nsdi '23

Acoustic Sensing and Communication Using Metasurface

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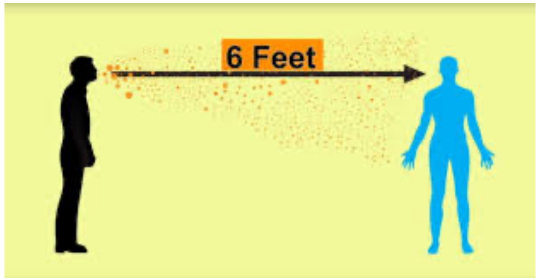
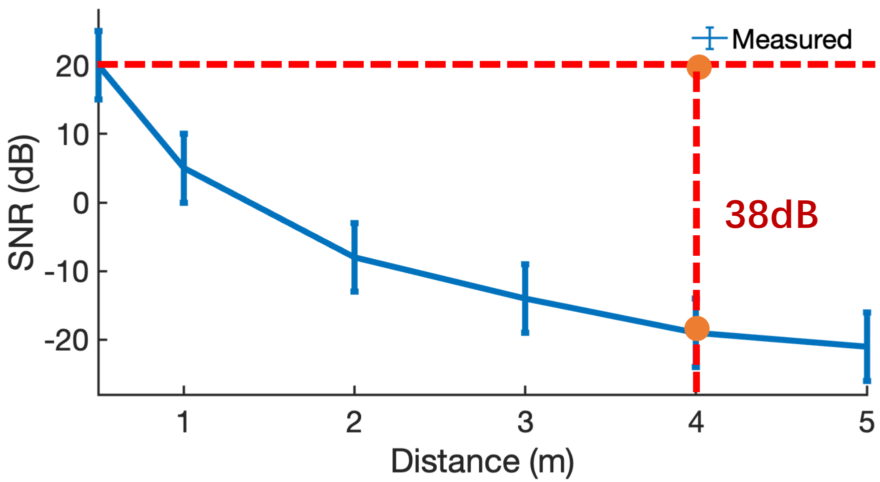
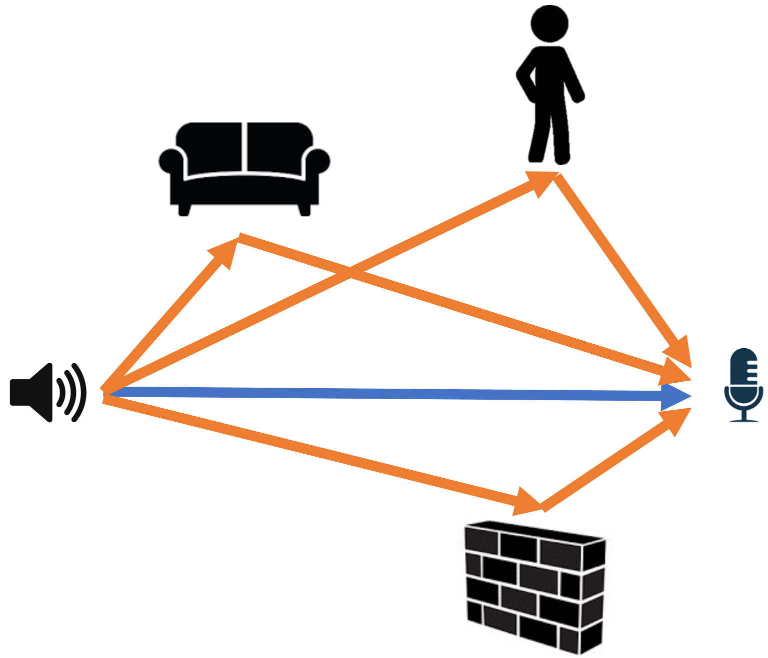
Acoustic sensing and communication are becoming pervasive



Major Challenge

Sound propagating in air attenuates rapidly and experiences multipath problems





Fast attenuation makes **SNR decay rapidly**

Multipath merging peaks introduces **tracking error**

Conventional Solution: Receiver Side

Current algorithms:

