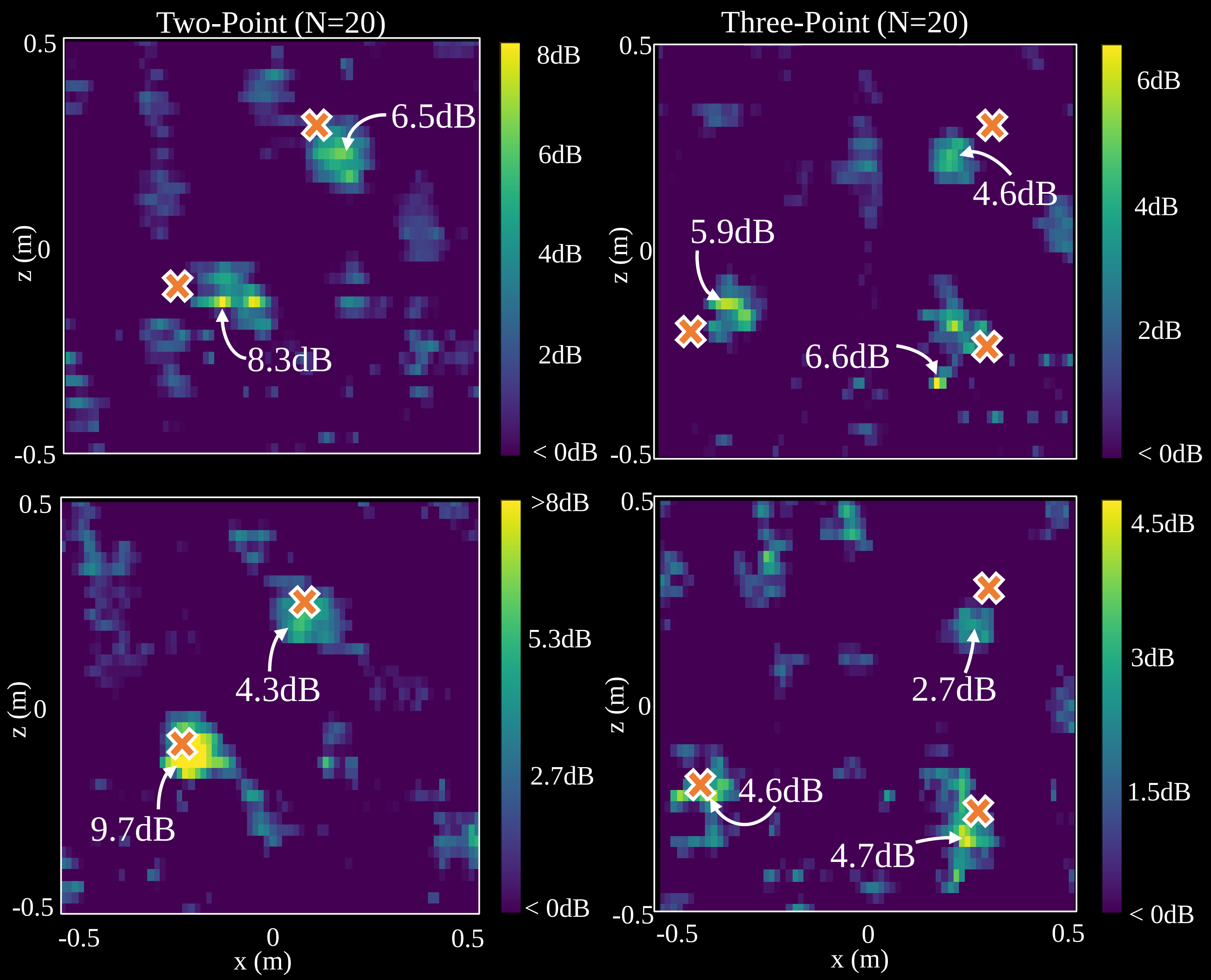


Robust Performance Across Environments

Conference Room

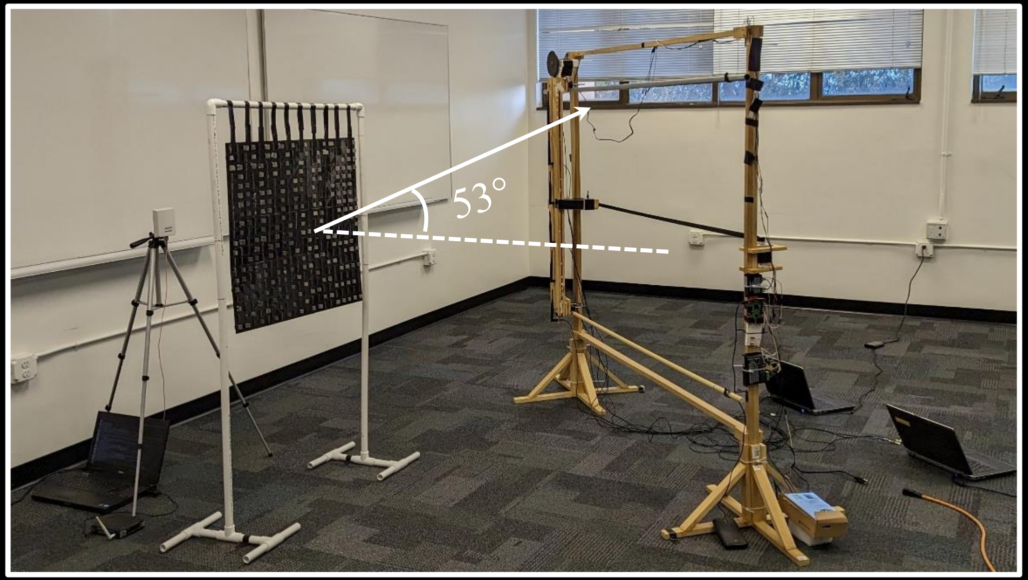


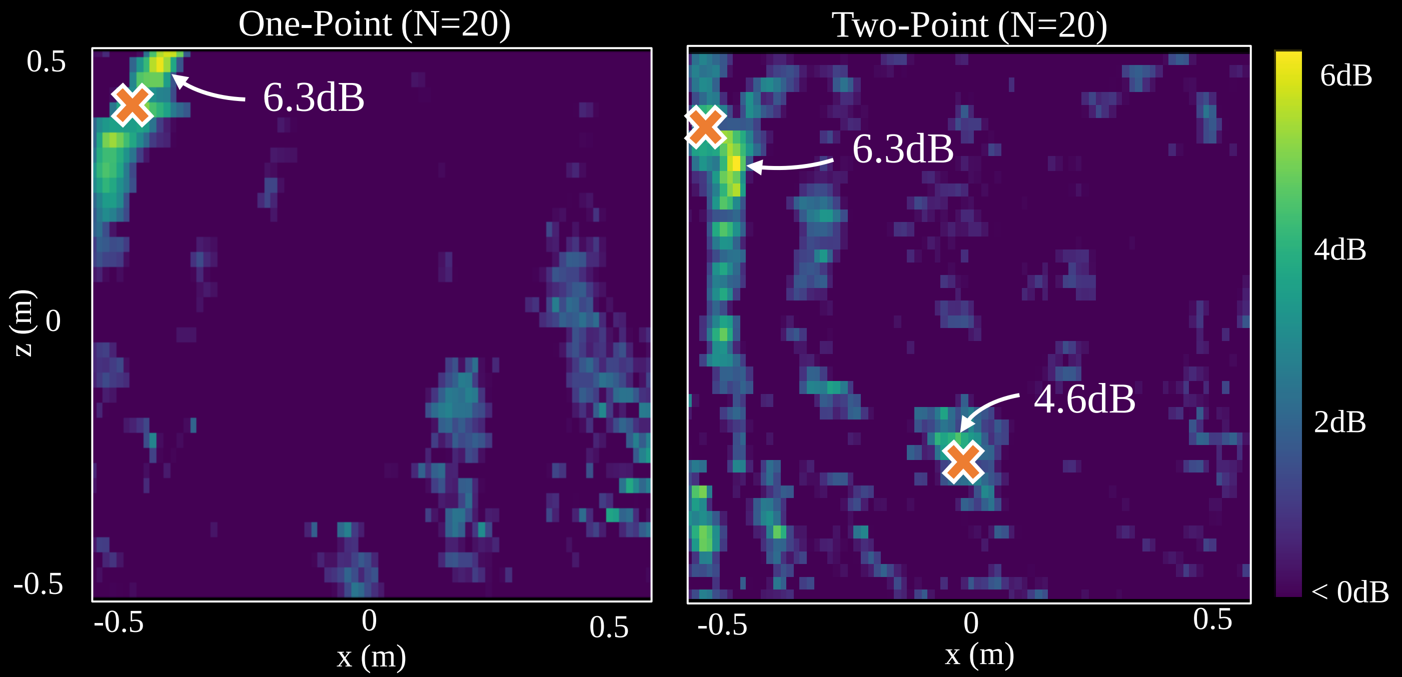
