mmWall: A Steerable, Transflective Metamaterial Surface for NextG mmWave Networks

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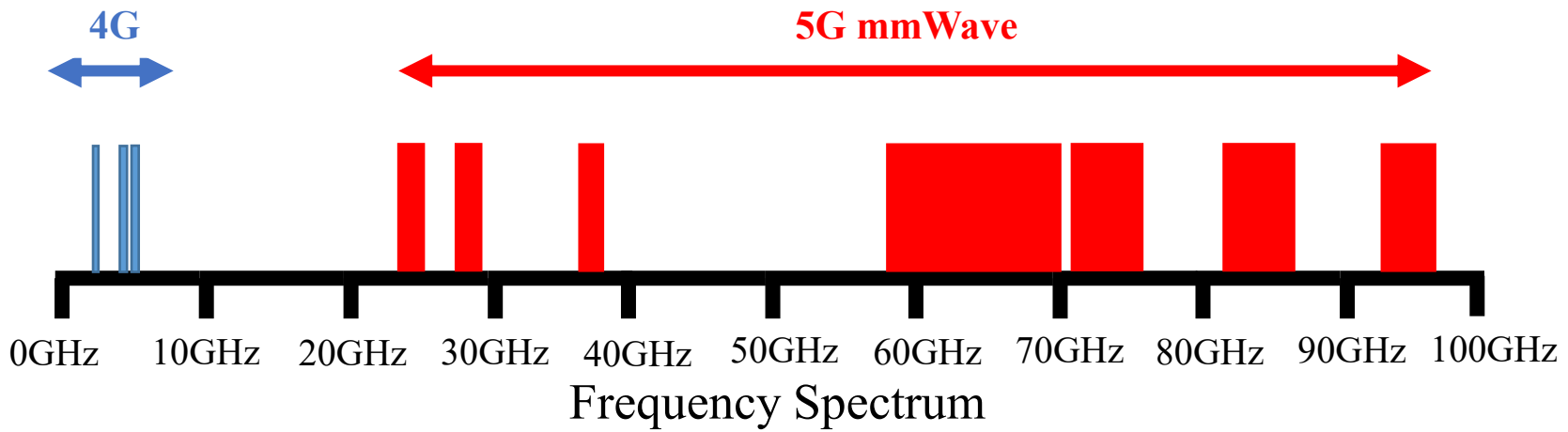
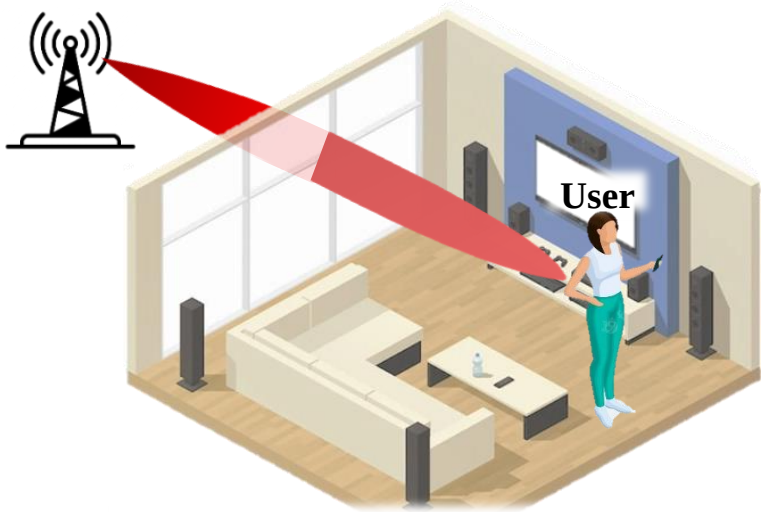
3 UMASS AMHERST

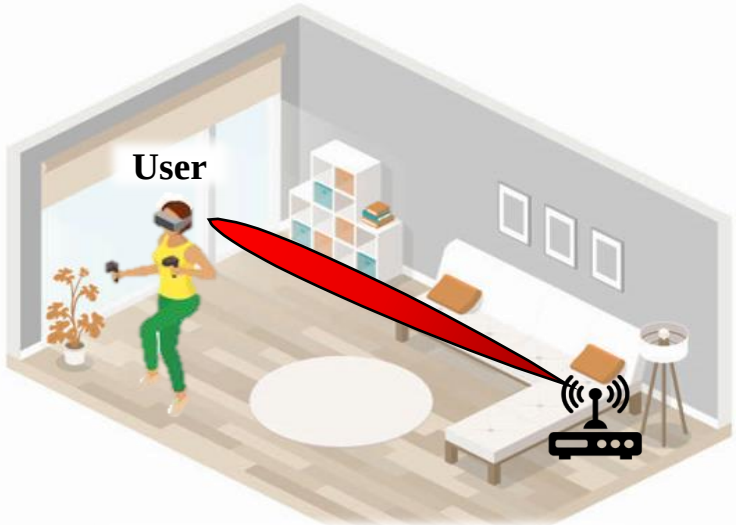
Myriad Use Cases for mmWave Networks

5G high band **mmWave** (FR2) **enables data rates of multi-Gbps**

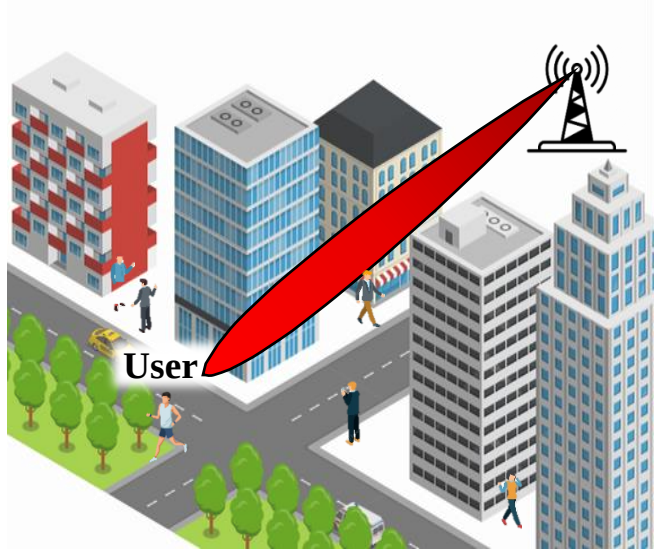




5G mmWave indoor coverage



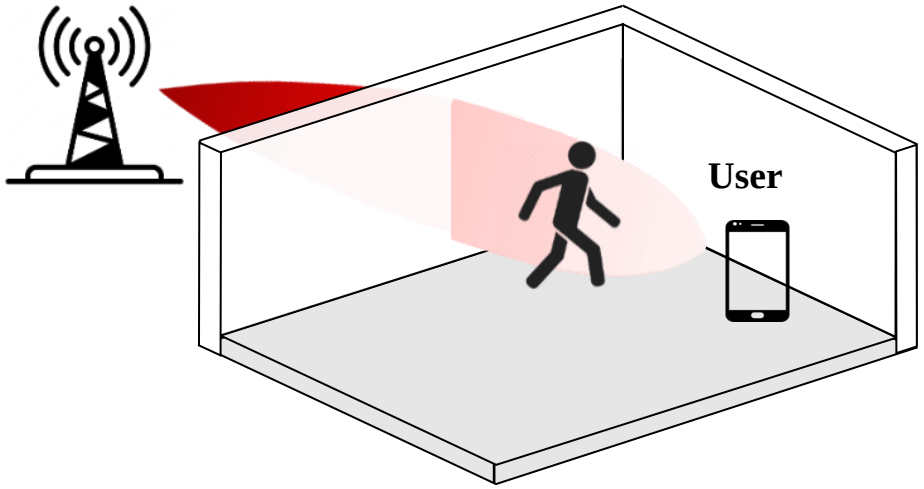
Indoor VR and AR



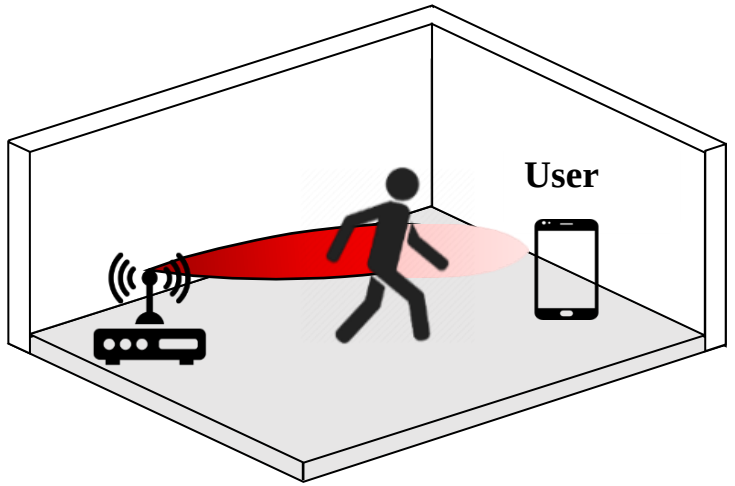
Outdoor crowded area capacity

Fundamental Challenges of mmWave

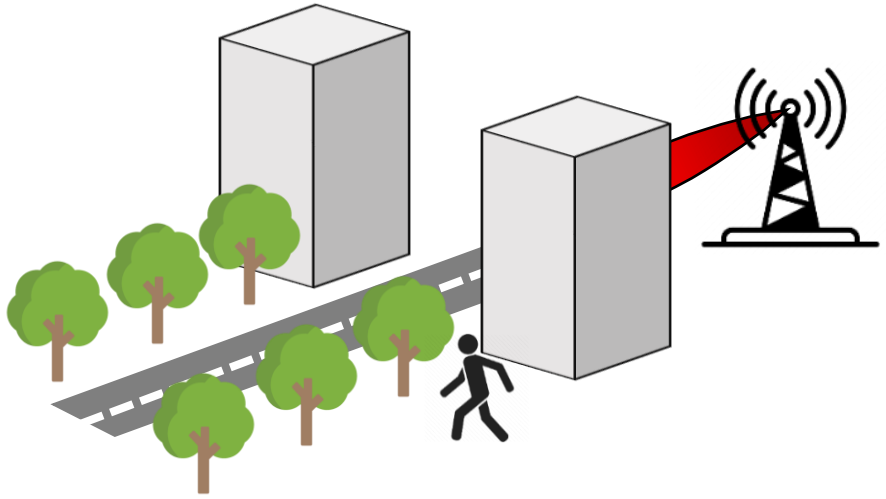
Wall Penetration



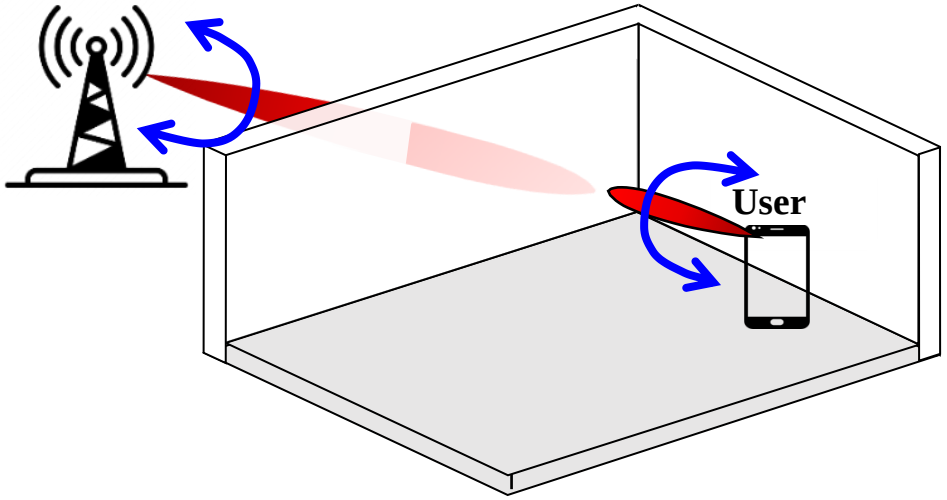
Body Blockage and Obstacles



Obstacles in Urban Canyon

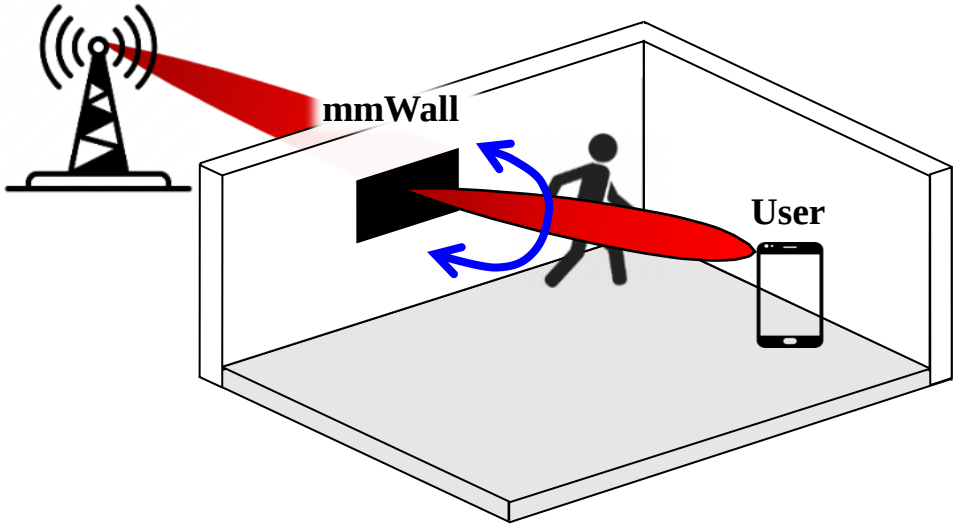


Complex Beam Alignment

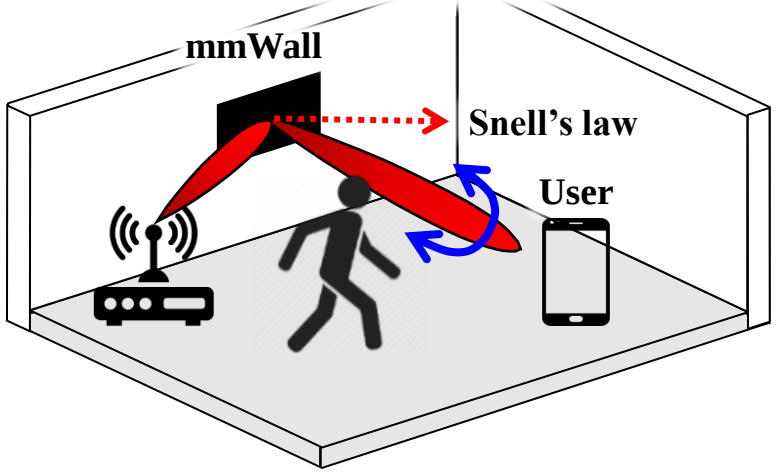


Our Solution: mmWall

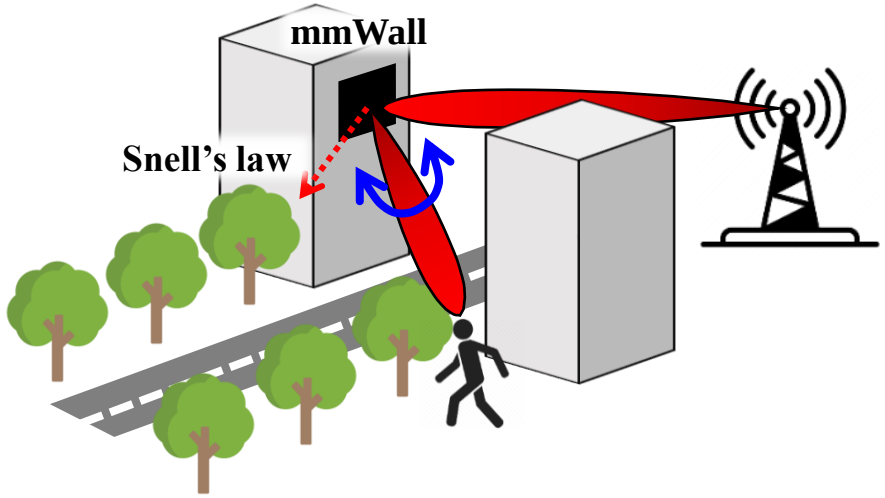
Bringing outdoor NextG service indoors



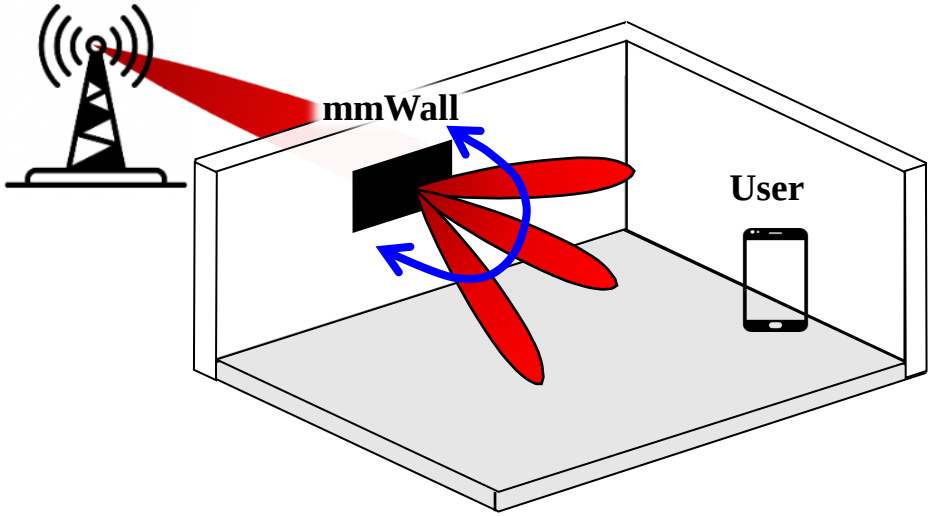
Non-specular reflection for routing around obstacles