- Filtering
- Beamforming
- Deep learning
- …

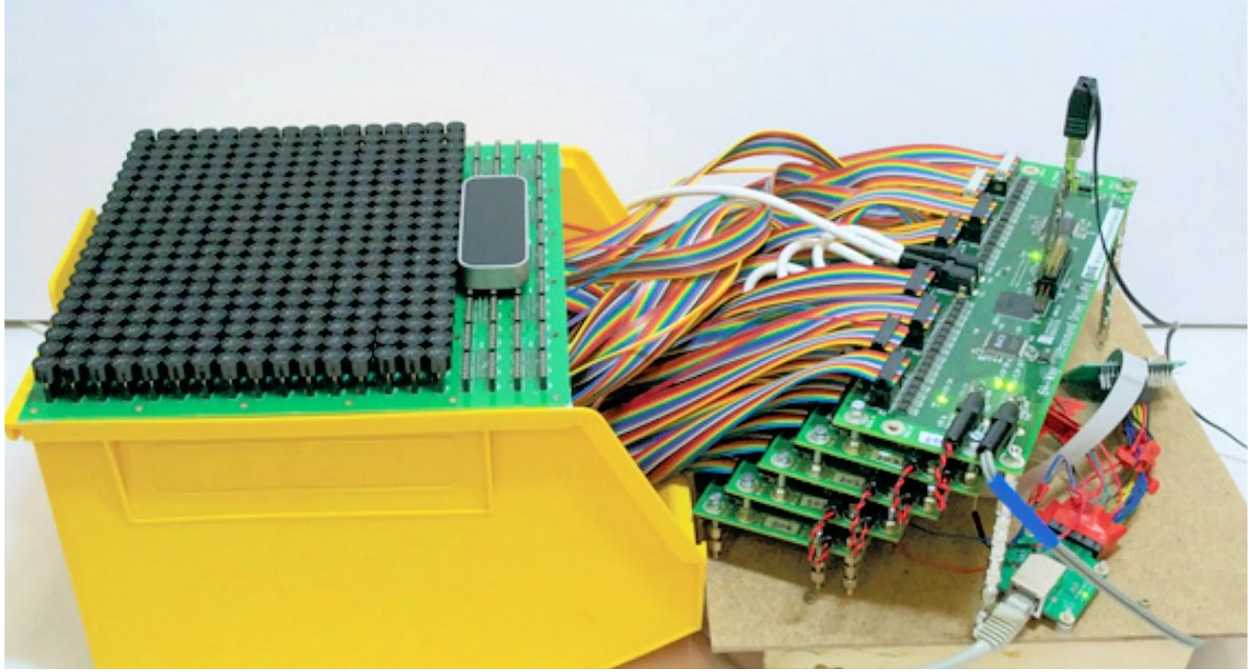
However,

Cramer-Rao Bound (CRB) – the sensing resolution is limited by SNR and the number of transmitters and receivers.

The improvement using algorithms is limited!

Conventional Solution: Transmitter Side

Using **speaker array** to beamform the acoustic signal



Bulky! Expensive! Power hungry!

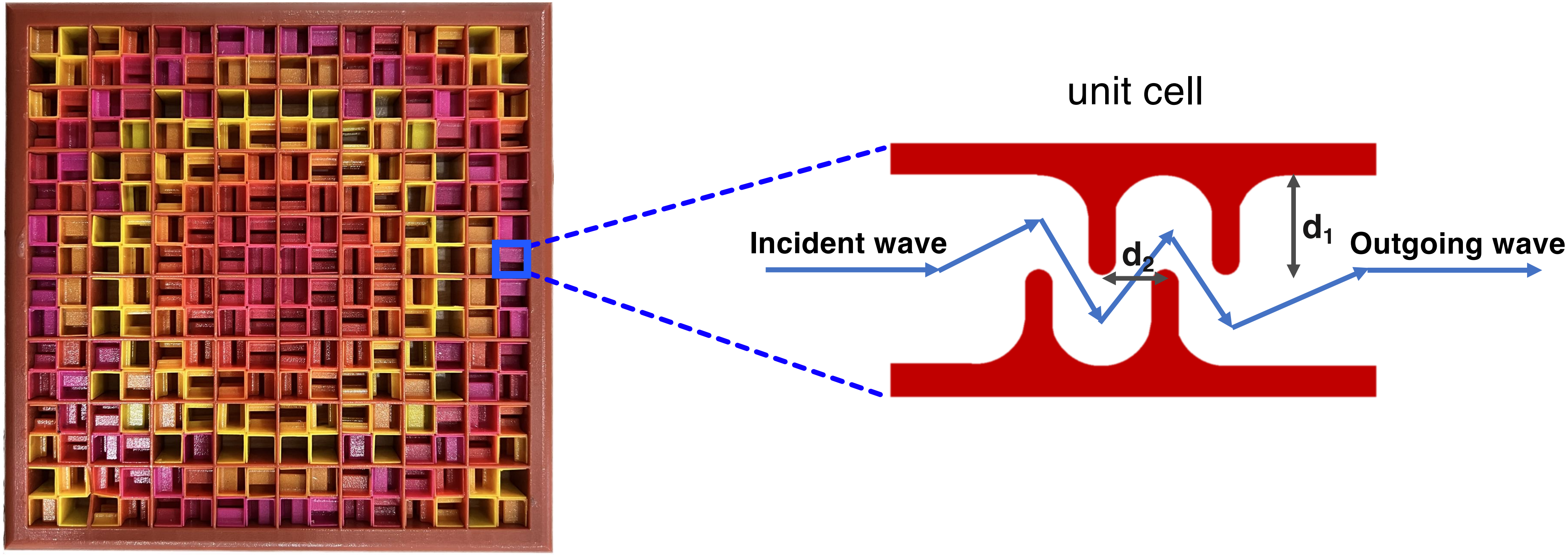
Potential Solution

How solve these problems?

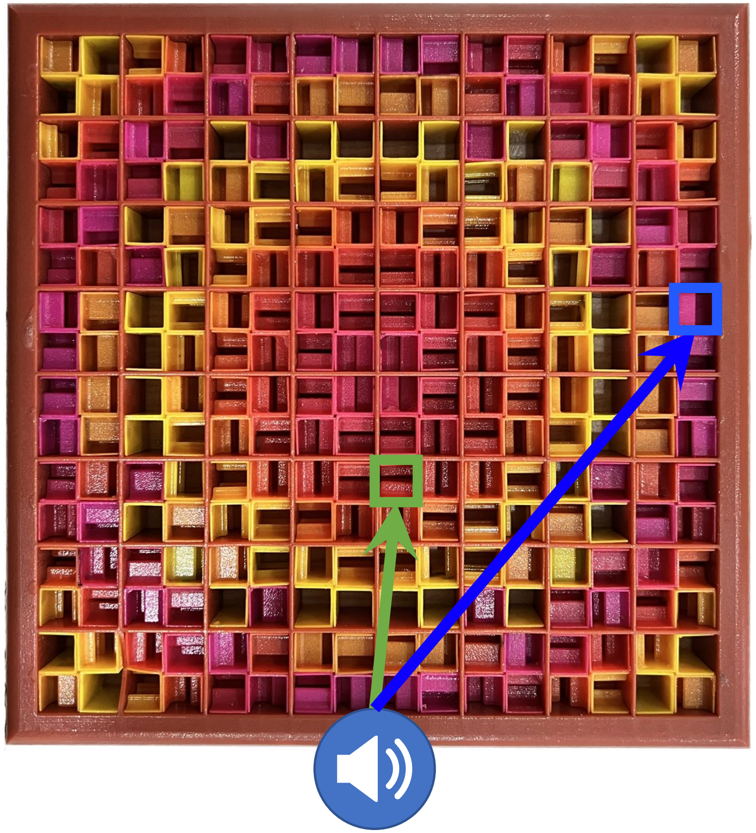
Using **passive acoustic metasurface** to enhance transmission channel!