Building Lobby



Wide Angle Focusing

Conference Room

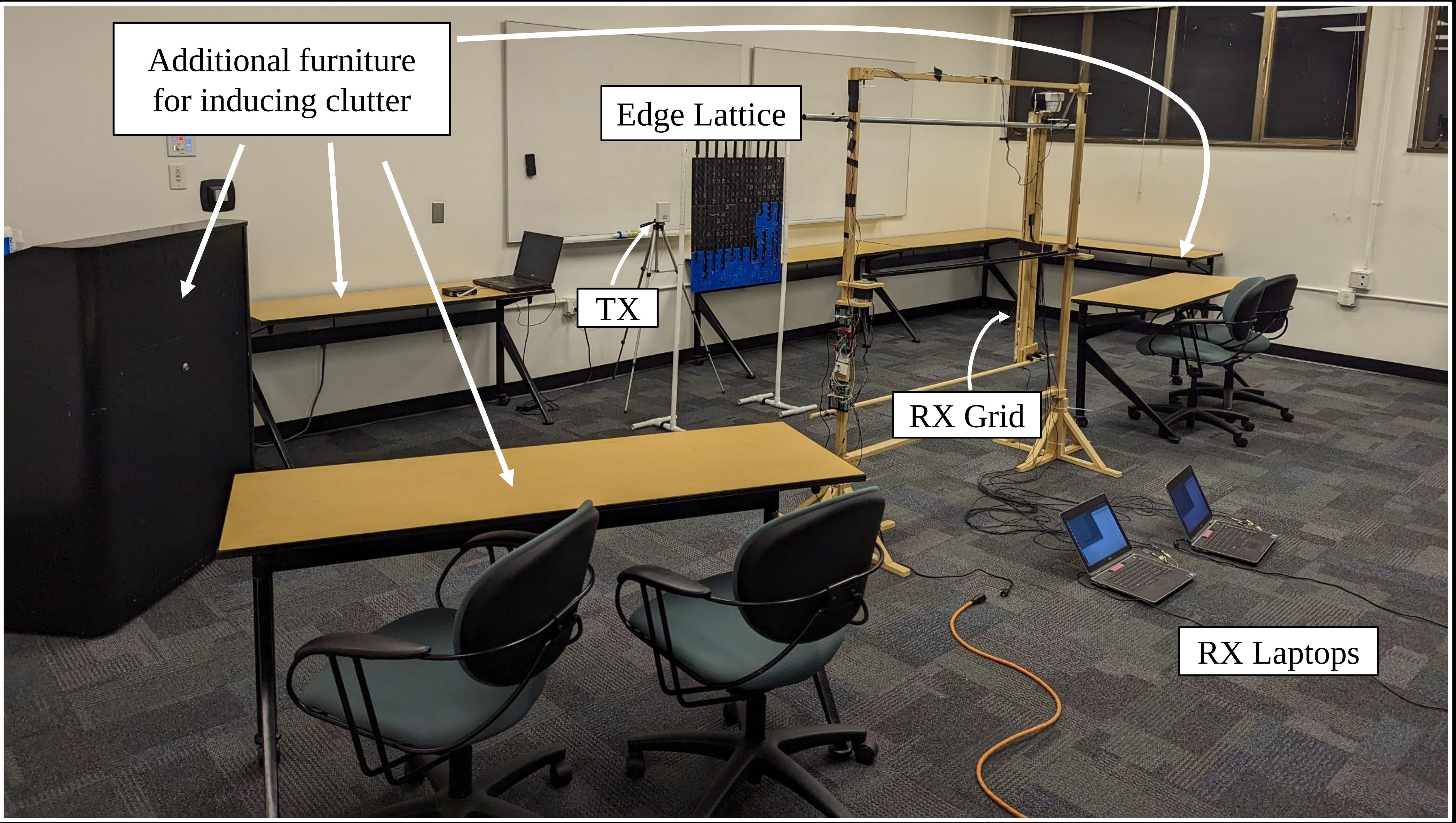




53° focusing

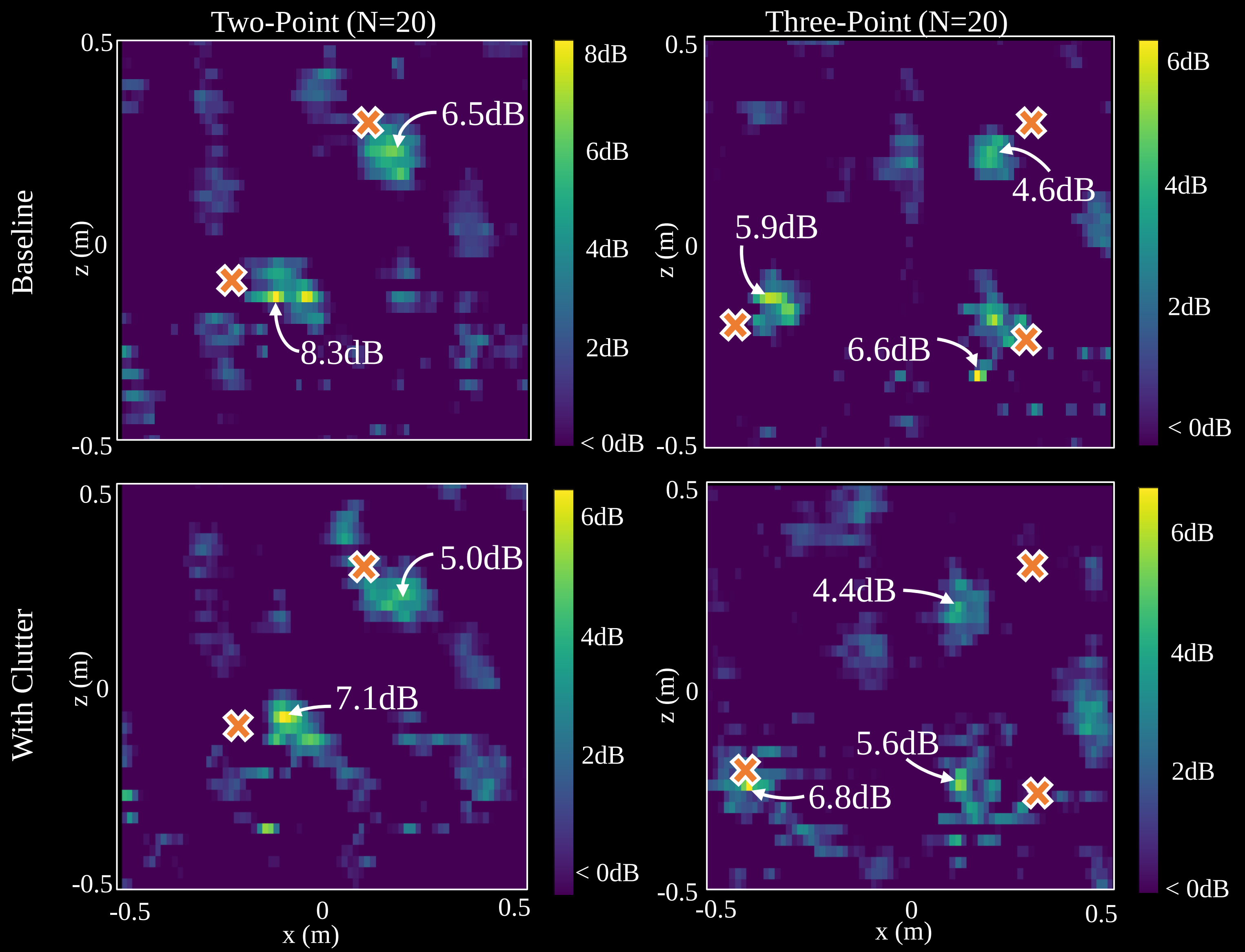