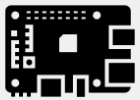
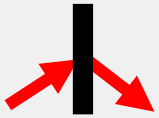
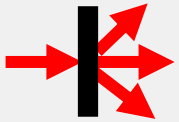
Overcoming outdoor obstacles in an urban environment



Beam splitting for fast beam search

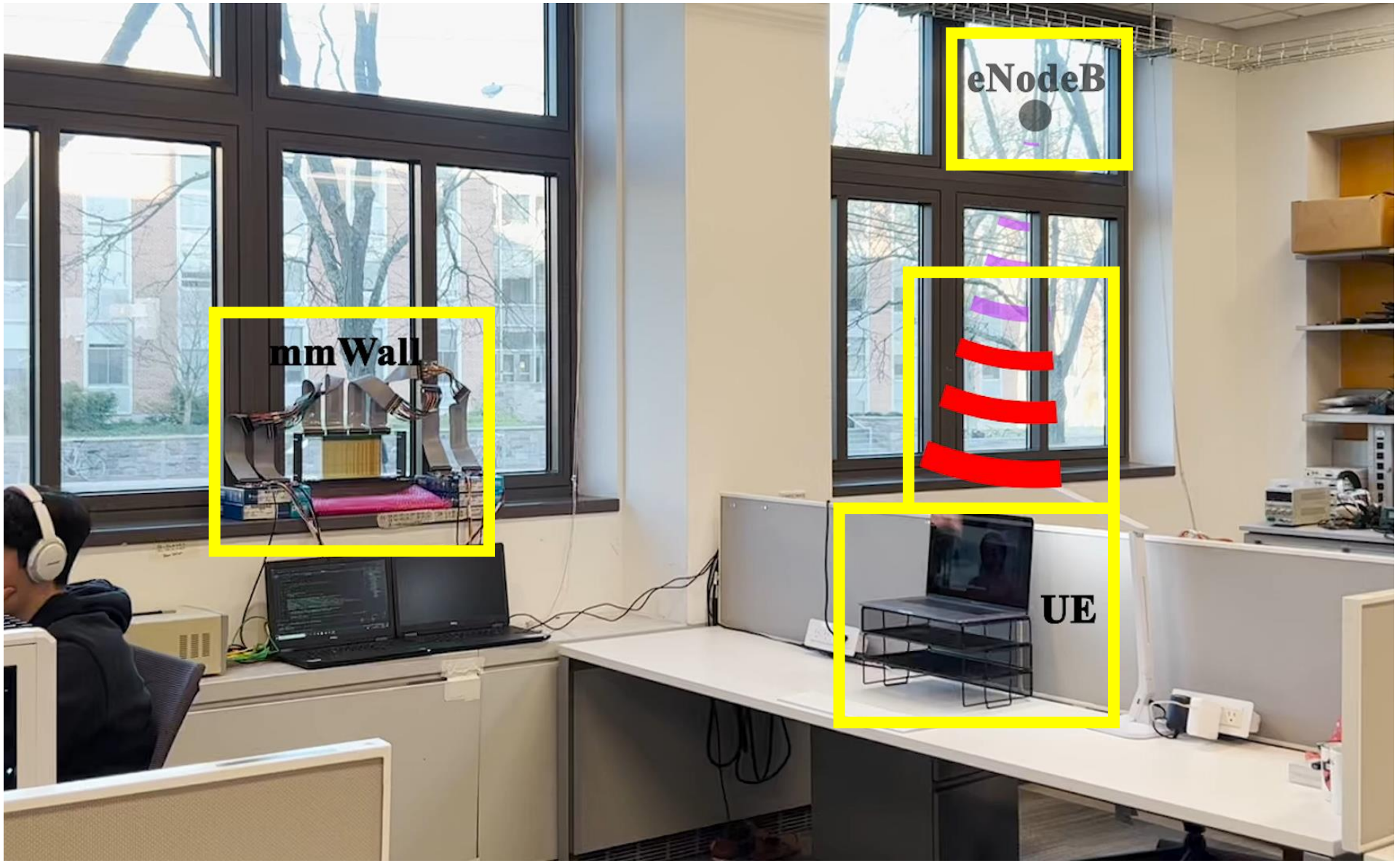


mmWall Offers Unprecedented mmWave Capabilities

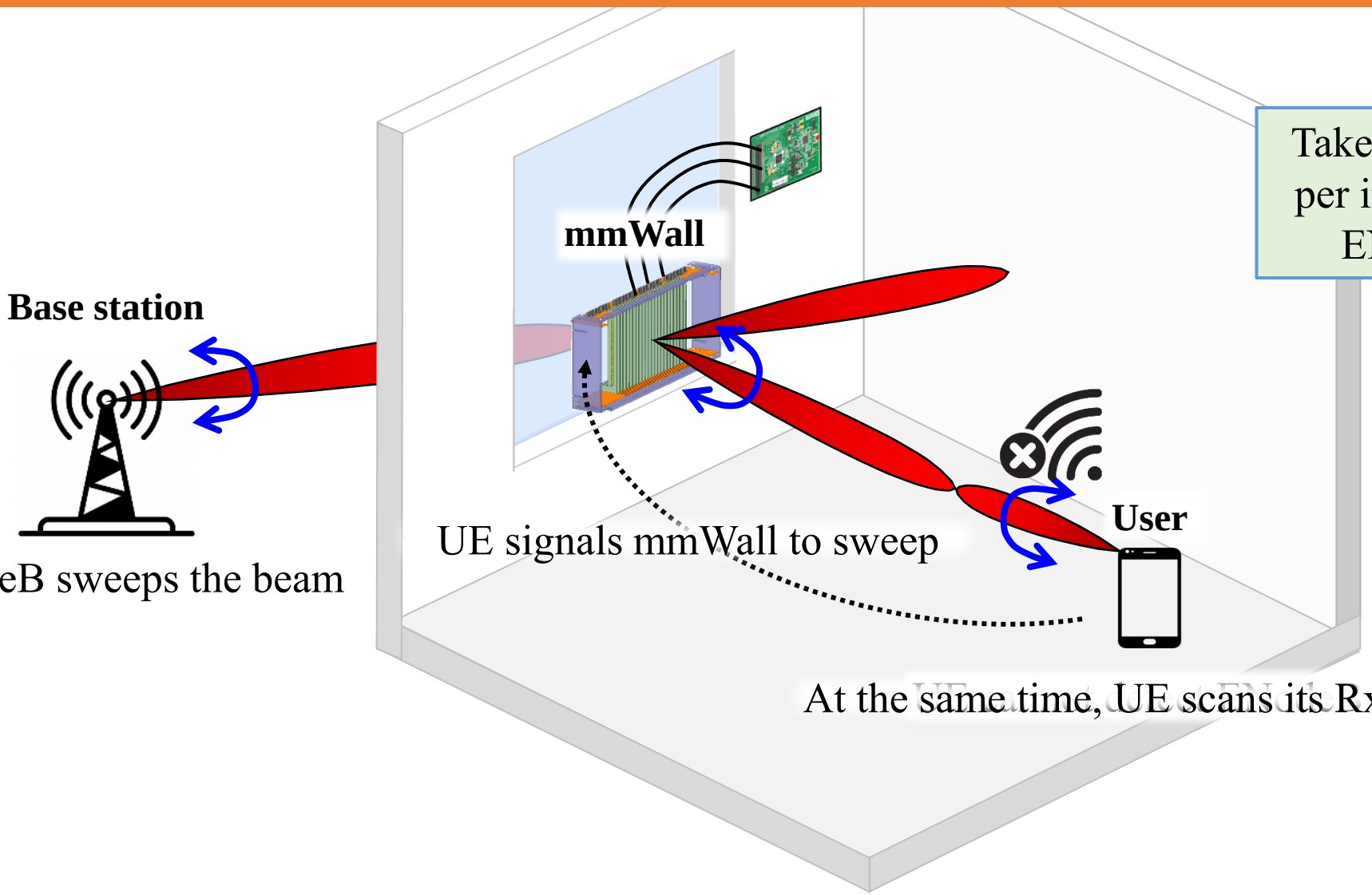
	mmWave 	Electronically reconfigurable 	Transmissive 	Reflective 	Low power consumption 	Multi-armed beam 	High steering resolution 
LAIA [1]	✗	✓	✓	✗	✗	✗	✗
MoVR [2]	✓	✓	✗	✓	✗	✗	✓
MilliMirror [3]	✓	✗	✗	✓	✓	✗	✗
RFlens [4]	✗	✓	✓	✗	✓	✓	✗
mmWall	✓	✓	✓	✓	✓	✓	✓

[1] Li, Zhuqi, et al. "Towards programming the radio environment with large arrays of inexpensive antennas." *NSDI*. 2019
[2] Abari, Omid, et al. "Enabling High-Quality Untethered Virtual Reality." *NSDI*. 2017
[3] Qian, Kun, et al. "MilliMirror: 3D printed reflecting surface for millimeter-wave coverage expansion." *MOBICOM*. 2022.
[4] Feng, Chao, et al. "RFlens: metasurface-enabled beamforming for IoT communication and sensing." *MOBICOM*. 2021

mmWall: High-Level System Overview



Link Layer Design – Refractive Establishment

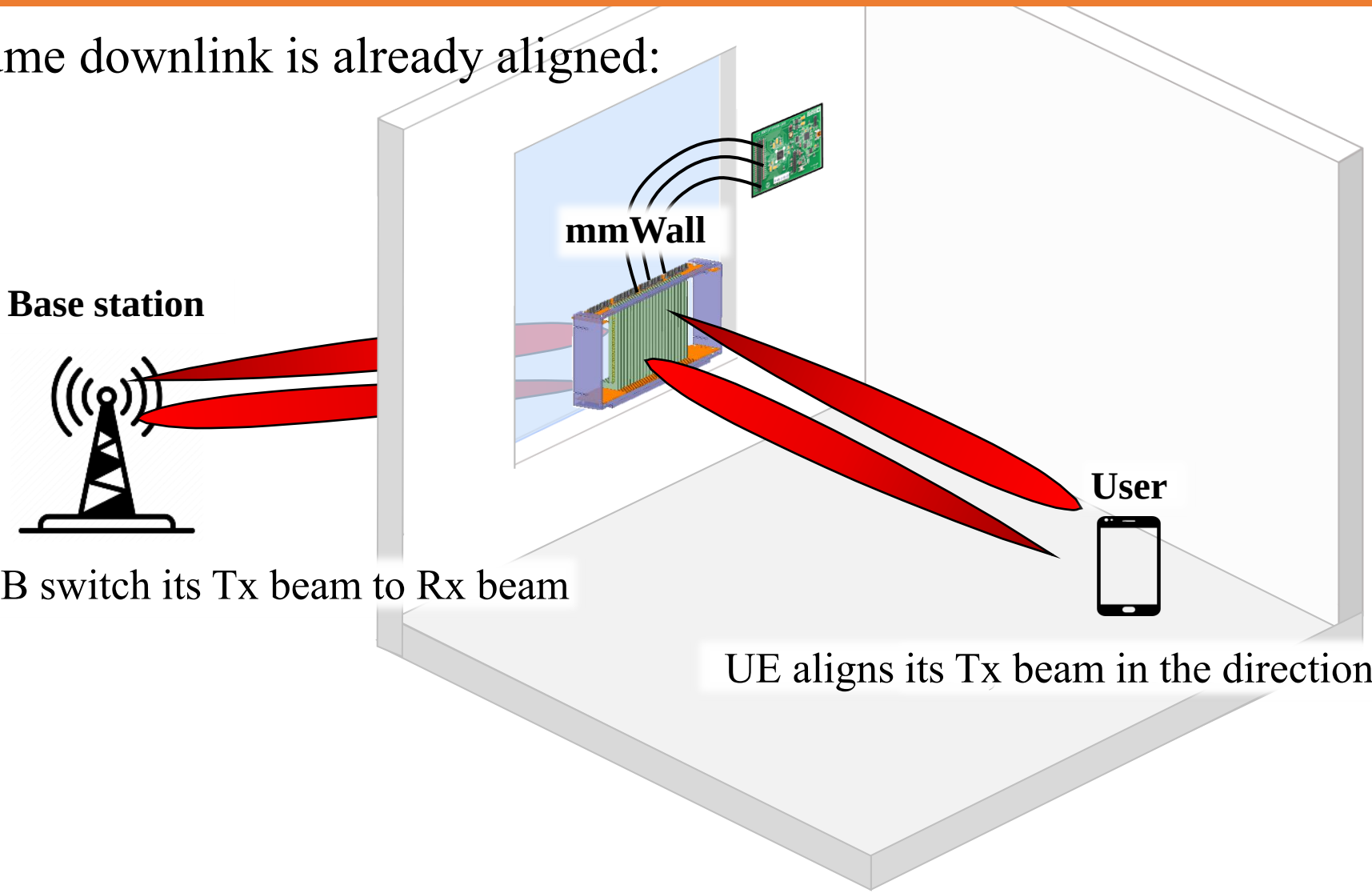


Takes $O(n^3)$ but only **once** per installation due to fixed ENodeB and mmWall

UE finds **combination of ENodeB, mmWall, and UE angles** that maximizes SNR

Fast Downlink/Uplink Conversion

Assume downlink is already aligned:



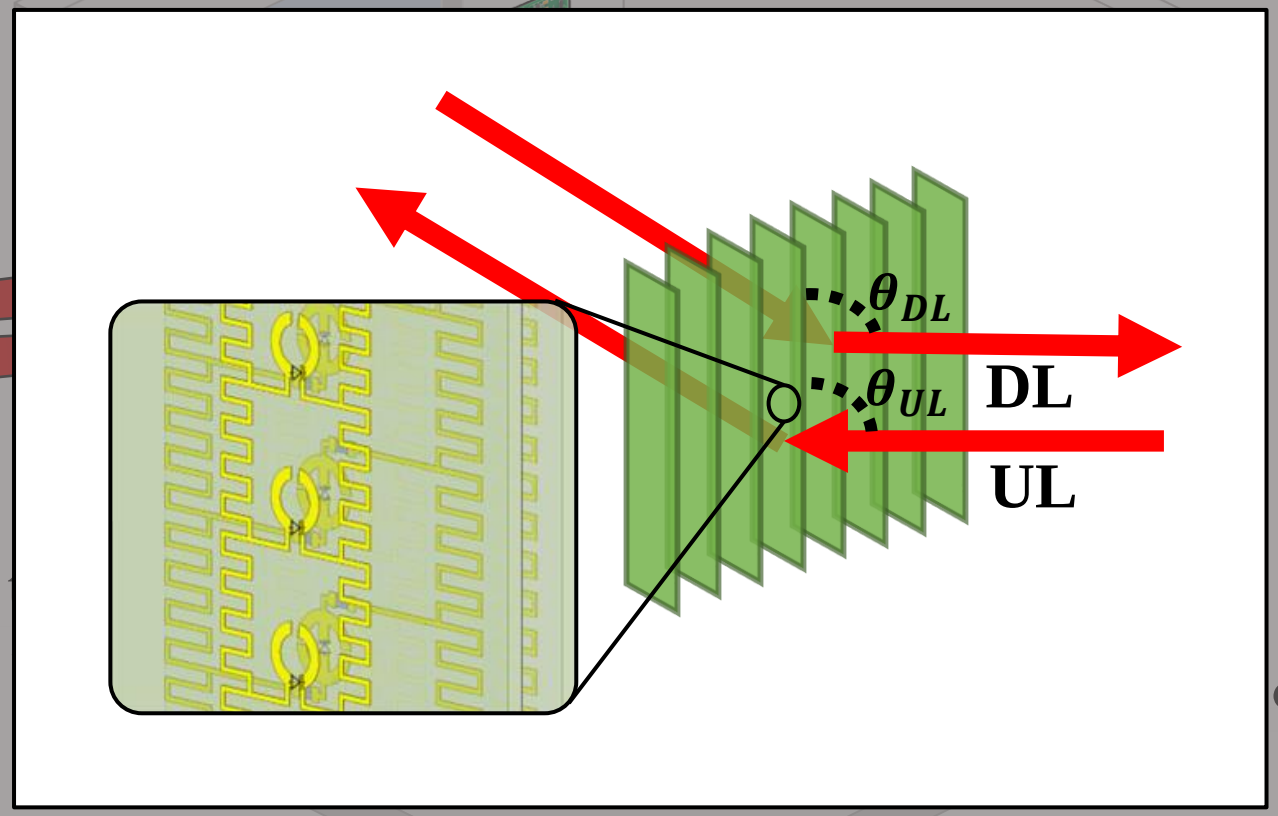
ENodeB switch its Tx beam to Rx beam

UE aligns its Tx beam in the direction of its Rx beam

Without reconfiguring mmWall, uplink beam is established!