Acoustic Metasurface

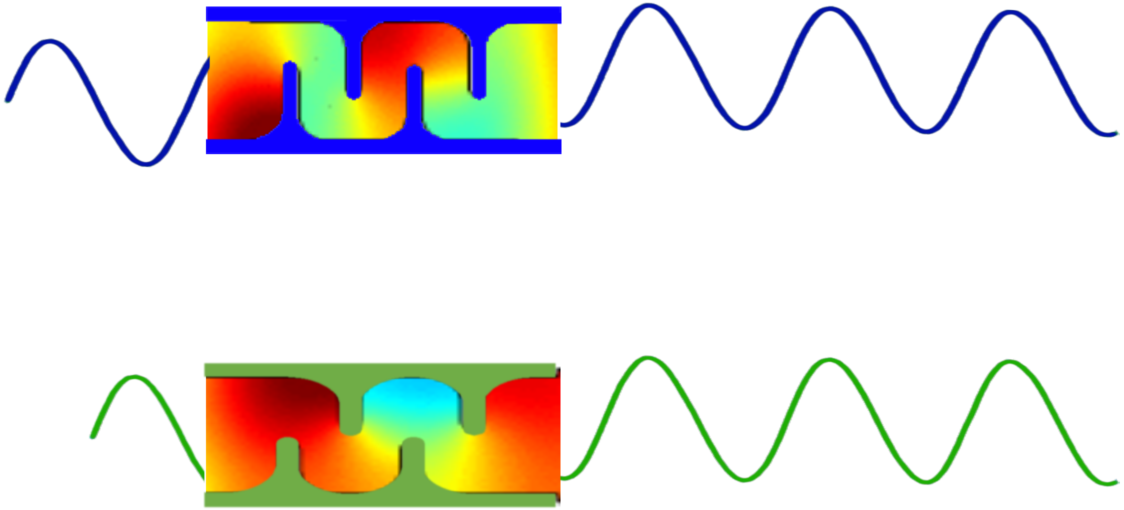
Front view of a 16x16 metasurface



Acoustic Metasurface



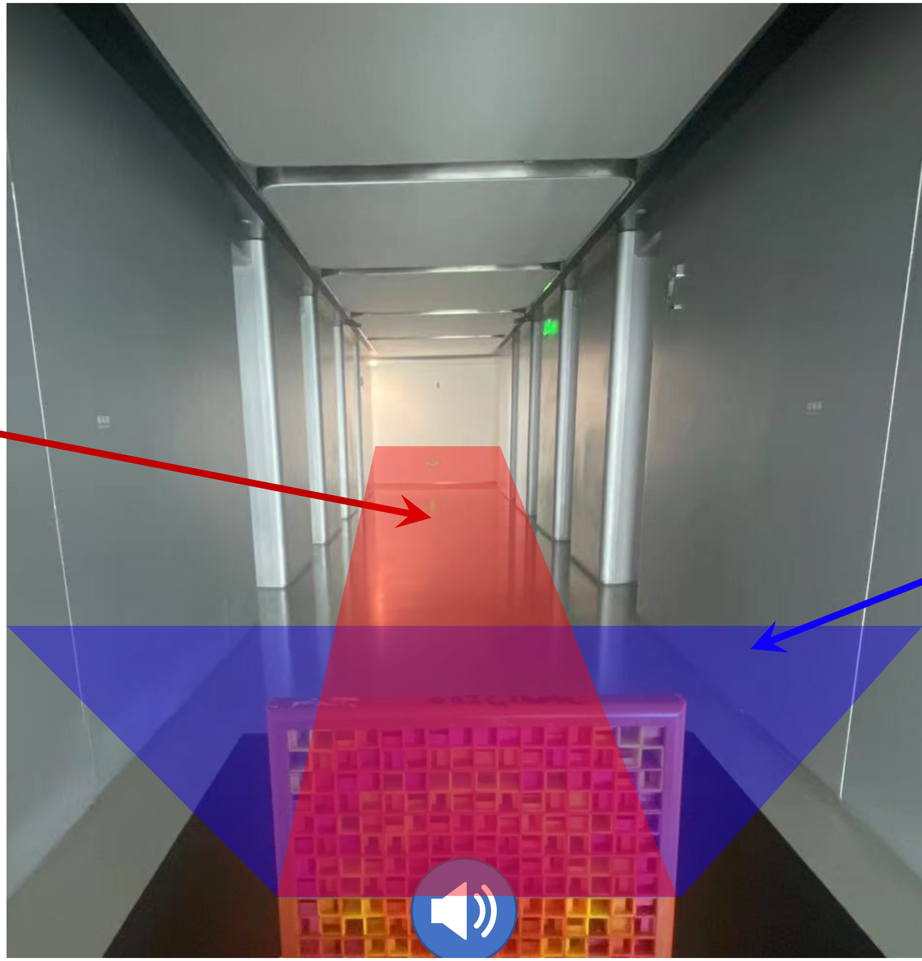
Introduce different **phase delay**



Acoustic Metasurface

By **designing cells**, metasurface can act as **phased array**!