53°, 48° focusing

Impact of Clutter



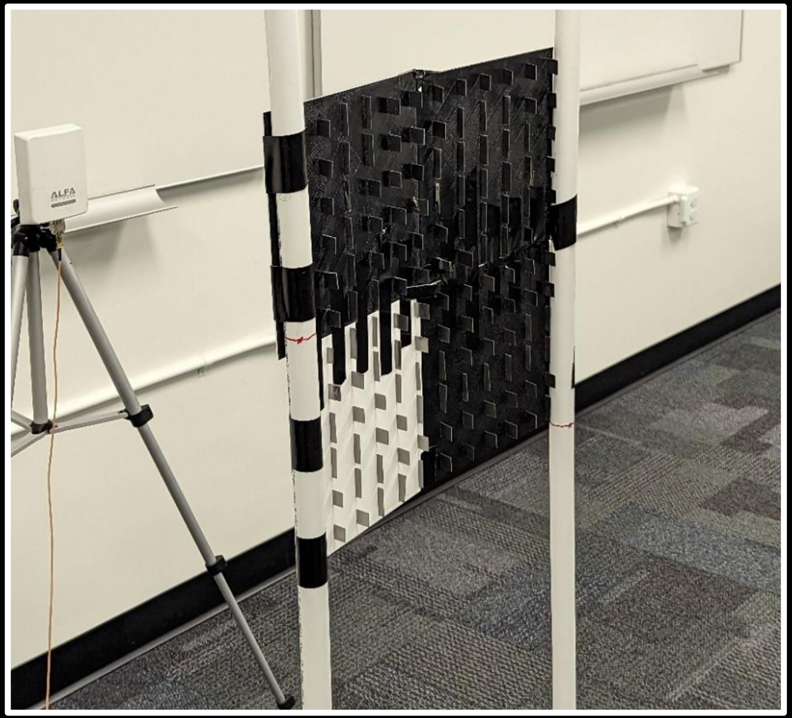
Impact of Clutter

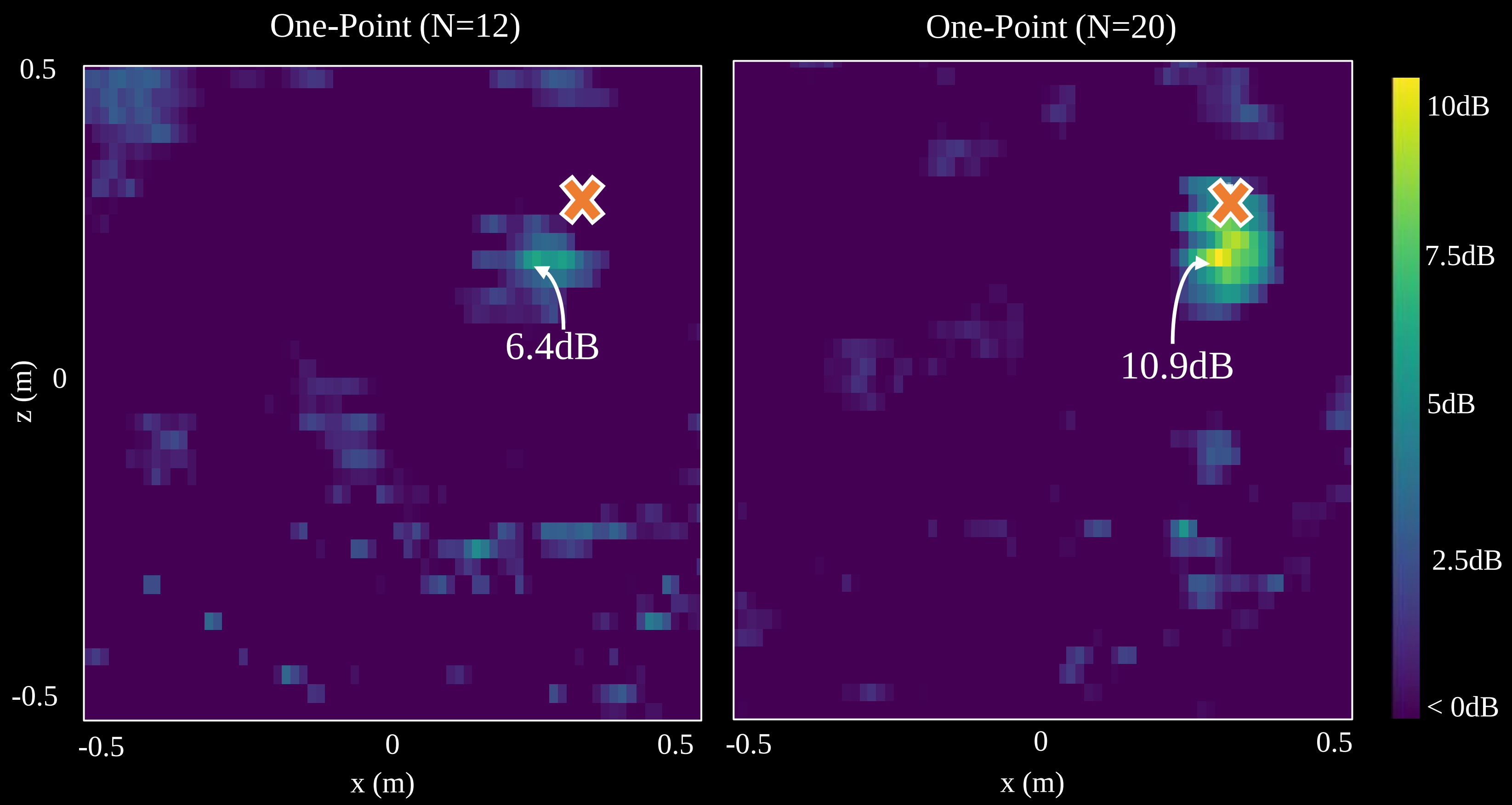
Conference Room



Impact of Lattice Size

Conference Room, N = 12





Comparison Table

Ref.	# Elements	# Beams	#Elements/Beam	Max Steer. Angle	Resolution	Freq.	# Expmts.
[31]	21,464	4	5,366	28°	0.12rad	20GHz	1
[62]	3,500	4	875	45°	0.13rad	13GHz	1
[3]	1,600	4	400	39°	0.07rad	16GHz	2
[68]	625	4	156.25	30°	0.13rad	9.6GHz	2
[60]	512	2	256	45°	0.07rad	5.8GHz	2
[69]	408	1	408	55°	0.12rad	4.8GHz	4
[64]	2,400	1	2,400	32°	0.09rad	672GHz	5
[40]	48,400	1	48,400	72°	0.09rad	1THz	4
Our Paper	**484**	**4**	**121**	**53°**	**0.06rad**	**5.18GHz**	**13**