Fast Downlink/Uplink Conversion

Assume downlink is already aligned:

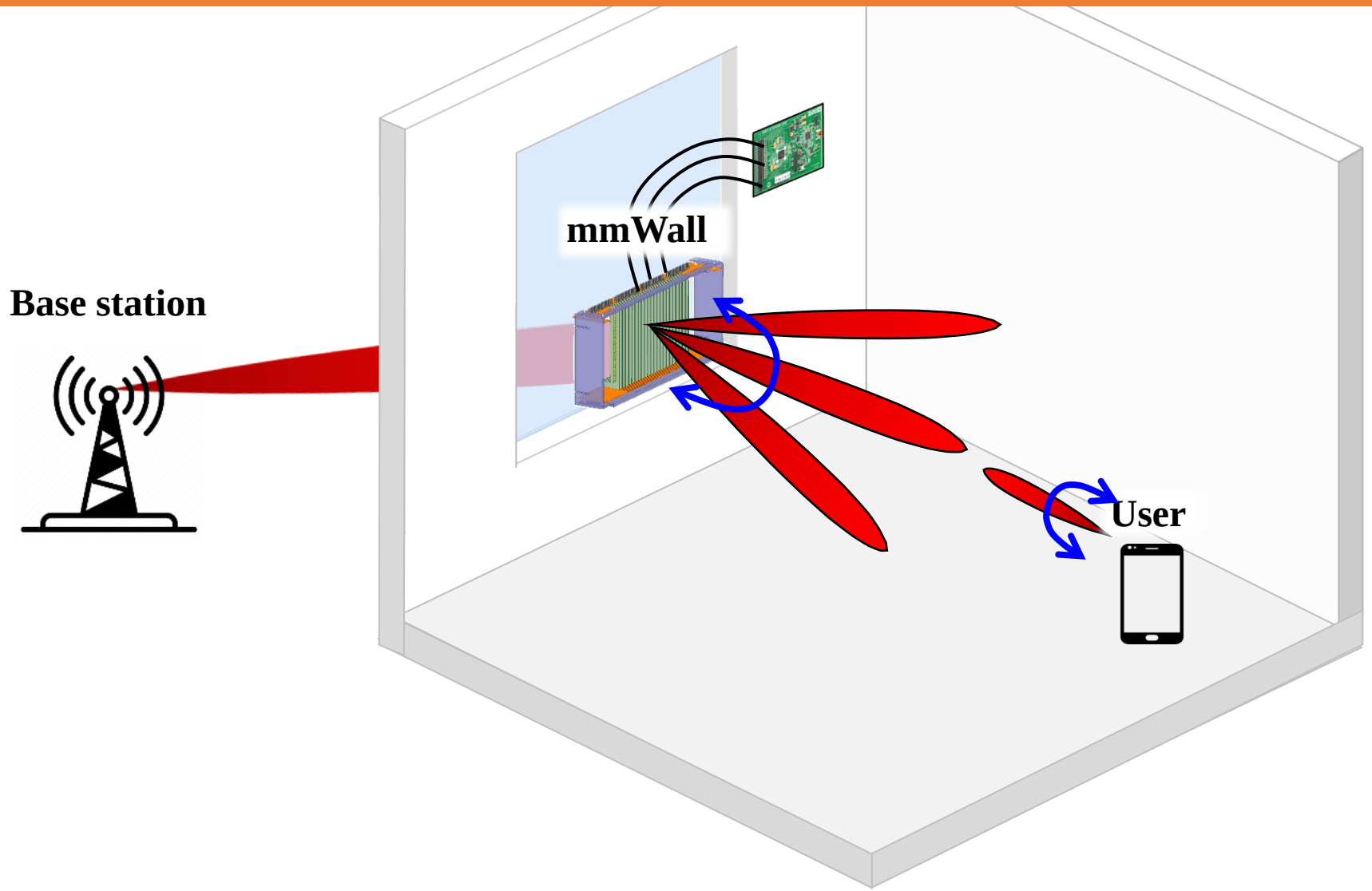


ENodeB switch its Tx beam

of its Rx beam

Angular reciprocity allows fast downlink/uplink conversion

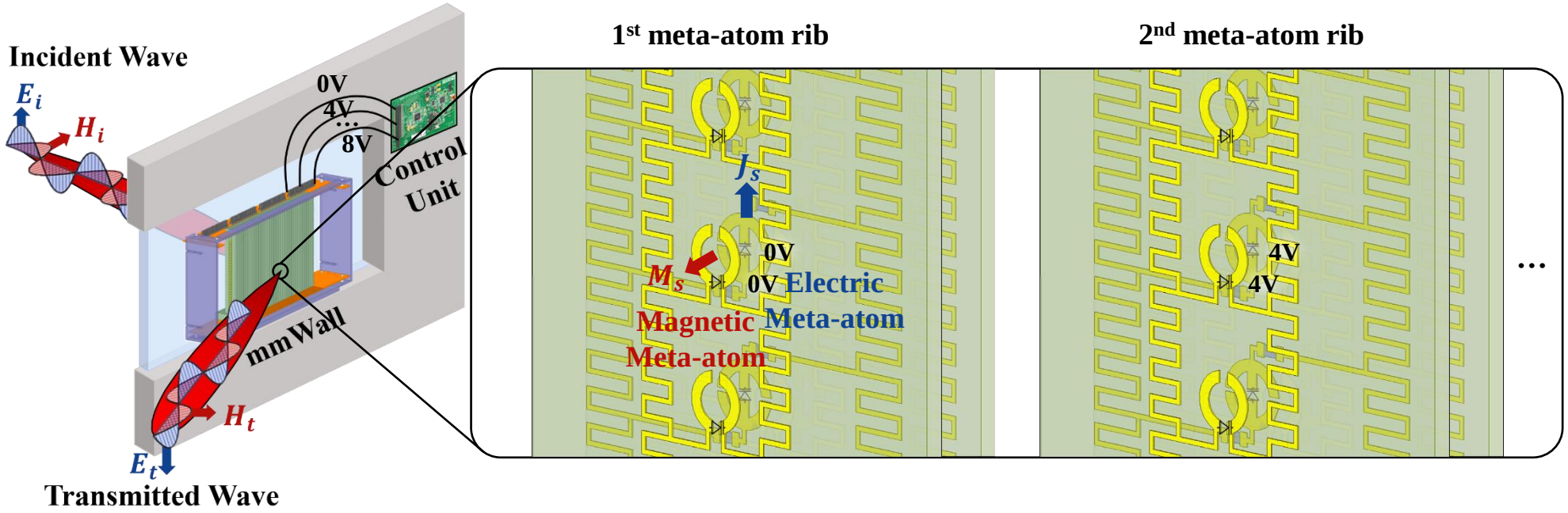
Fast User Tracking with Multi-beam

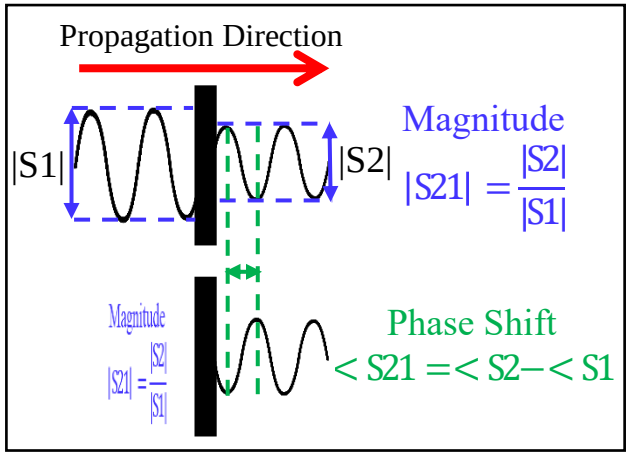


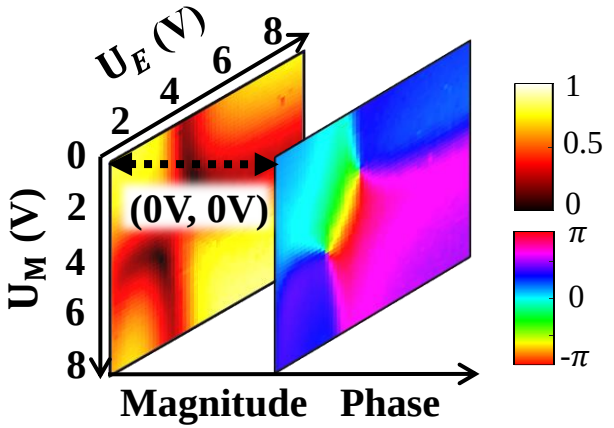
Accelerate beam search by orders of magnitude improvement

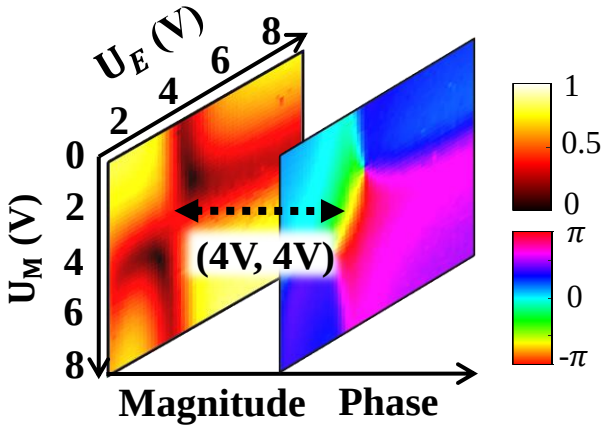
[1] Hassanieh, Haitham, et al. "Fast millimeter wave beam alignment." *Proceedings of the 2018 Conference of the ACM Special Interest Group on Data Communication*. 2018.

mmWall: High-Level Design Overview



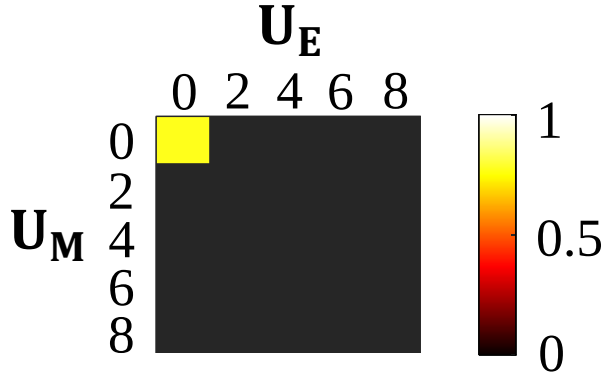


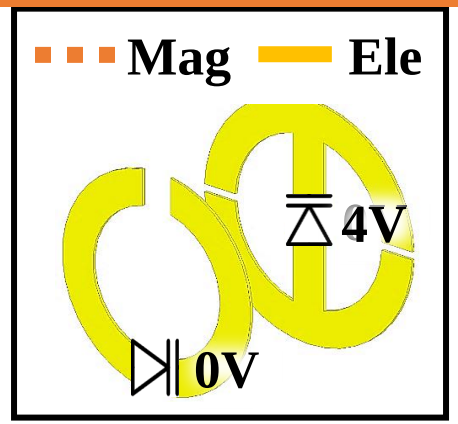




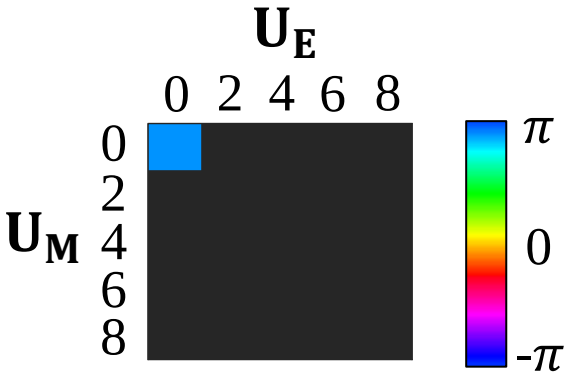
How Does it Work: Unit Cell Response

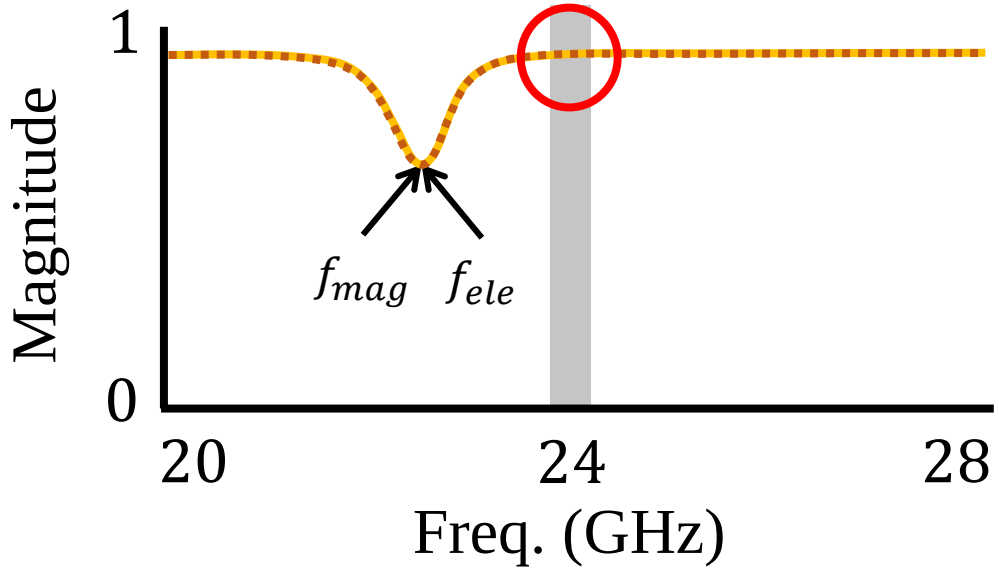
Magnitude:

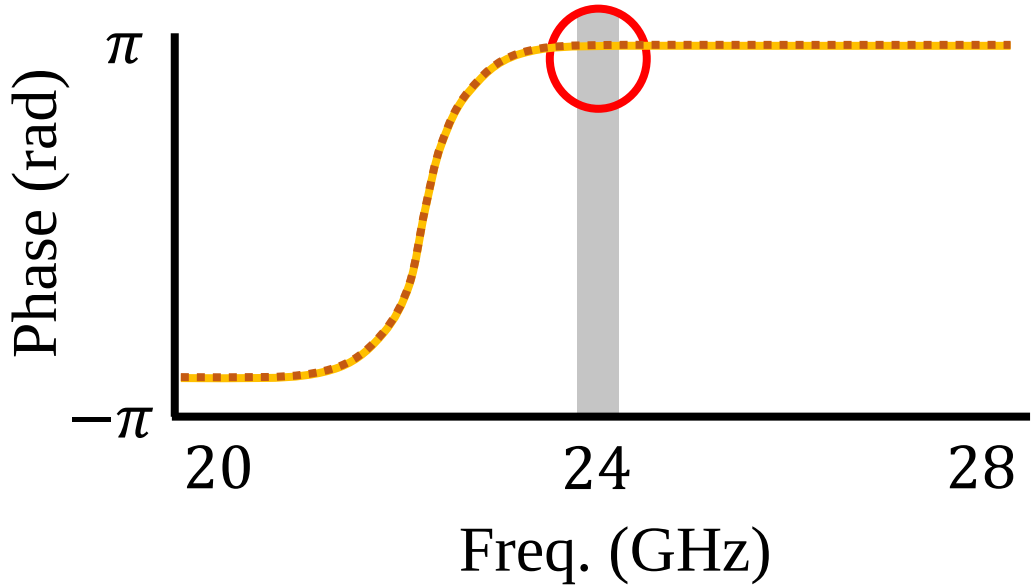




Phase:







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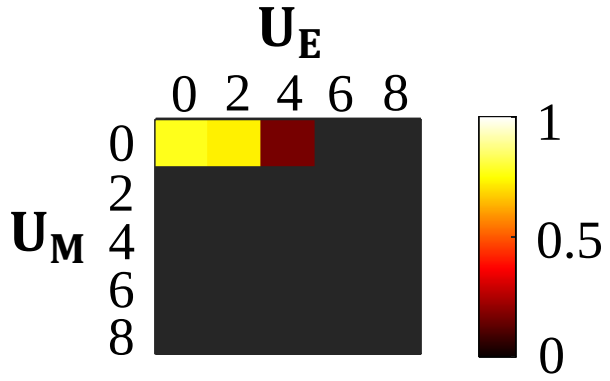

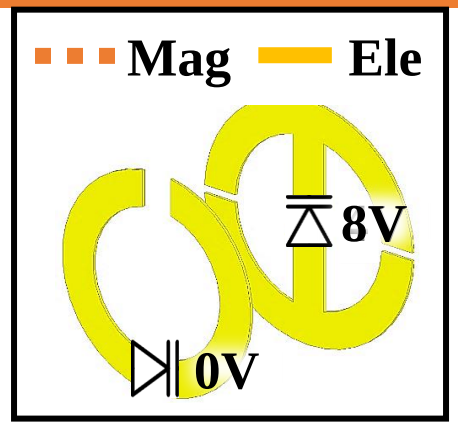

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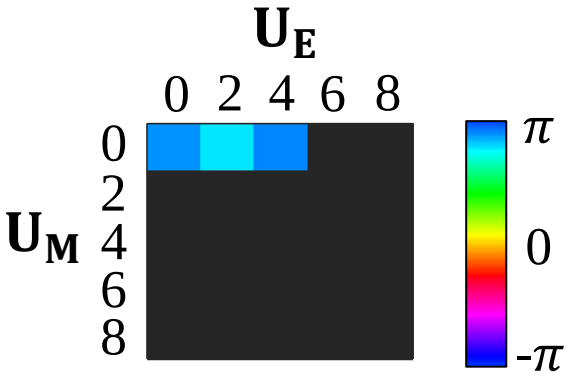

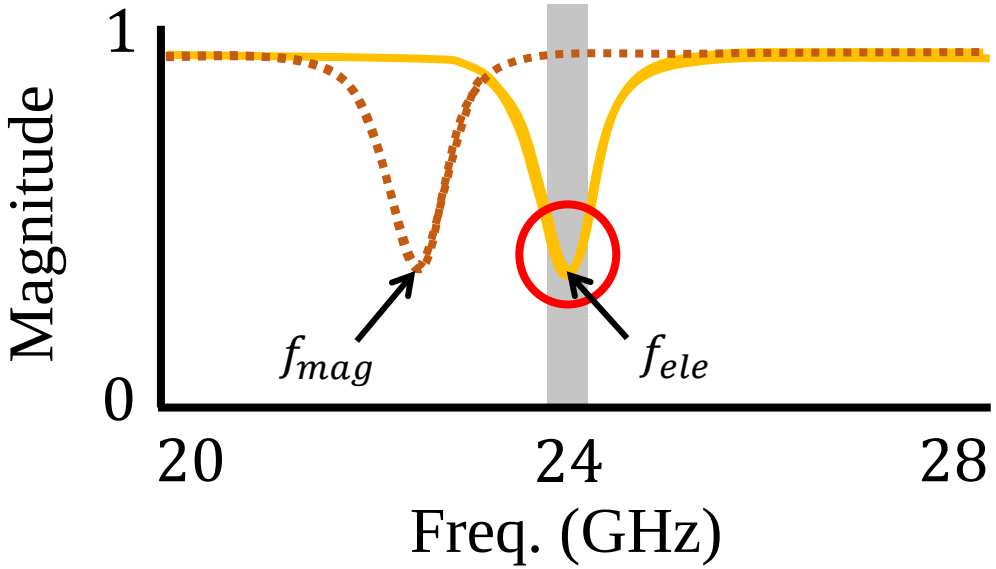

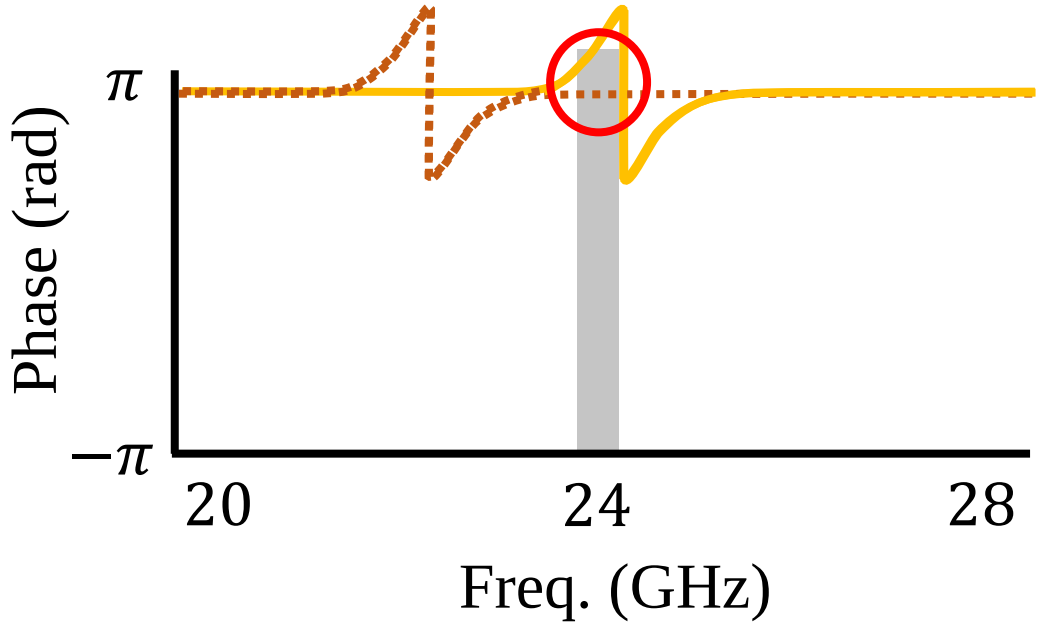

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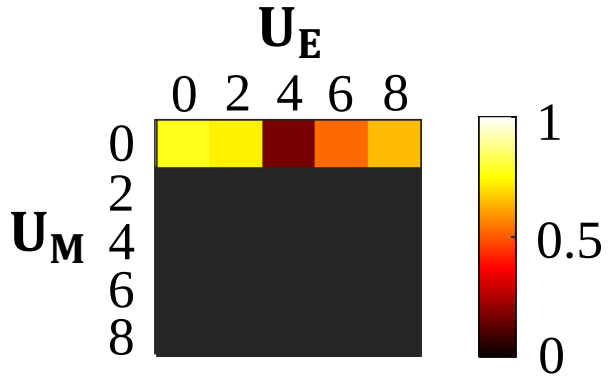

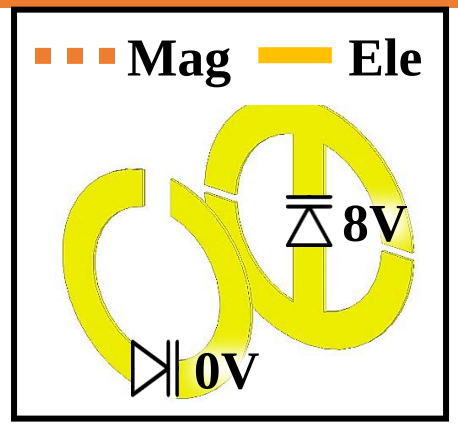

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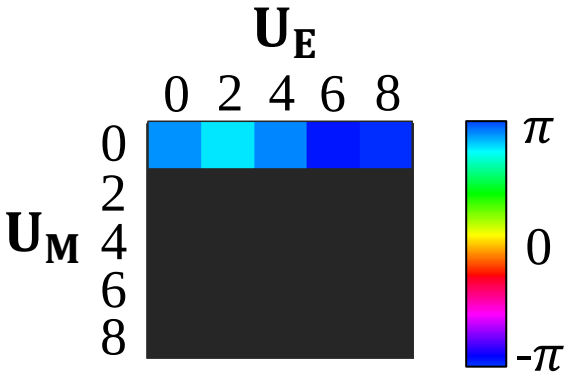

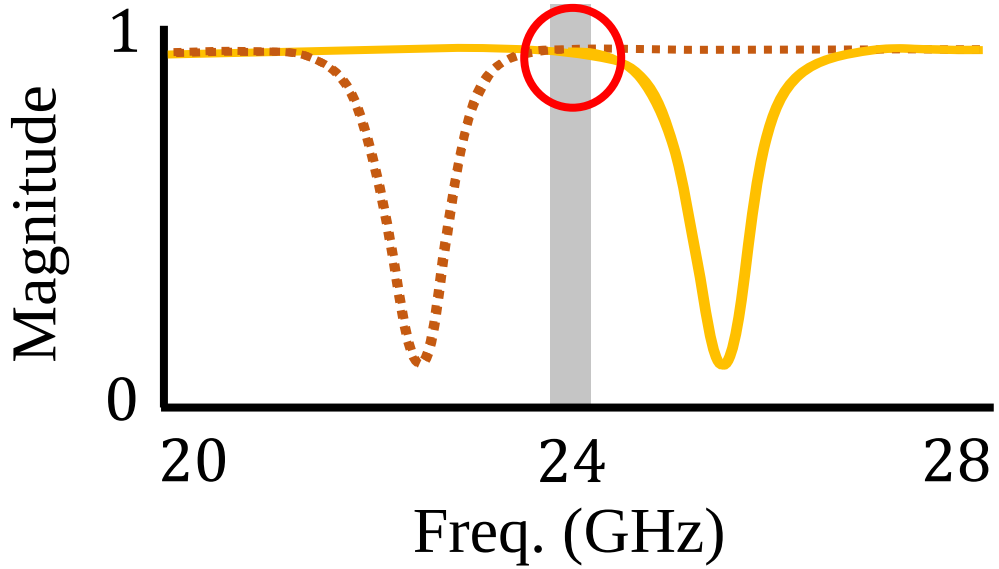

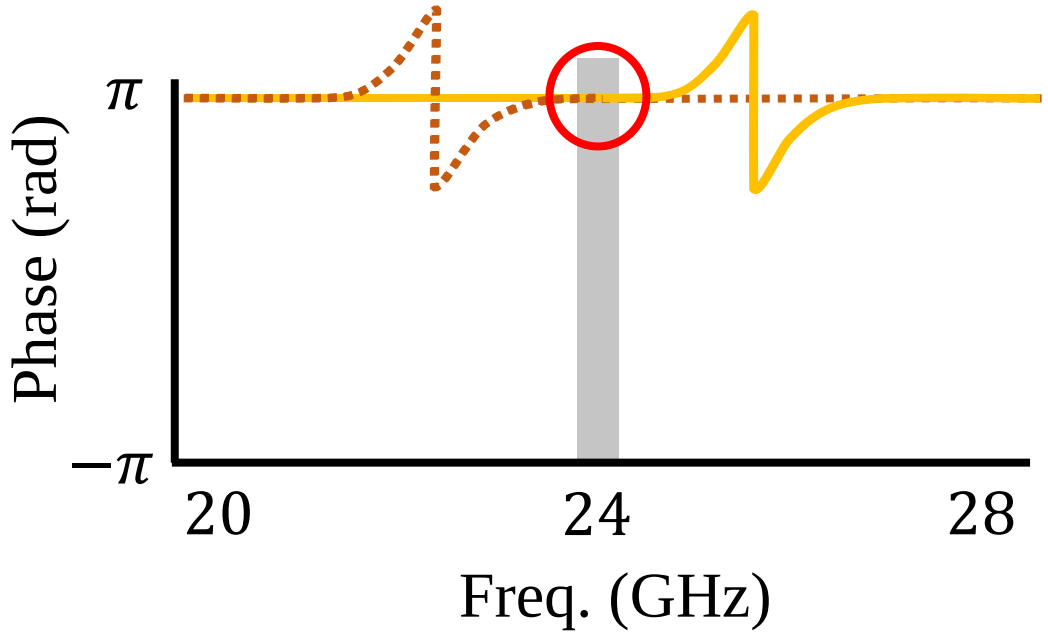

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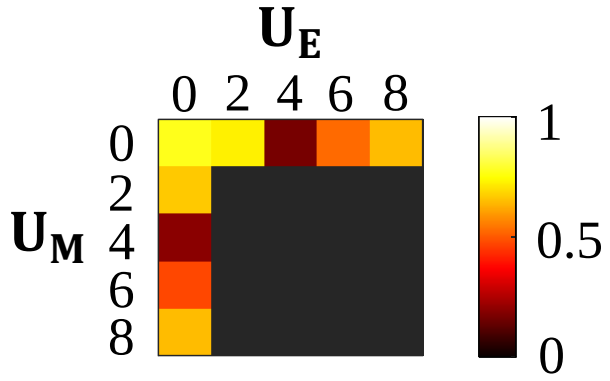

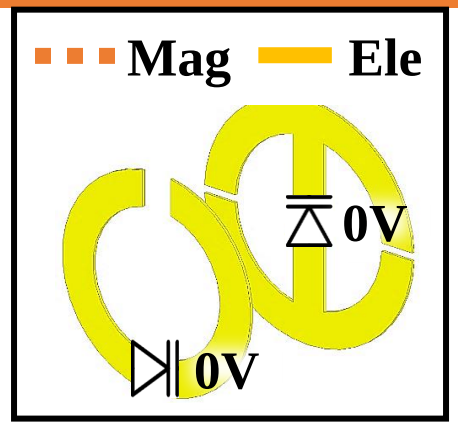

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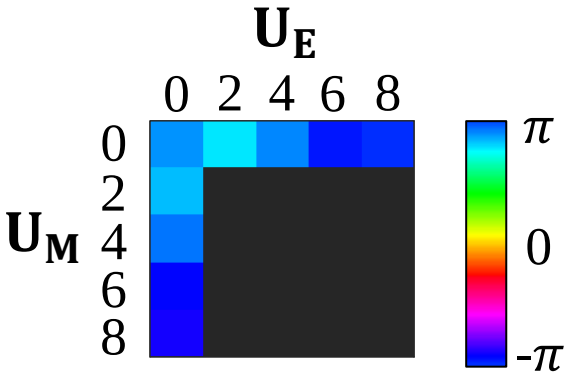