w/ metasurface



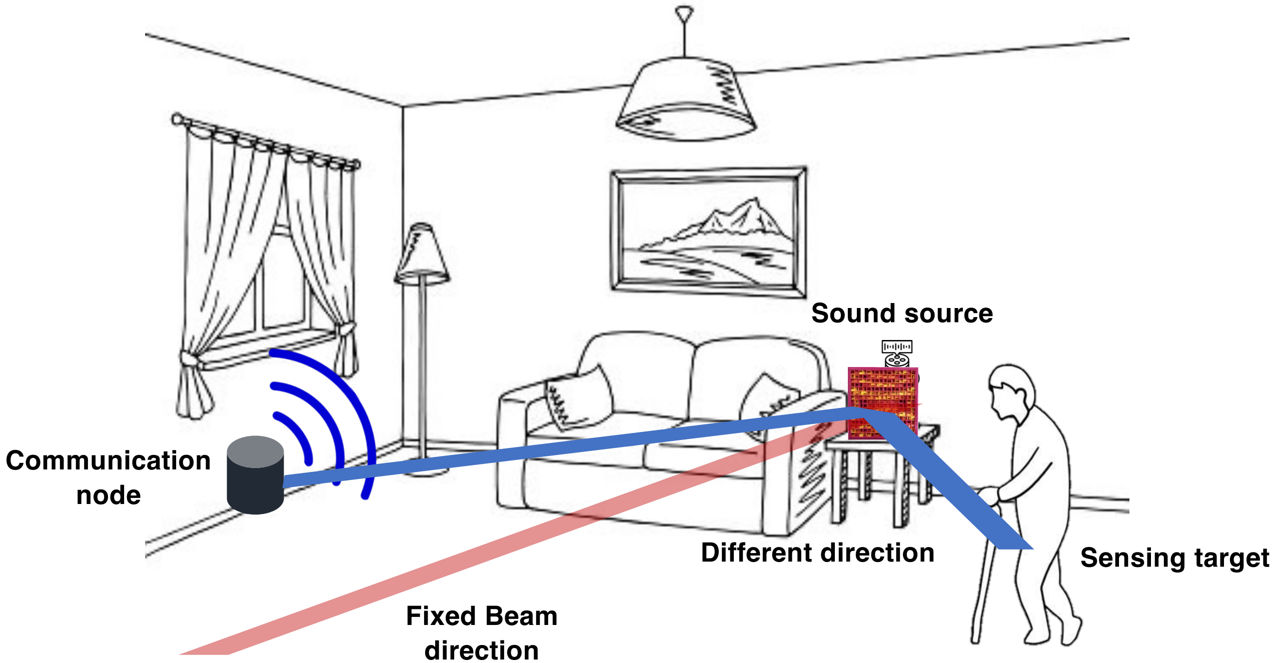
w/o metasurface

Acoustic Metasurface Pros & Cons

Pros:
- Much cheaper: 3D printed (≤10$)
- No power supply
- Compact
- Significant power gain