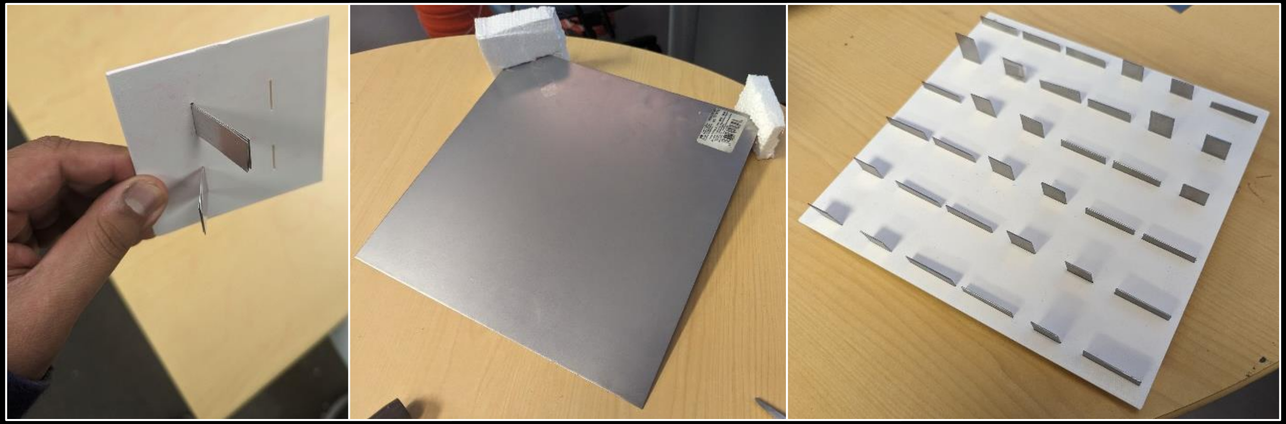
- Achieved 4 beams
- Least #elements per beam (121 elements/beam)
- Wide steering angle of 53°
- Achieved the best median resolution of 0.06 radians
- Highest experimental validation (13 experiments, all non-anechoic)

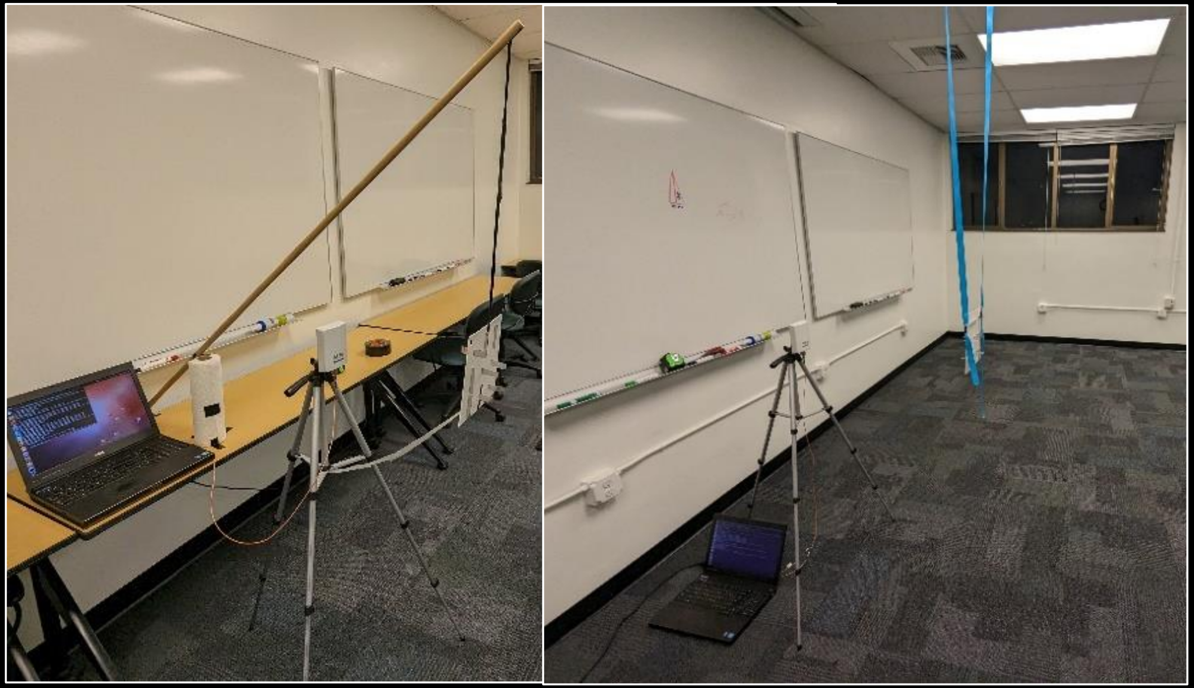
All of this with the **lowest cost per unit cell of 7 cents**