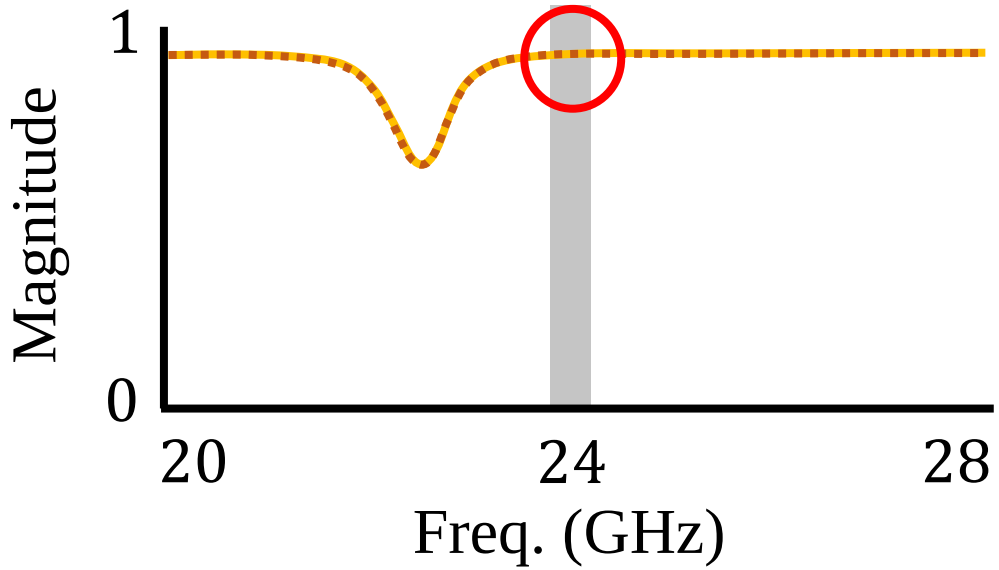

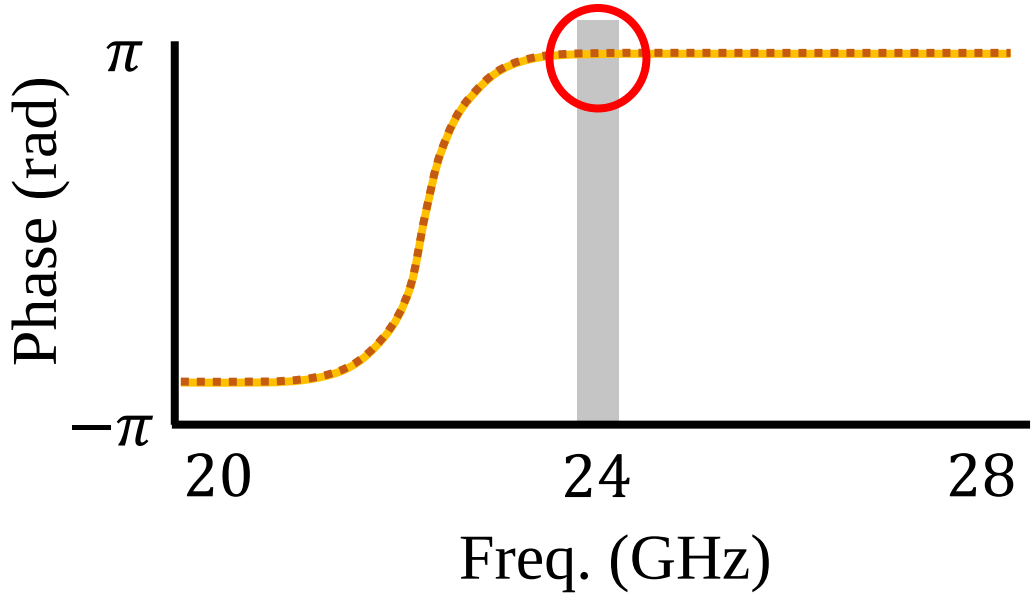

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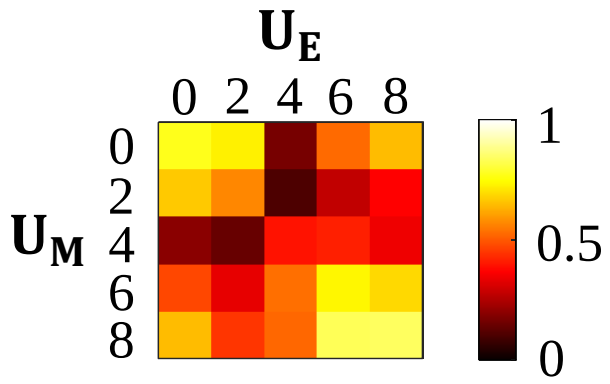

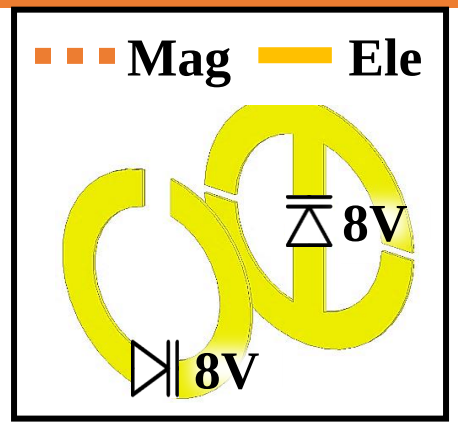

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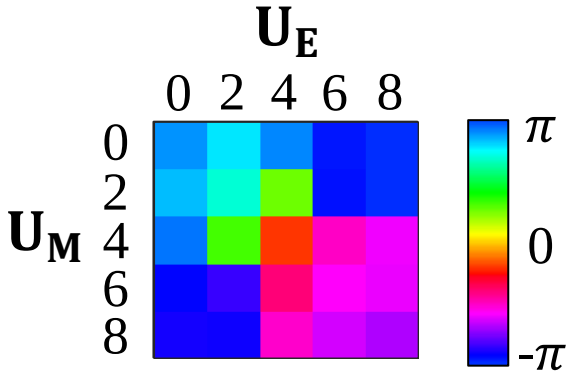
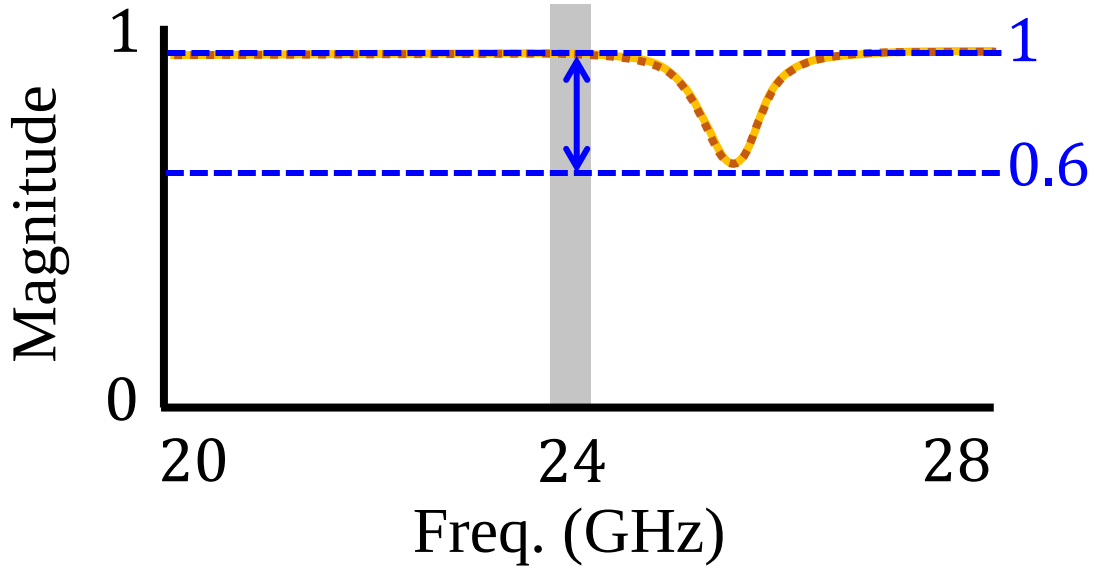
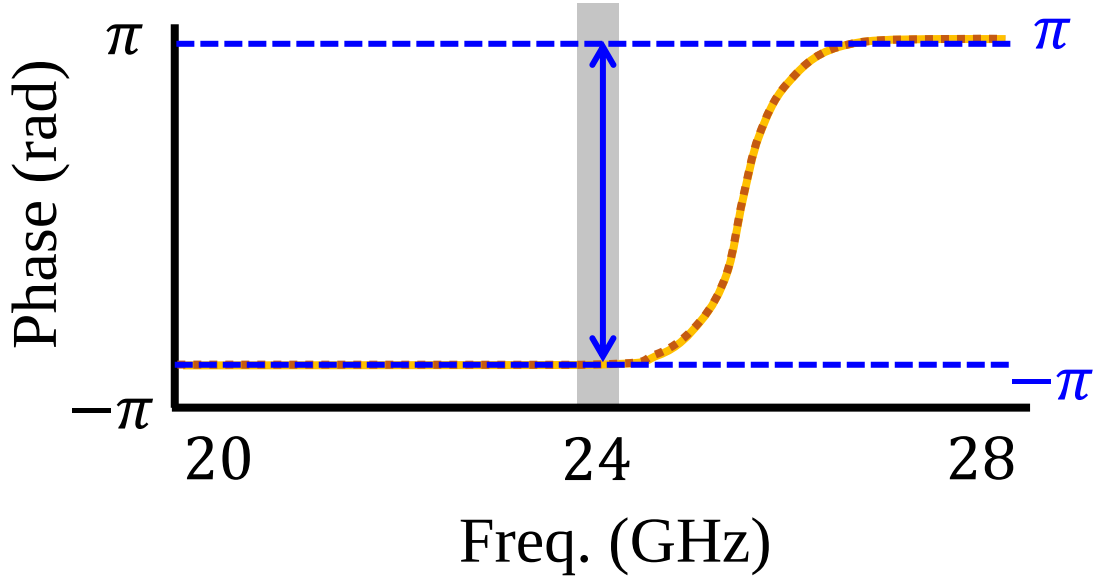
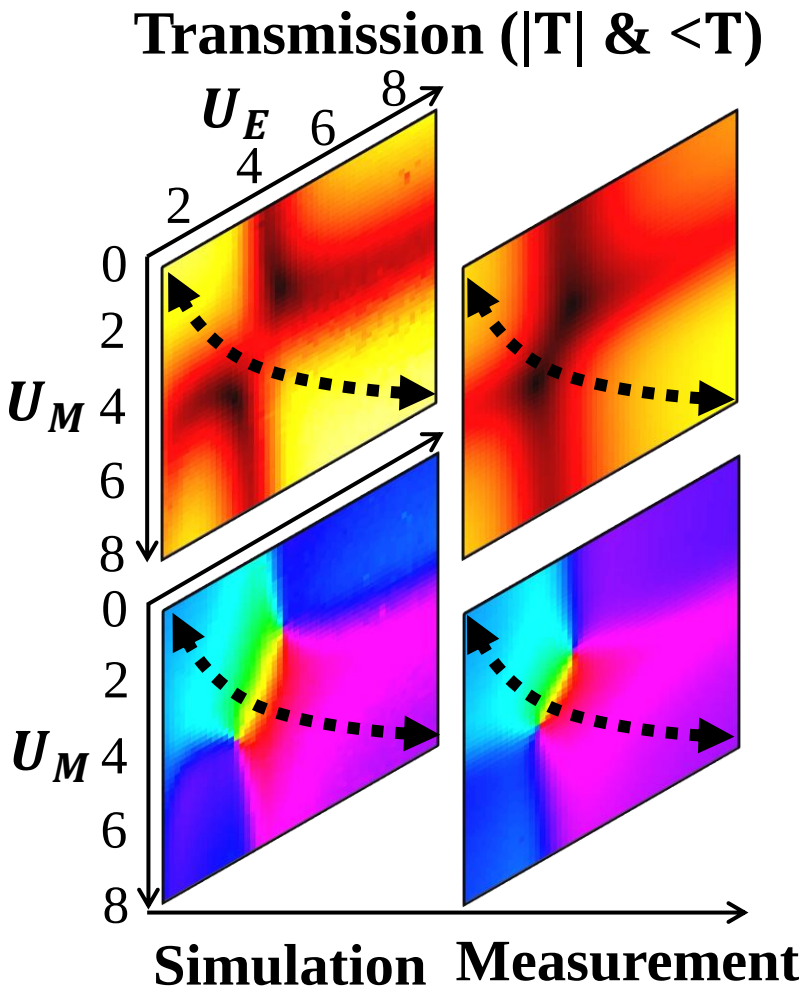
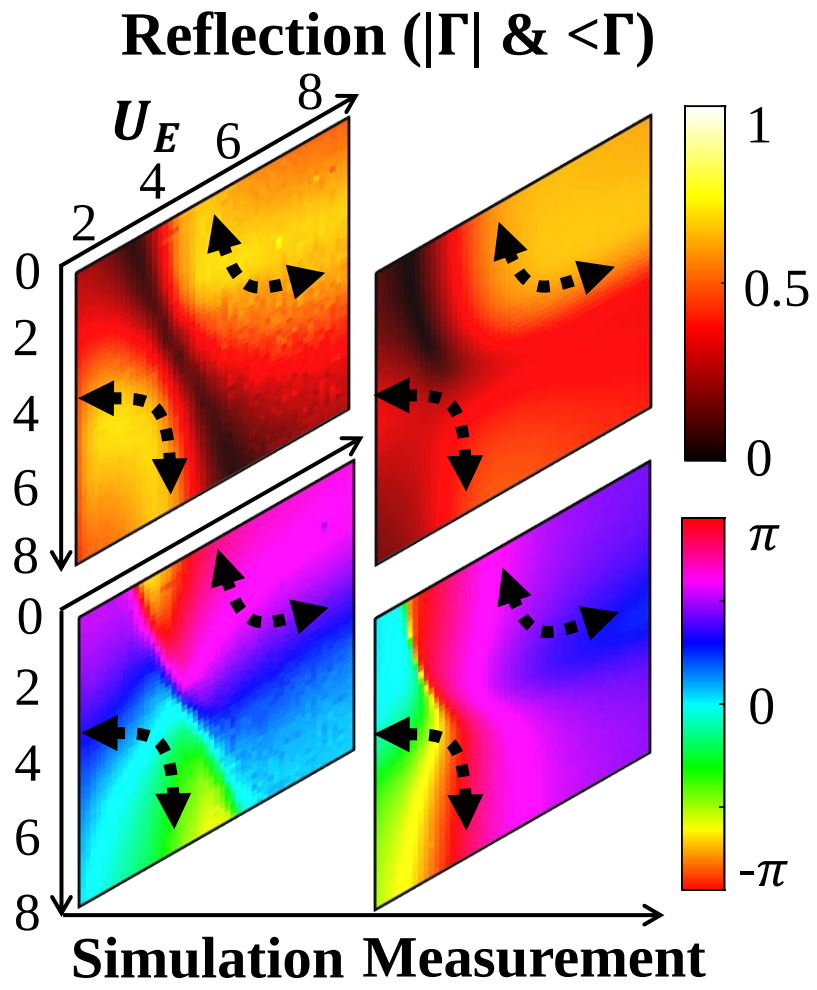