Cons:
- Fixed beam direction

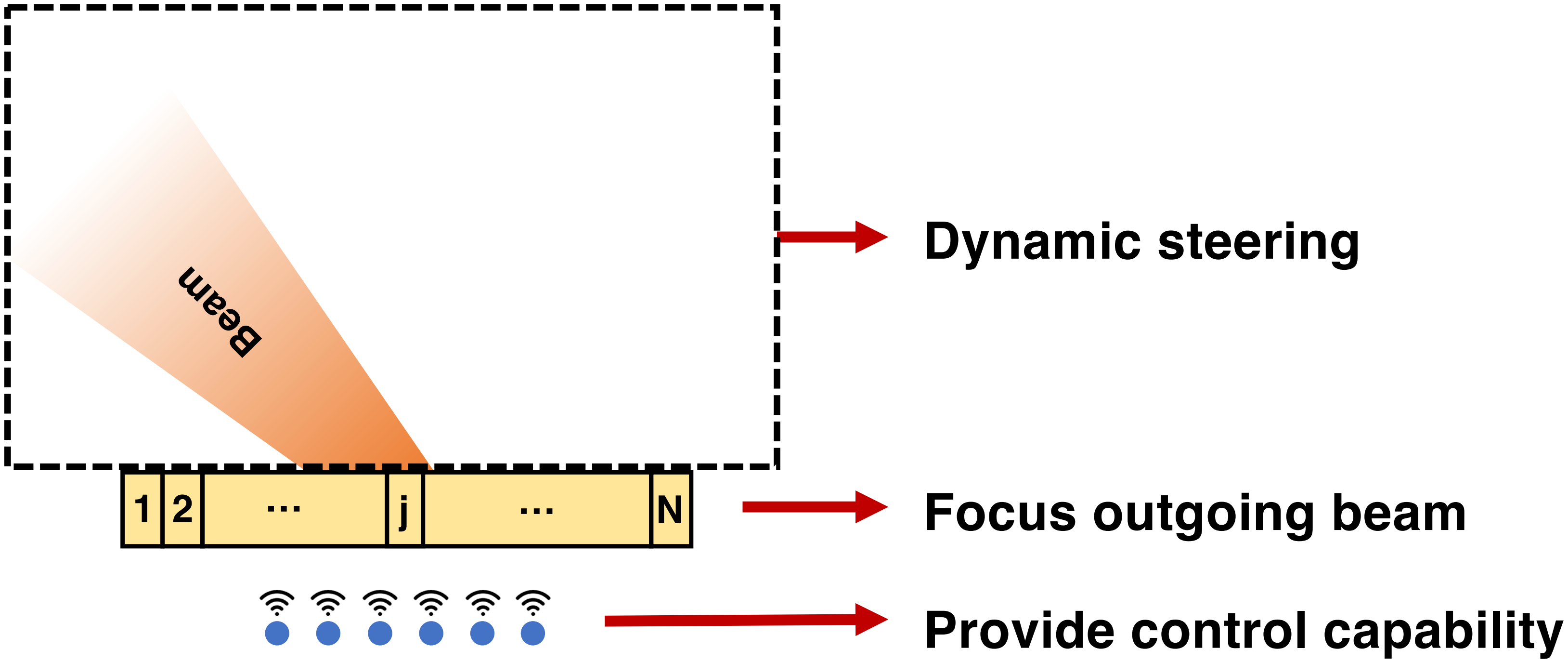
Adaptation in Sensing and Communication



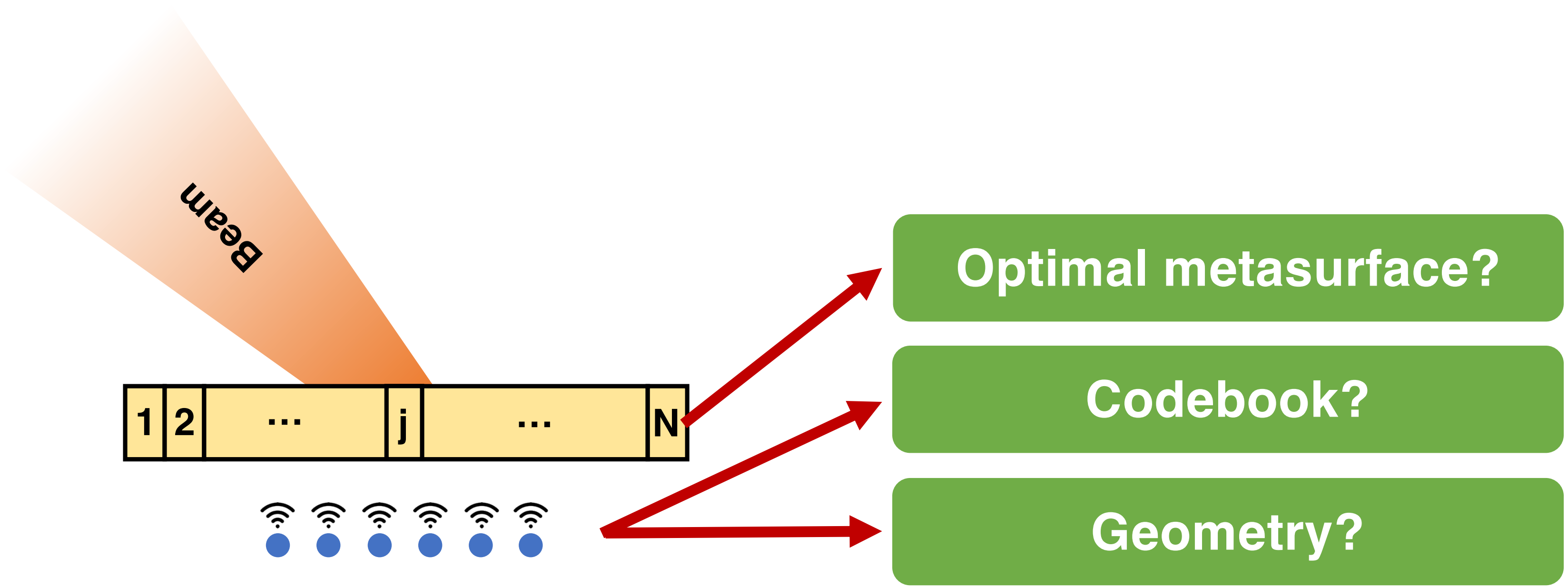
How to get adaptive steering for sensing and communication?

Our Proposed Model

a small phased array + a passive metasurface



Proposed Model

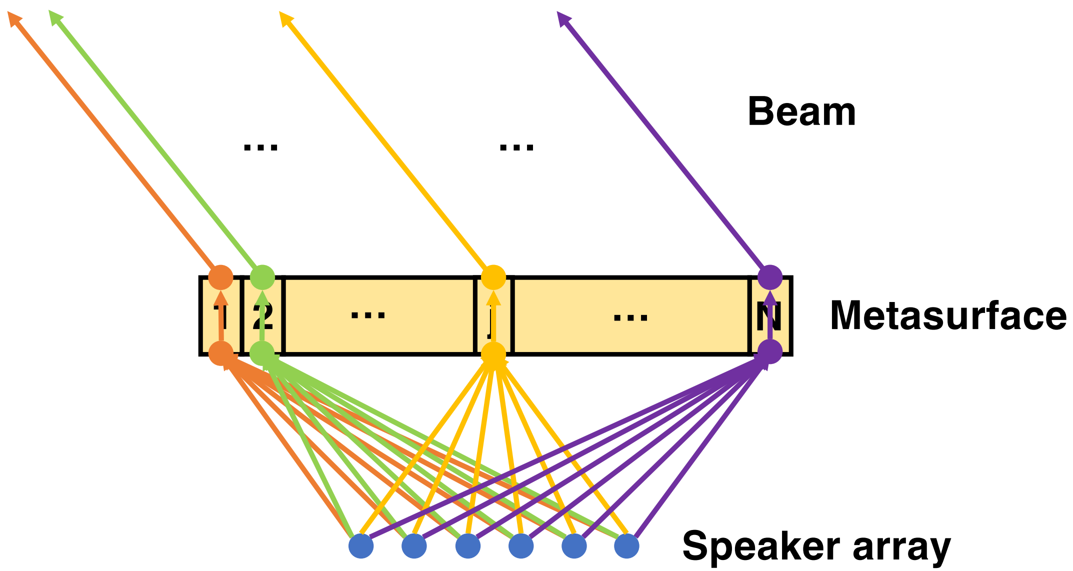


How to jointly design **metasurface** and **phased array codeword**?