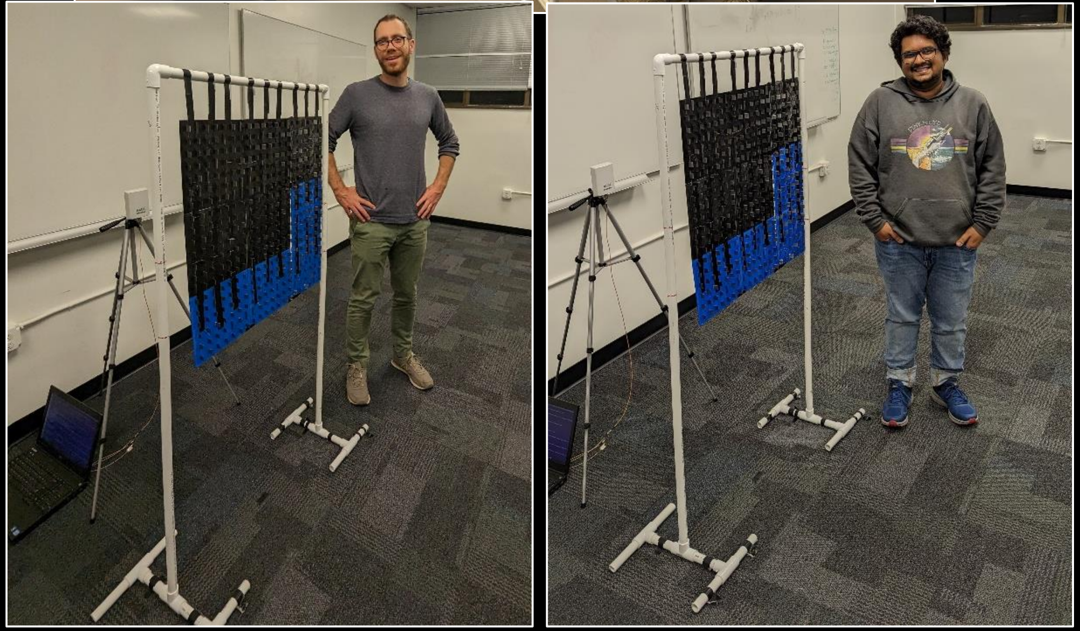
Conclusions

- New paradigm for intelligent surface design
- Lattice of edge elements
  - Rich knobs for programmability using GTD and Keller cones
- Efficient algorithm to configure edge orientations
- Extensive validation
  - 13 experiments
  - 3 different multipath-rich indoor areas
  - Simultaneous focusing up to & including 4 focal points
- First paper to demonstrate simultaneous focusing in non-anechoic settings without complex unit element designs
  - Off-the-shelf, 7 cent, thin metal plates

An Exciting Journey!







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