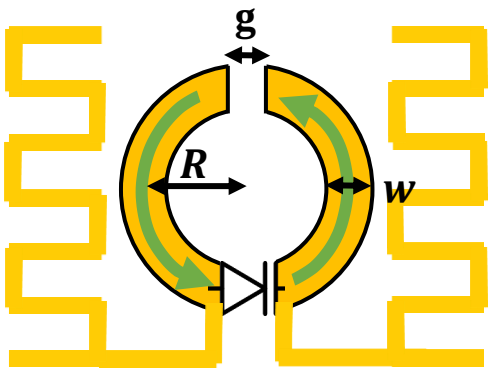


How Does it Work: Huygen's Pattern

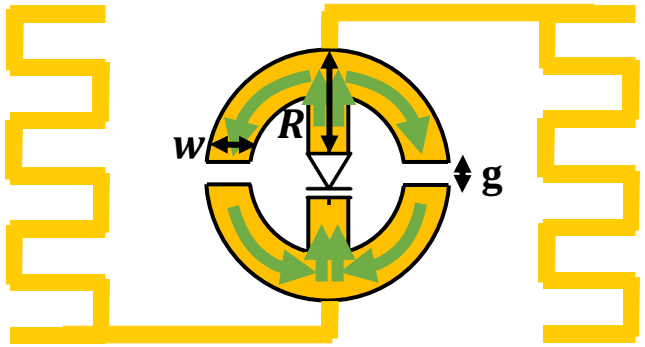




Challenge: Scaling to mmWave

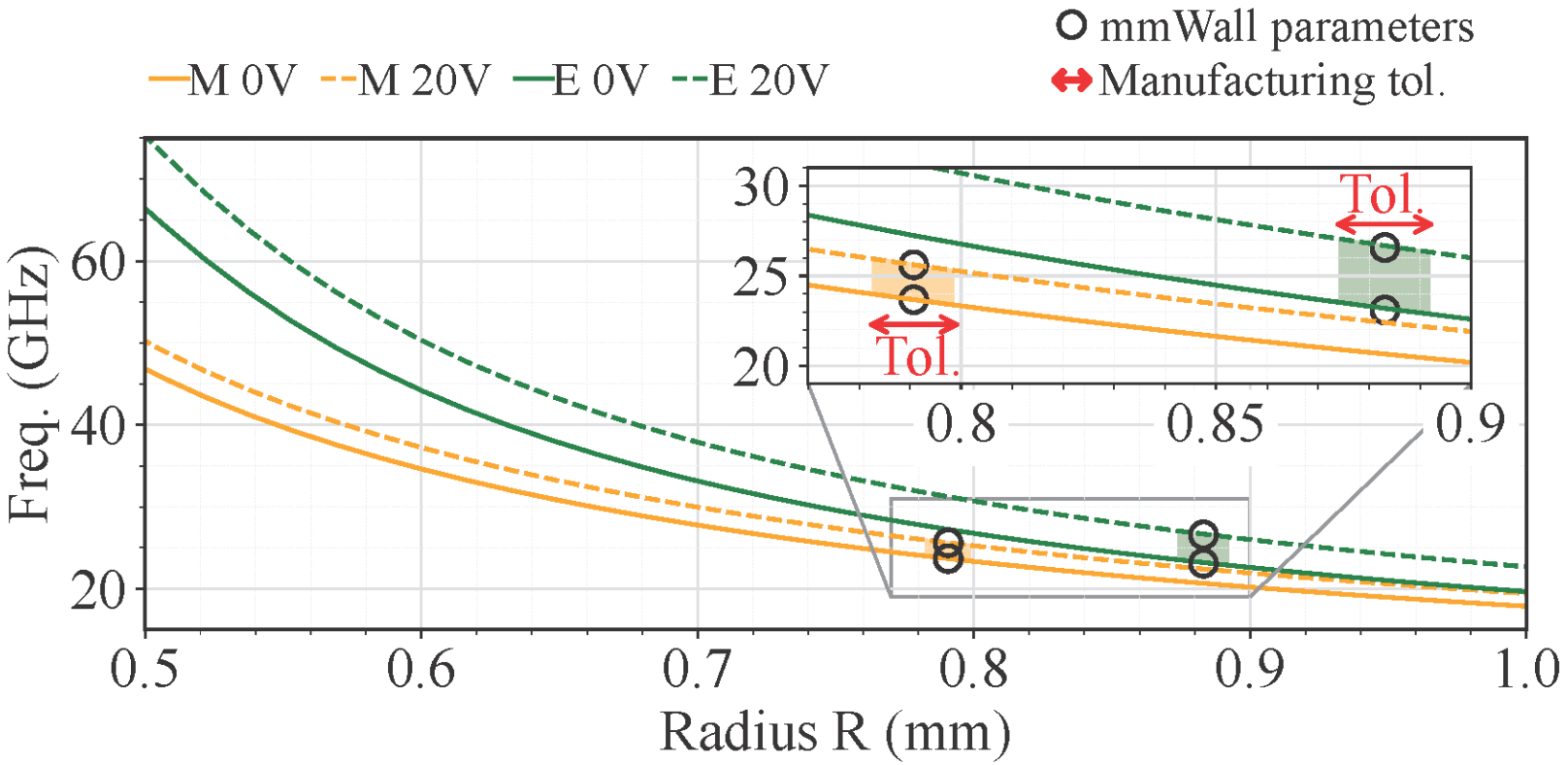


Magnetic side



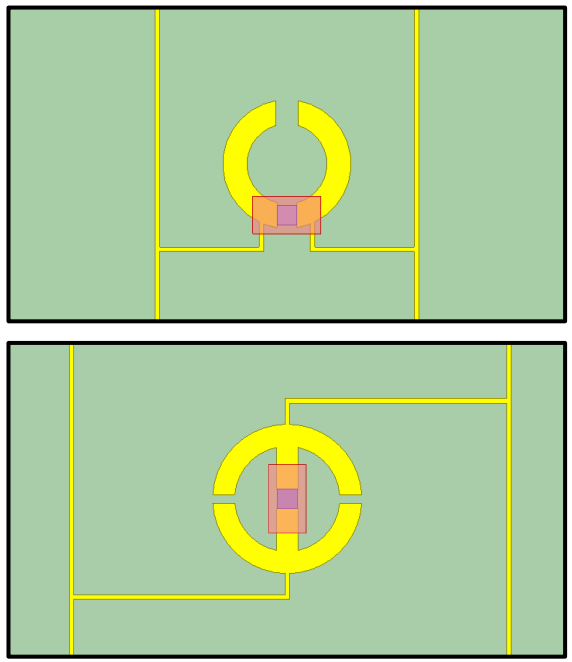
Electric side

Miniaturization (radius, width) is key to scaling up to mmWave frequencies!

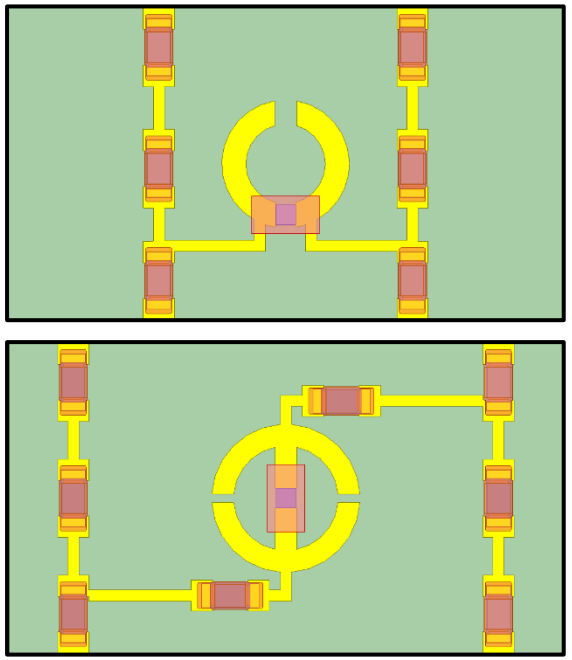


Biasing Design – failed attempts

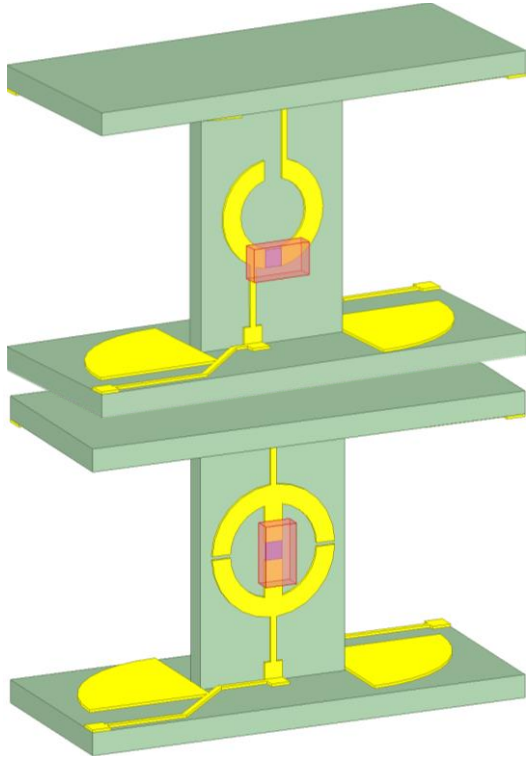
Goal: RF "choke" to block mmWave signals from interaction with control lines



Copper Lines



Coil Inductors

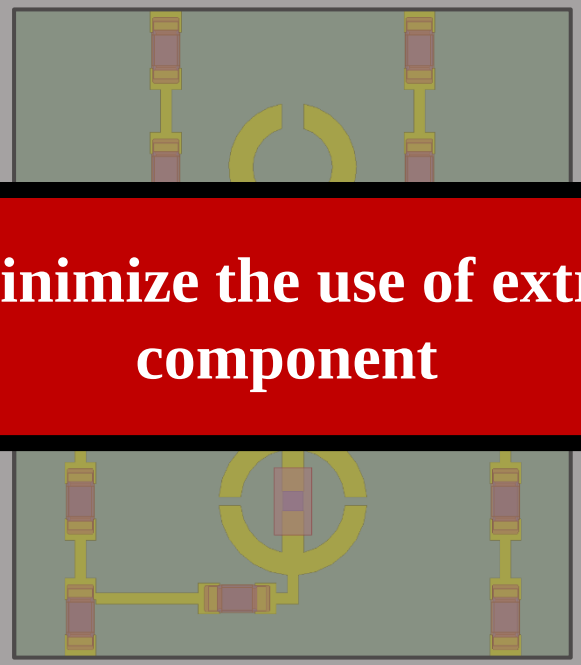


Radial Stub

Biasing Design – failed attempts

Easy to fabricate

Copper Lines



Minimize the use of extra component

Coil Inductors

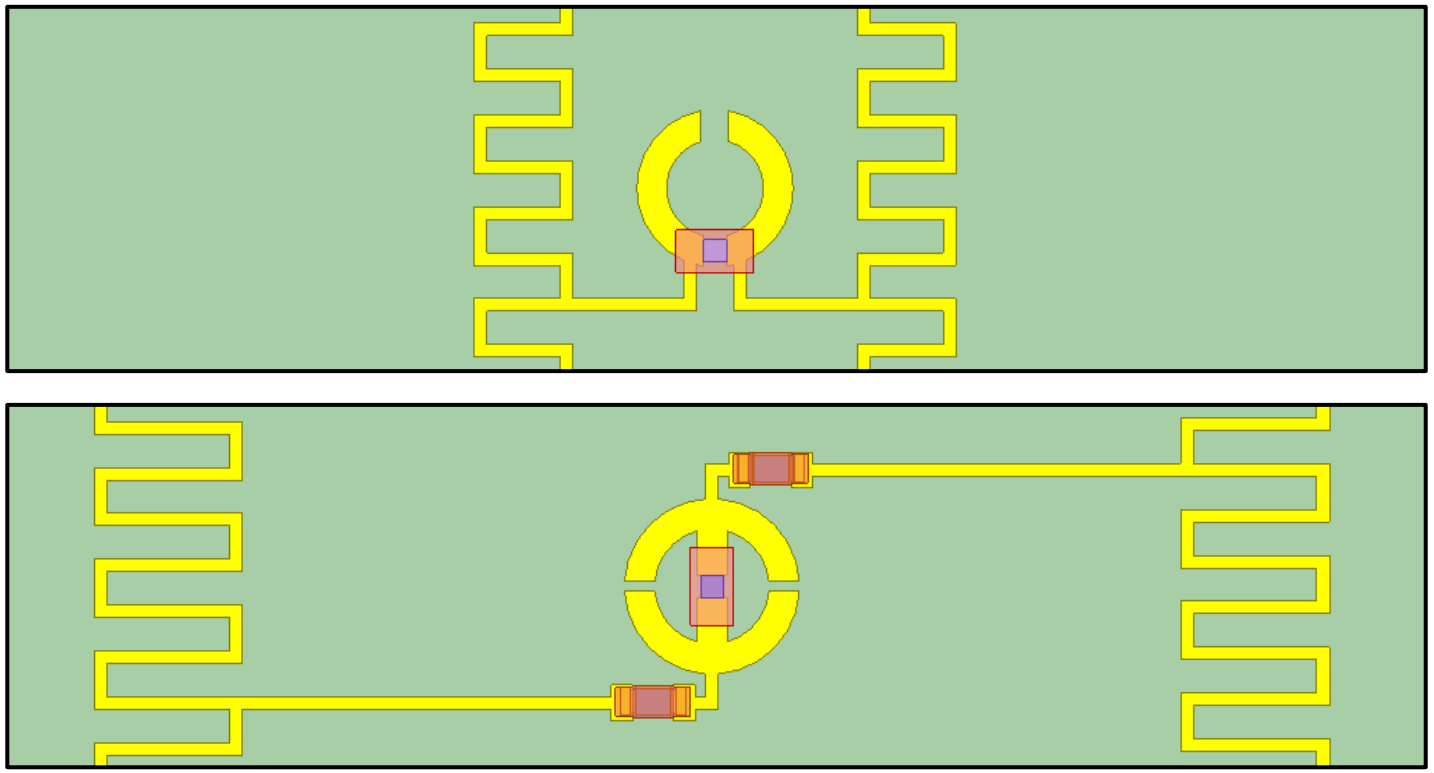
Avoid large copper on the panel

Radial Stub

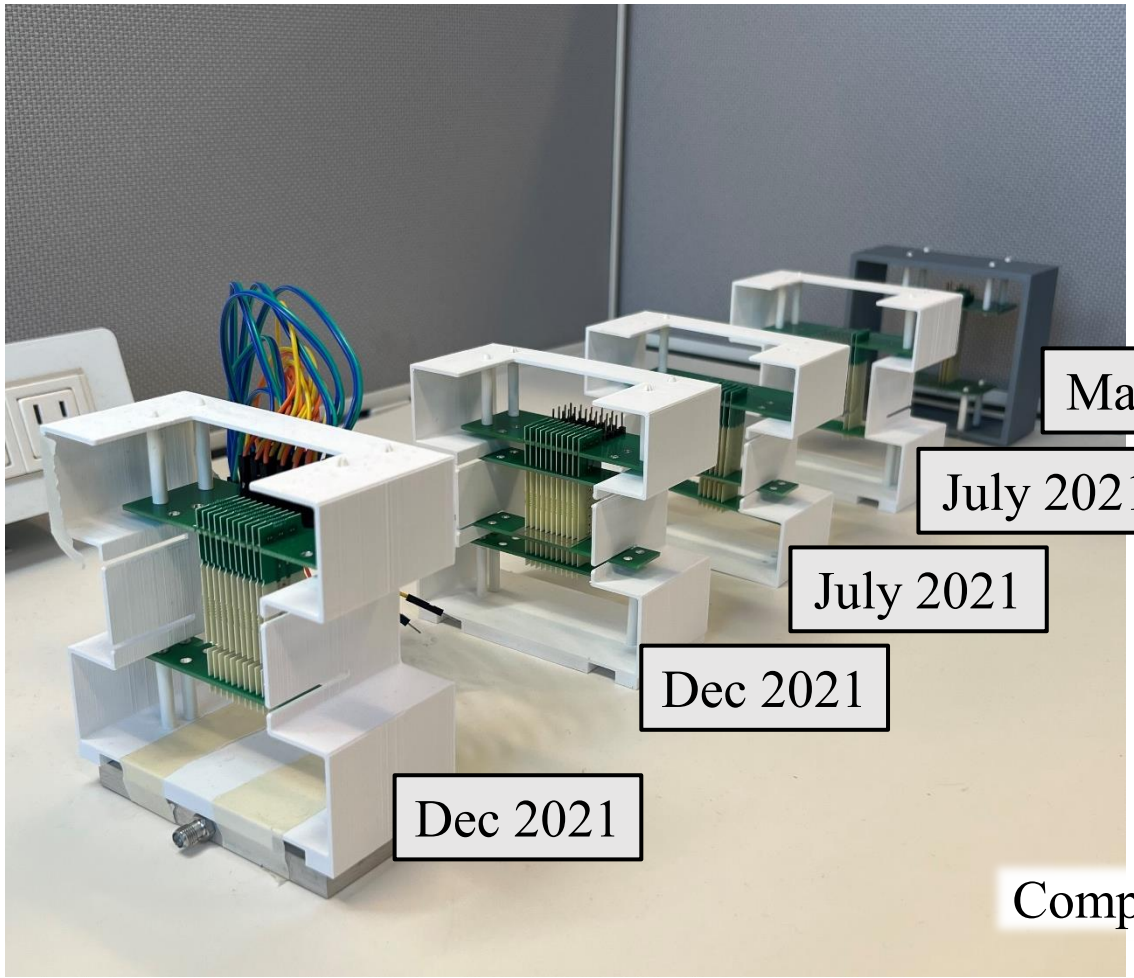
mmWall's Proposed *Meander* Structure

Goals:

1. Minimize the use of extra components
2. Avoid a large amount of copper on the panel
3. Retain ease of fabrication

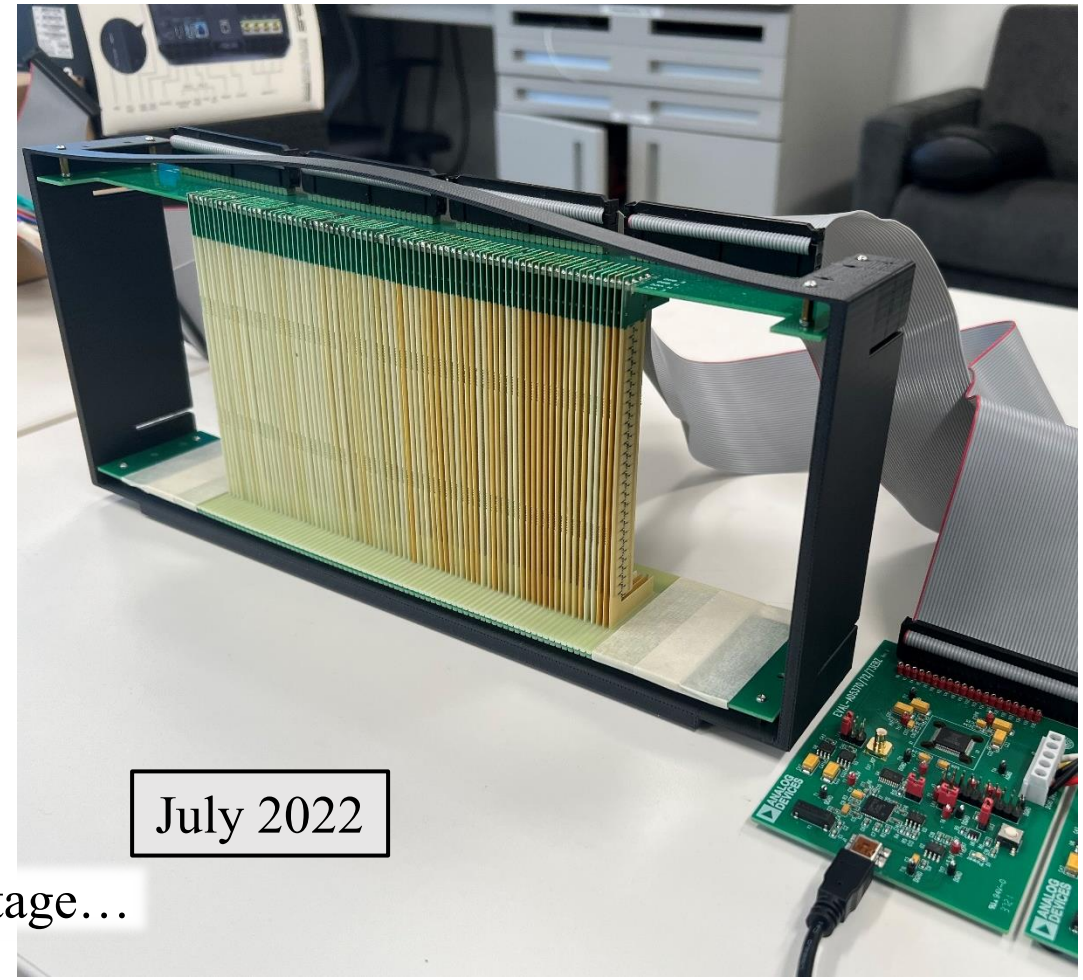


The Evolution of Prototyping



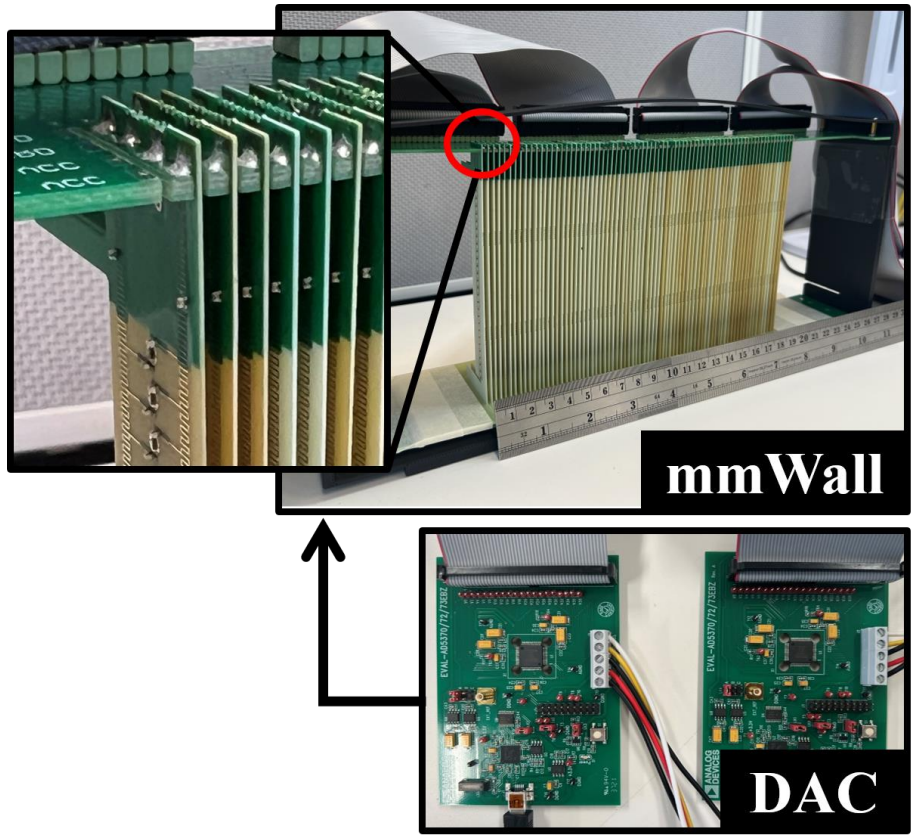
● ● ●

Component shortage…

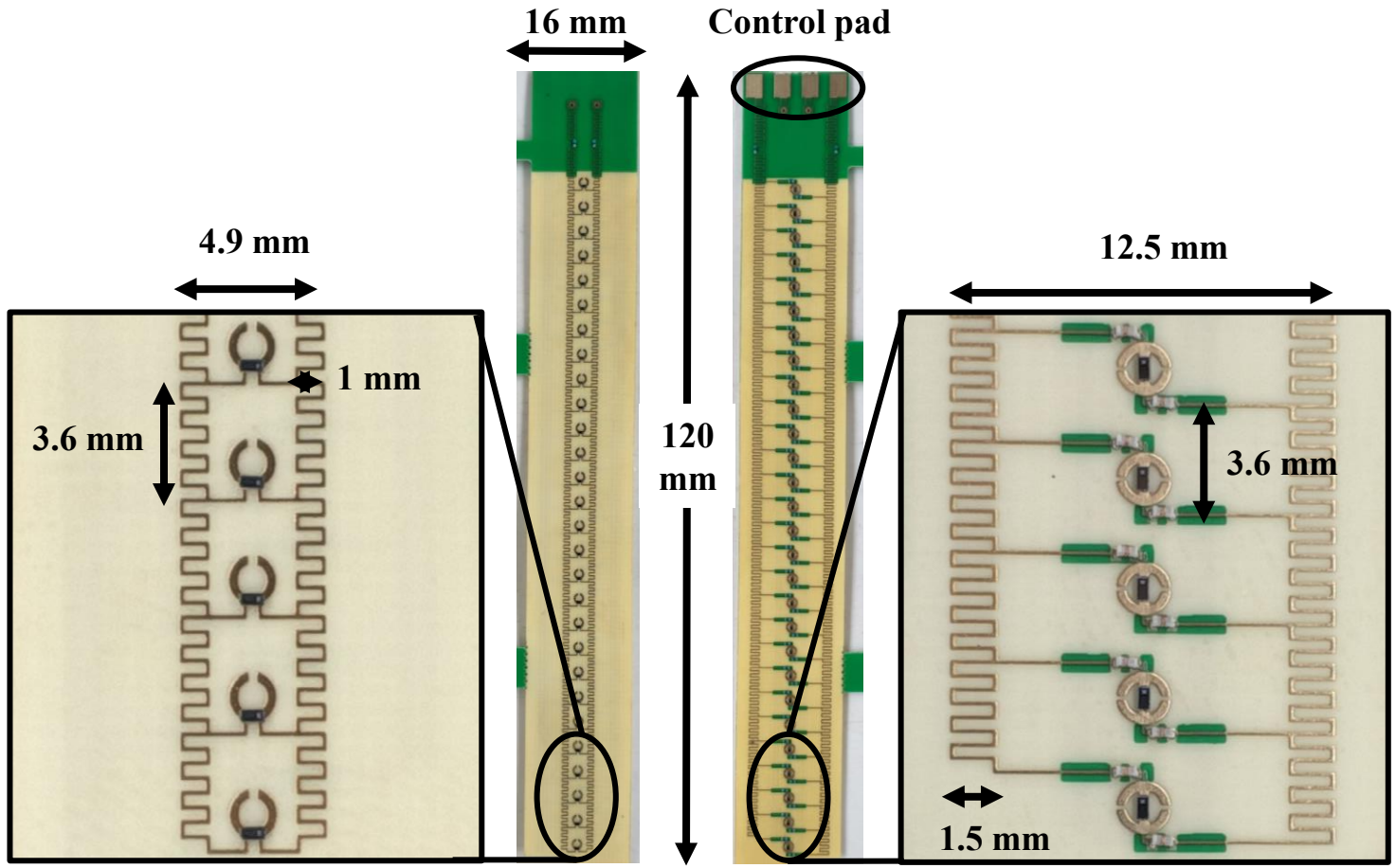


Implementation

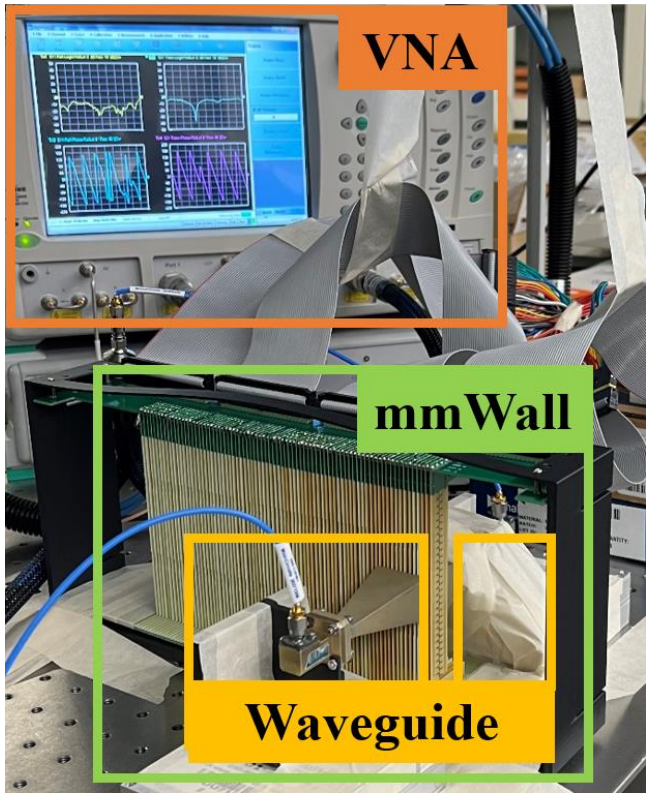
mmWall hardware



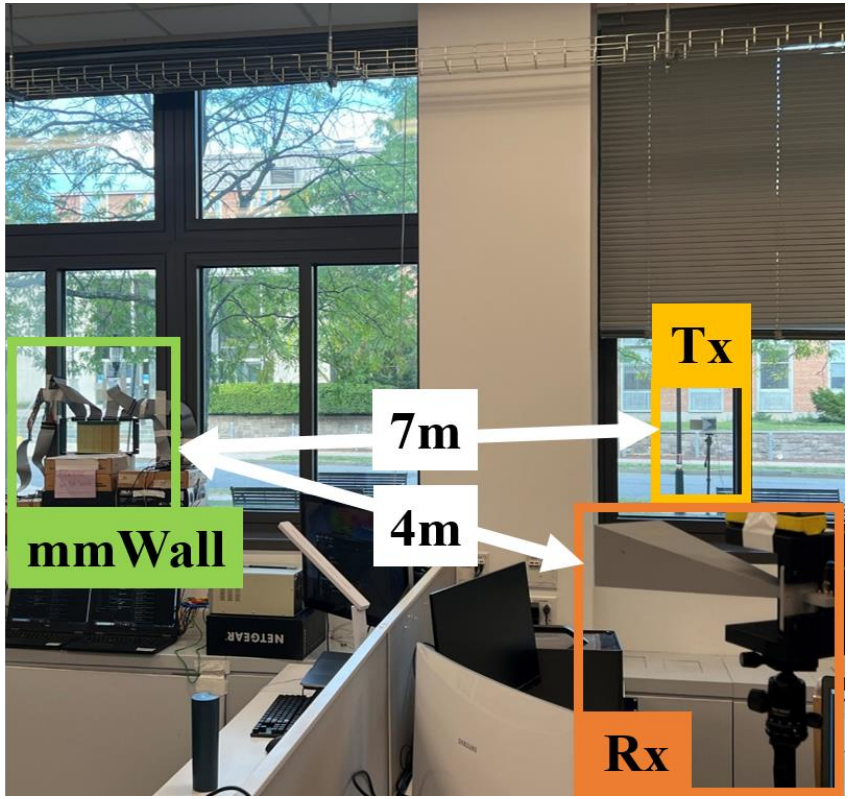
mmWall's PCB *ribs*



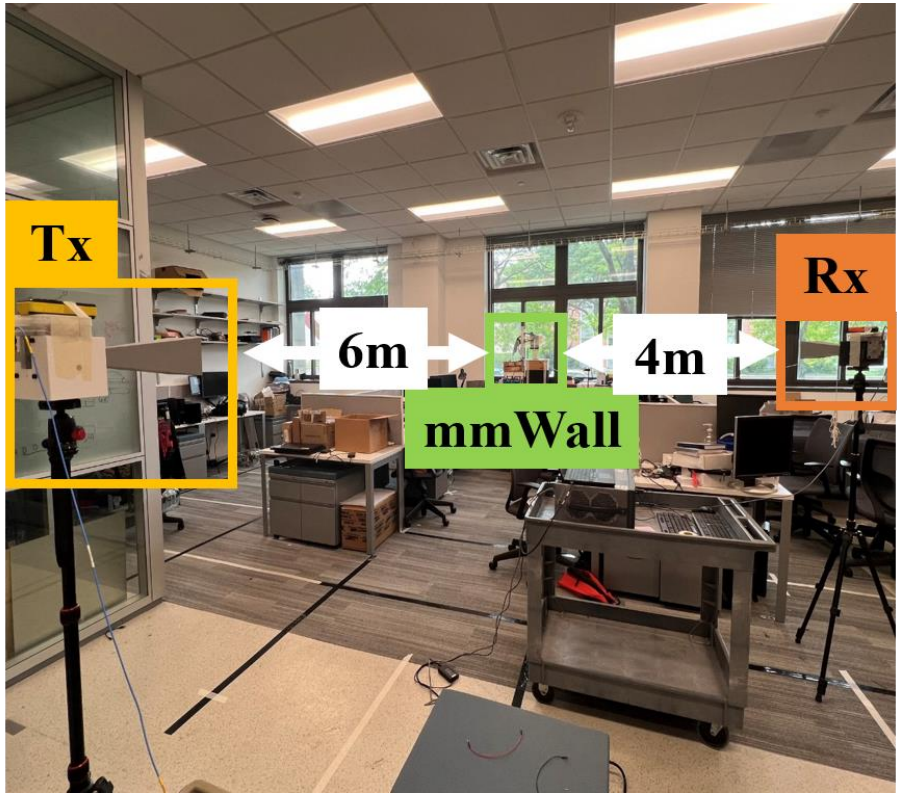
Implementation



Near-field testing



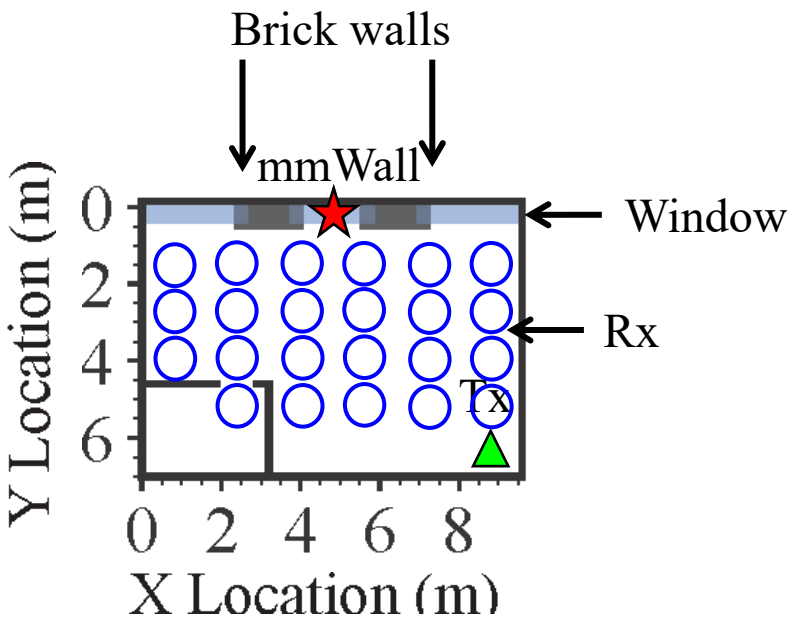
Outdoor-to-Indoor



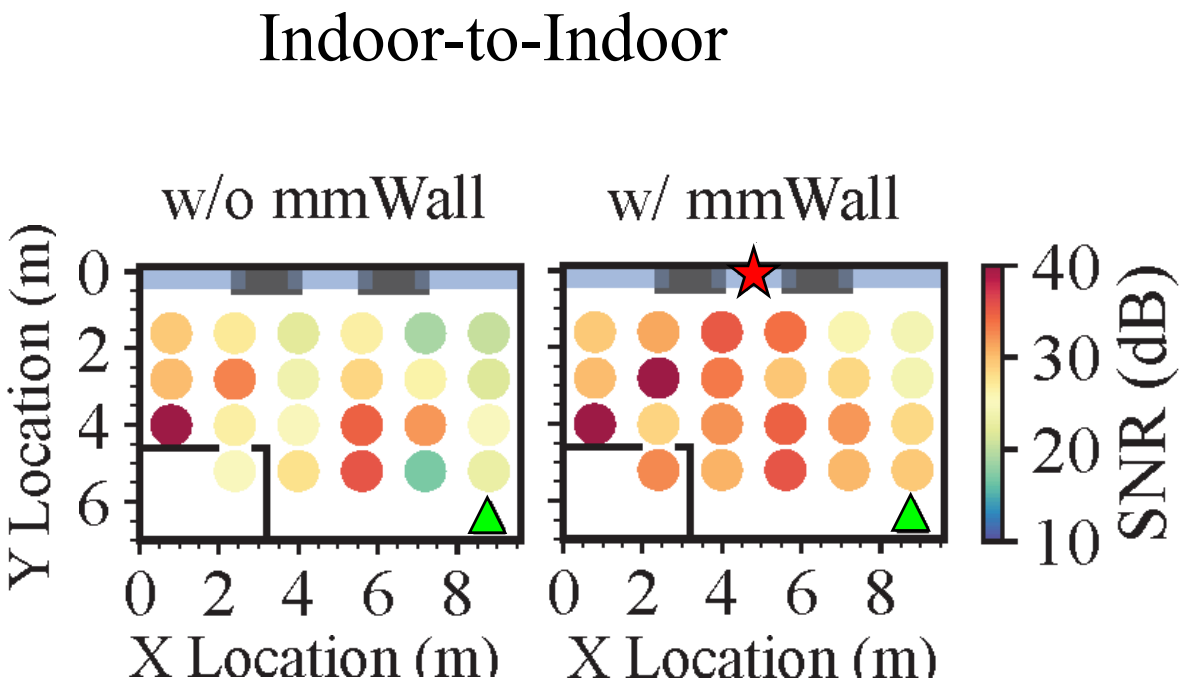
Indoor-to-Indoor

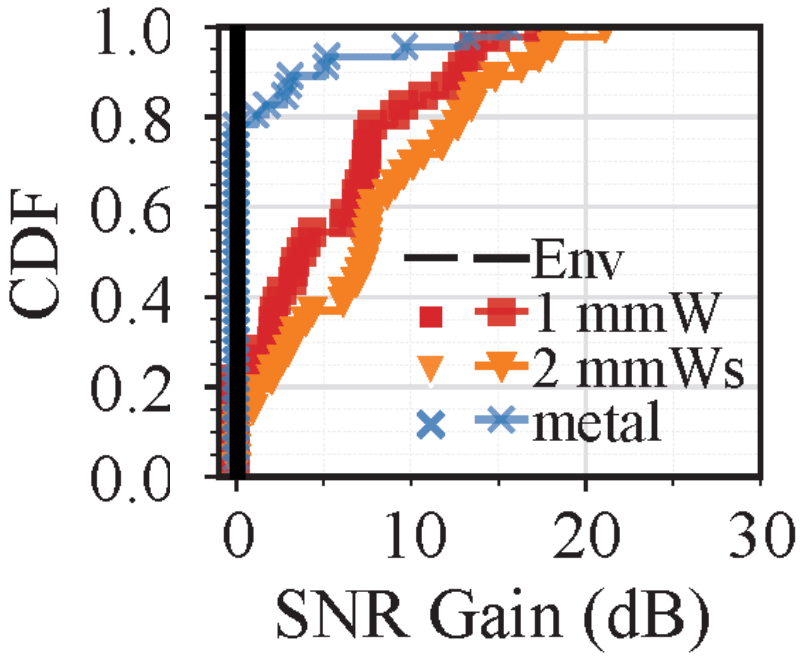
mmWall improves the corner coverage

Indoor-to-Indoor



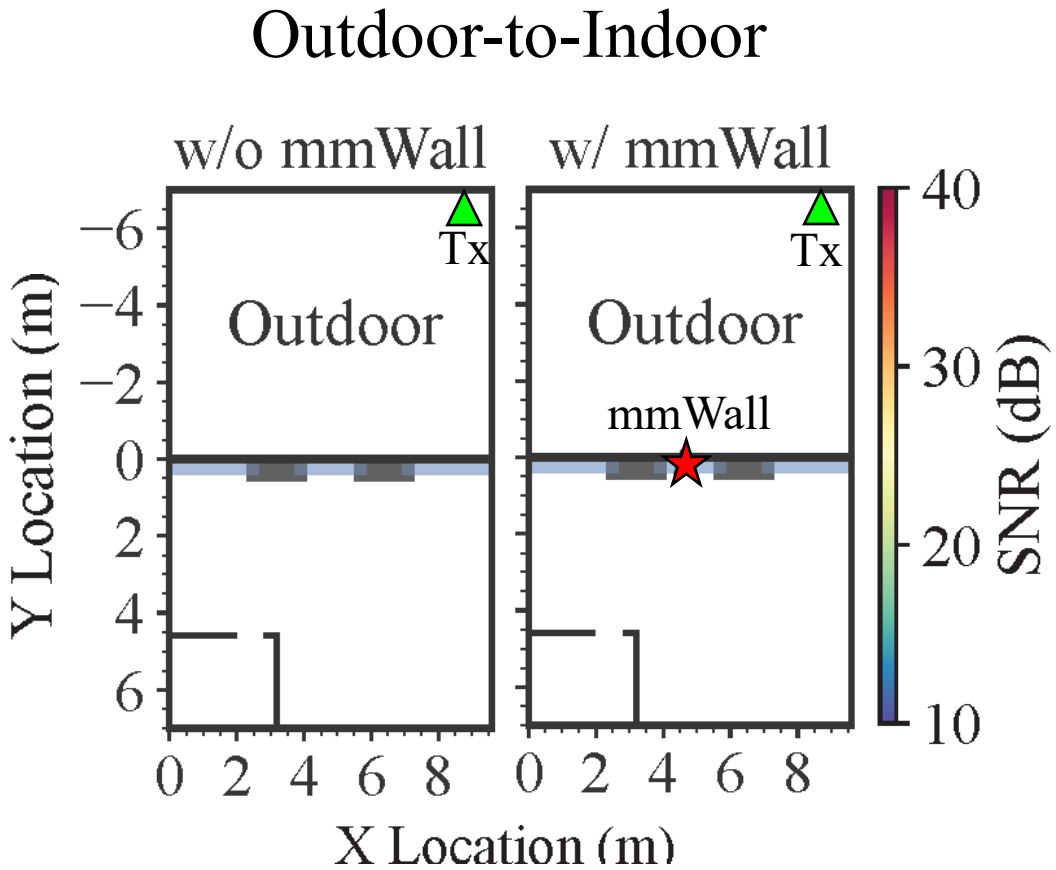
mmWall improves the corner coverage



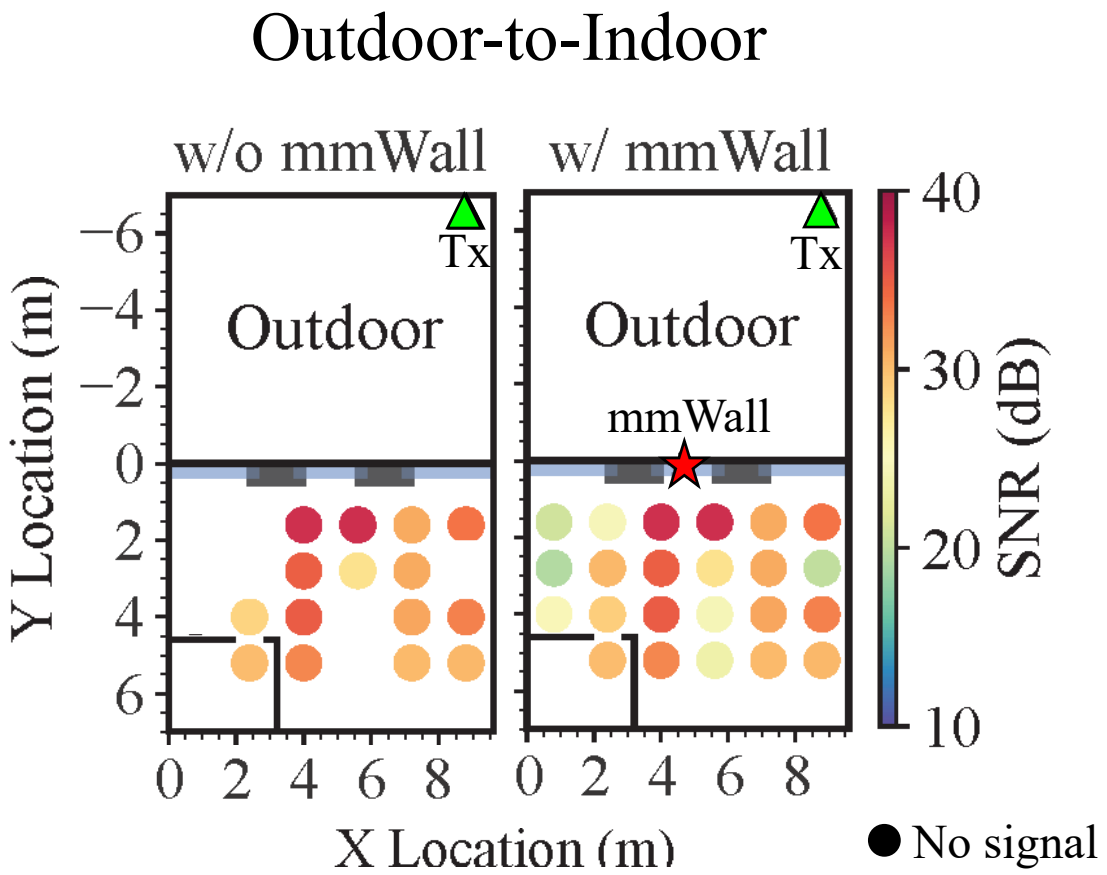