Perform **Joint optimization** to effectively manage the interdependence

System Model

- Model the propagation of sound in air

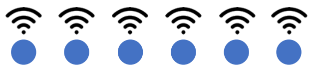


System Model

- Model the propagation of sound in air

codebook of speakers

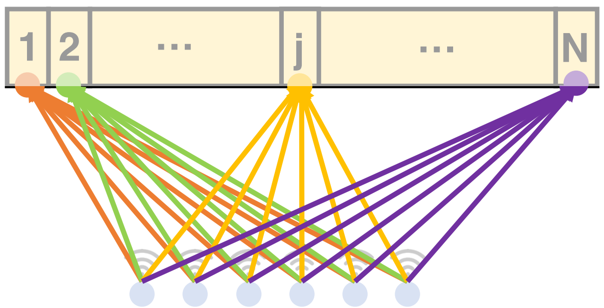
w



Speaker array

System Model

- Model the propagation of sound in air

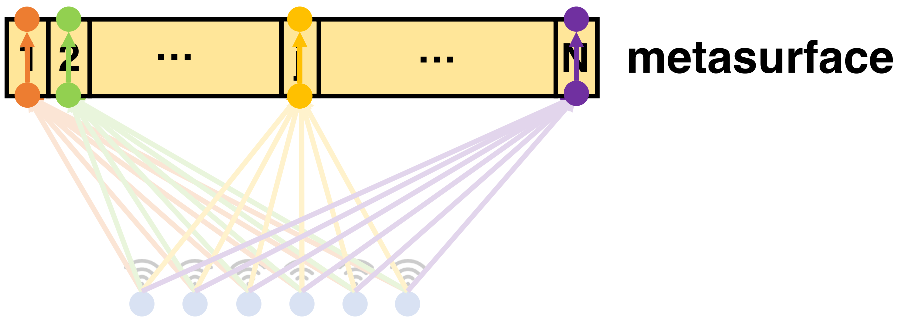


channel

$H(x)w$

System Model

- Model the propagation of sound in air

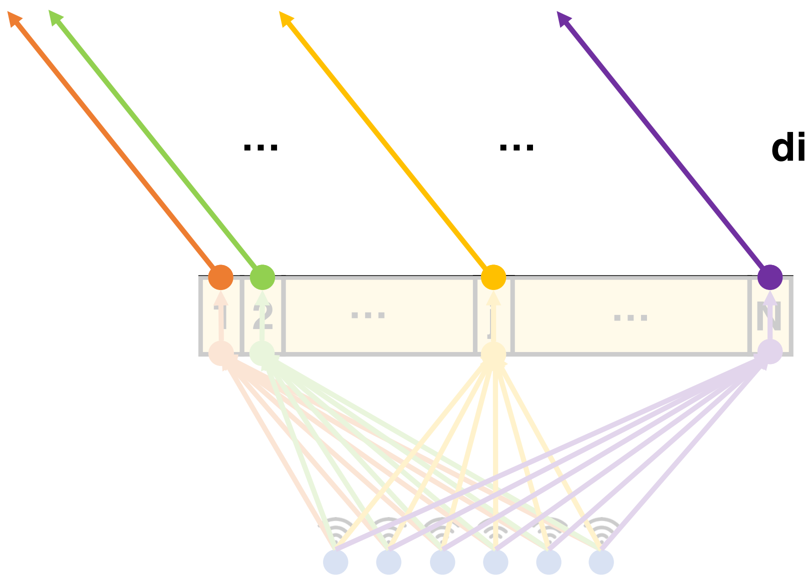


metasurface

$$\color{red}{G}H(x)w$$

System Model

- Model the propagation of sound in air

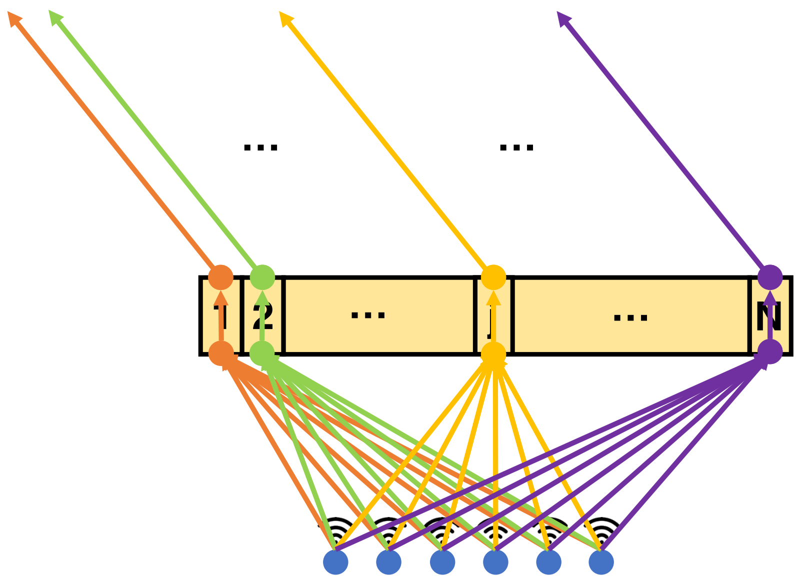


steering vector

$$K_d GH(x)w$$