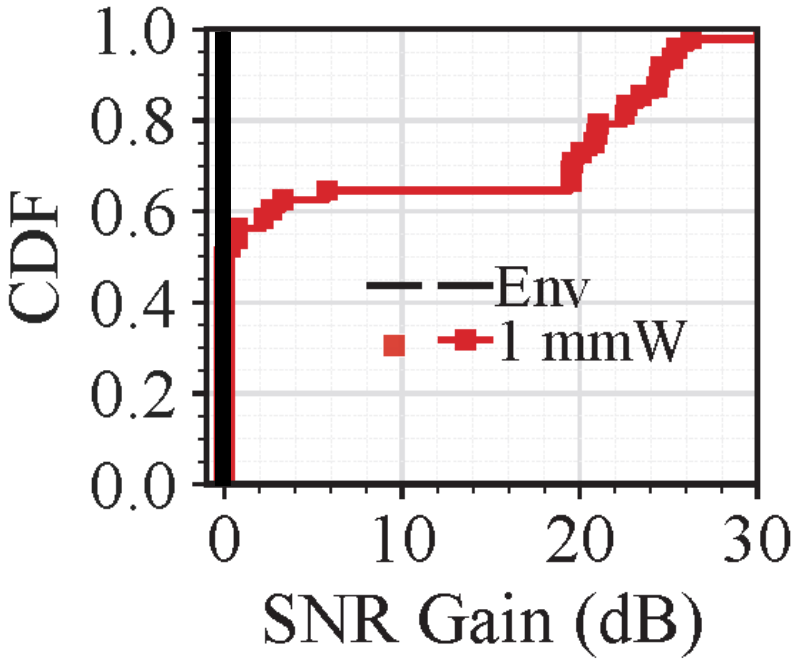
- mmWall improves room corner coverage by up to 15 dB (guarantees 24 dB across all locations).
- mmWall guarantees >90% of in locations outage-free under 128-QAM

mmWall cuts outages, improving coverage



mmWall cuts outages, improving coverage



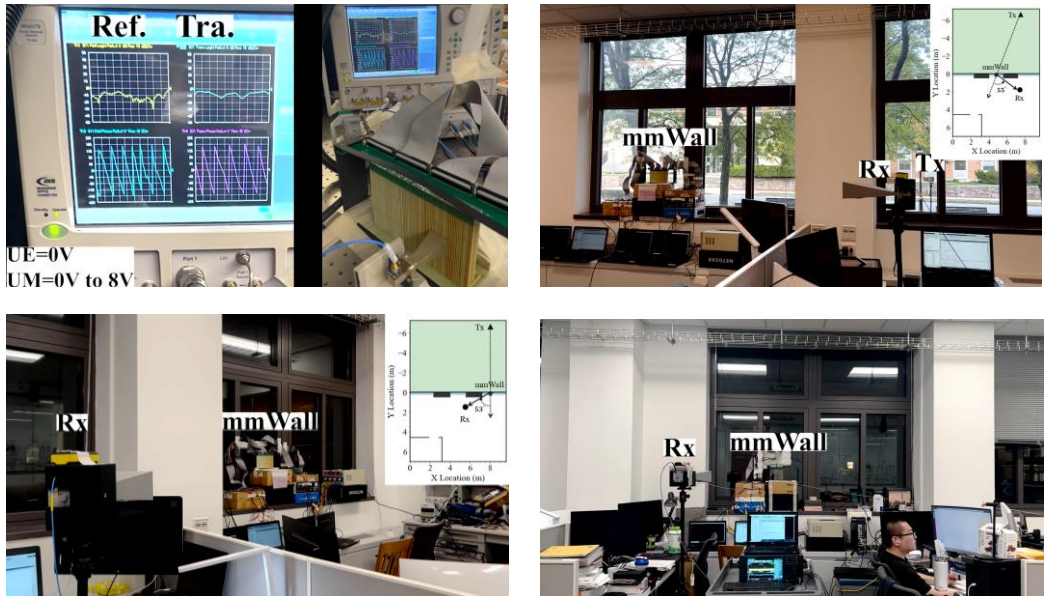


- mmWall boosts SNRs by up to 30 dB for outdoor-indoor.
- mmWall guarantees >90% of in locations outage-free under 64-QAM for outdoor-indoor.

Conclusions

- **mmWall** for NextG wireless networks
  - Out-to-in, indoors, outdoor applicability
  - Steerable, beam splitting, and frequency shifting almost 360 degrees
  - **Overcome fundamental challenges** in mmWave RF design and control
  - Thank you!

Scan me to watch the DEMOs!



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Princeton Advanced Wireless Systems Lab