System Model

- Model the propagation of sound in air

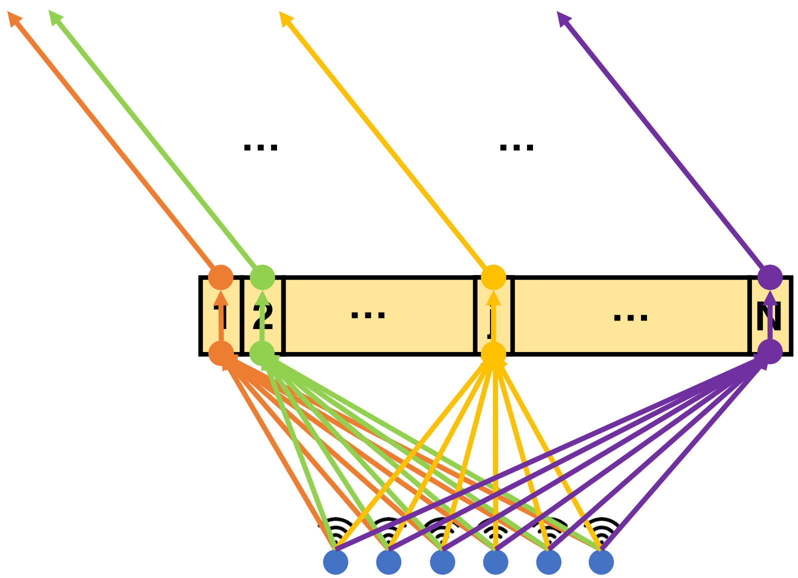


received signal at *d*

$$R_d = K_d G H(x) w$$

System Model

- Model the propagation of sound in air



received signal at *d*

$$R_d = K_d G H(x) w$$

Signals of all directions:

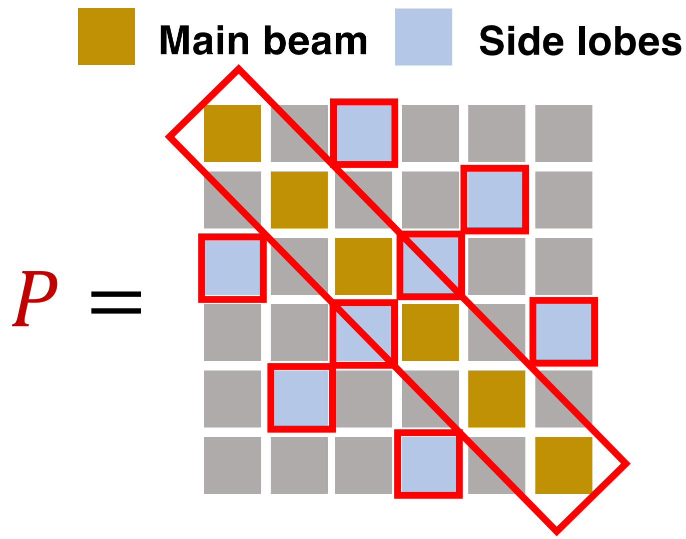
$$R = \color{red}{K} G H(x) \color{red}{W}$$

Sound power:

$$P = |R|^2$$

System Model

$$P = |R|^2$$



Optimize P with objective:

$$\min_{W,\Theta,x} -L_{power} + \mu L_{var} + \gamma L_{sidelobe}$$

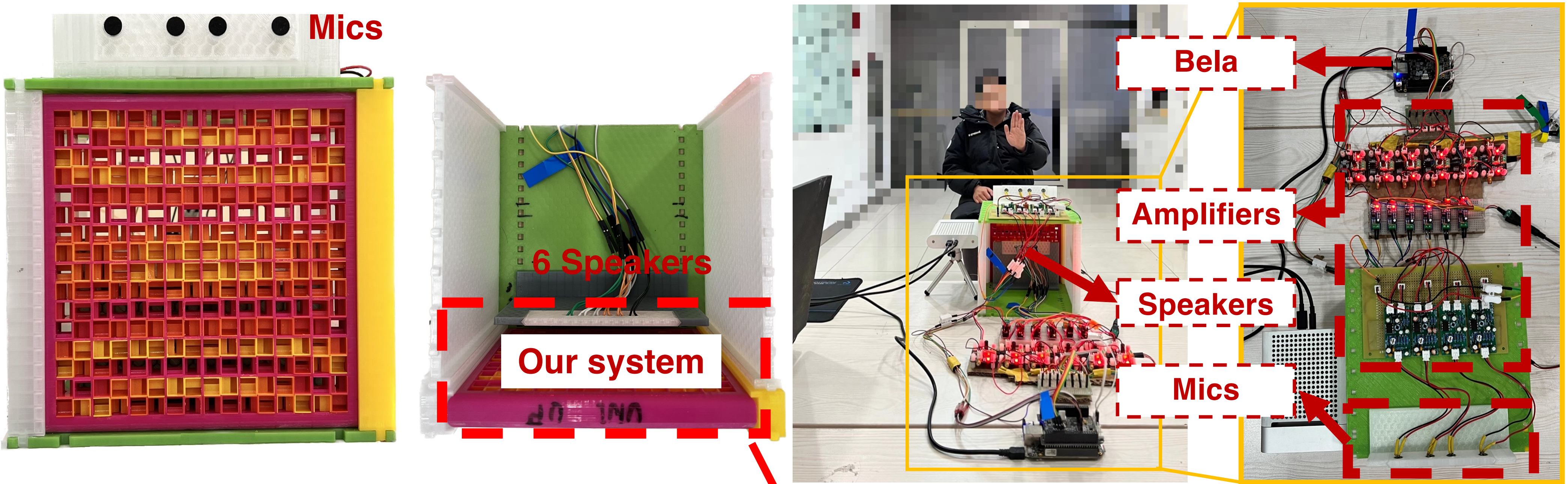
$$s.t. \begin{cases} |\Theta_i| = 1, (i = 1, 2, \dots N) \\ |W_{ij}| \le 1 \ (i = 1,2, \dots M, j = 1,2, \dots, d) \end{cases}$$

L_{power} overall power of all directions

L_{var} power variance of directions

$L_{sidelobe}$ sidelobe power

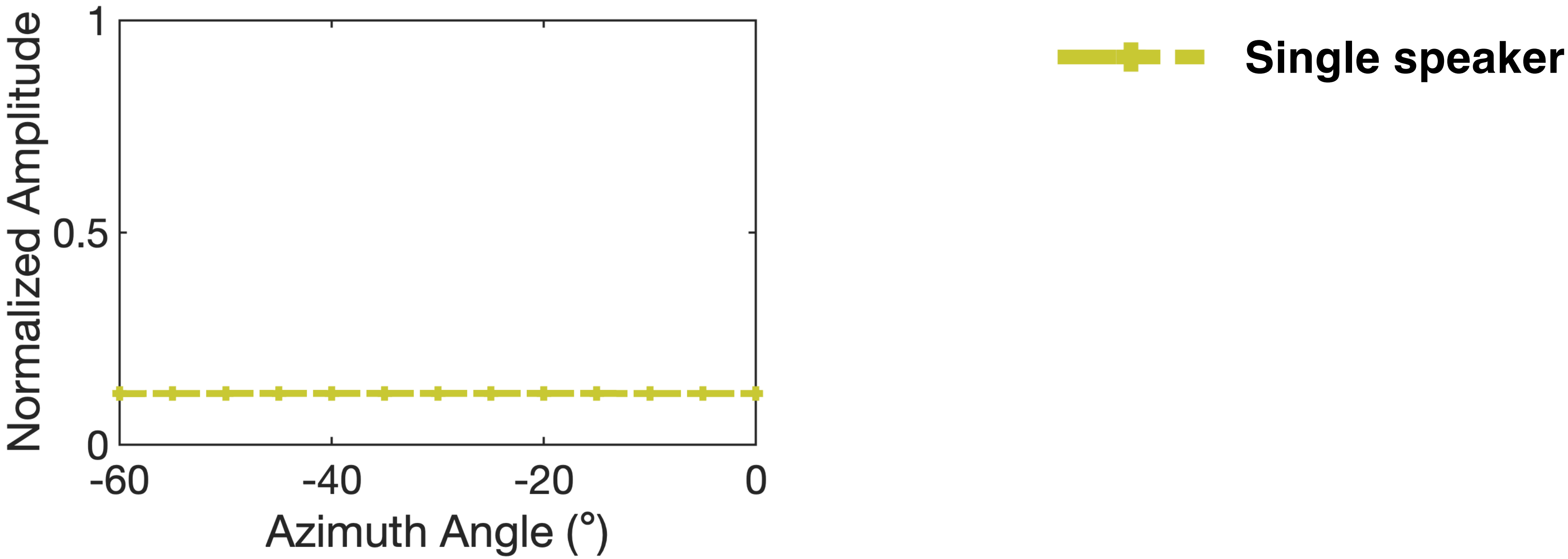
Prototype



(a) Front View (b) Inside View (c) Experiment setup

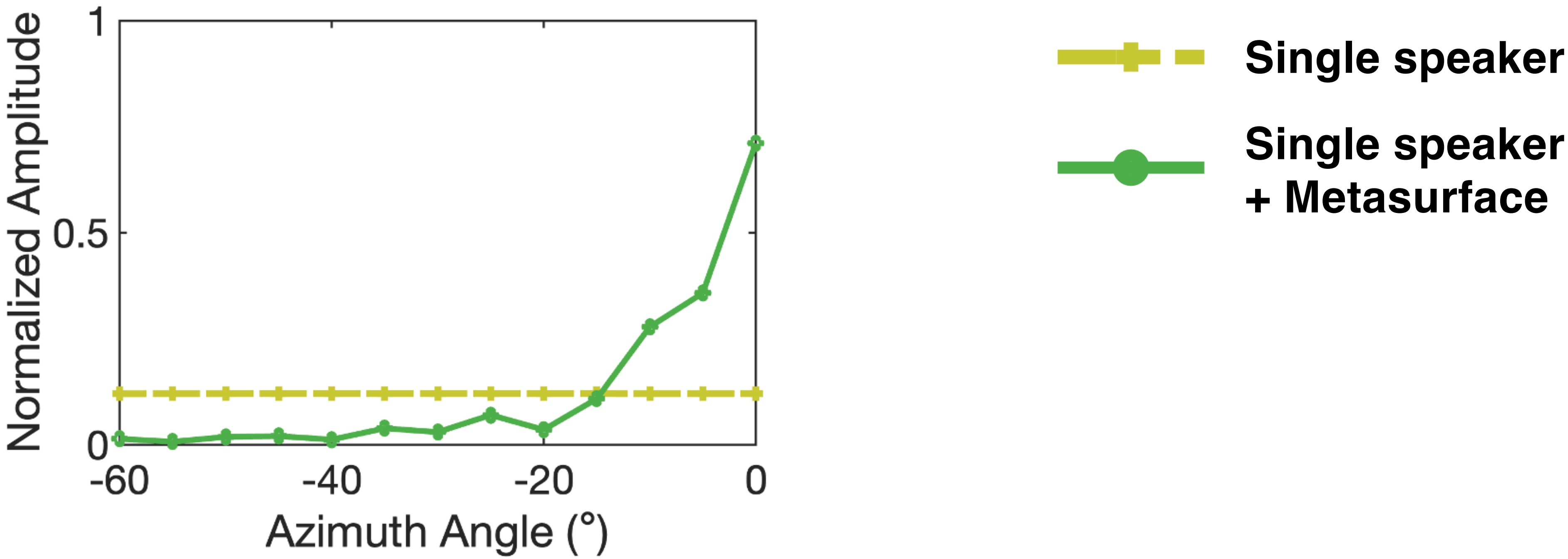
a small phased array + a passive metasurface

Evaluation: SNR Comparison



Power Gain At Different Steering Angles

Evaluation: SNR Comparison



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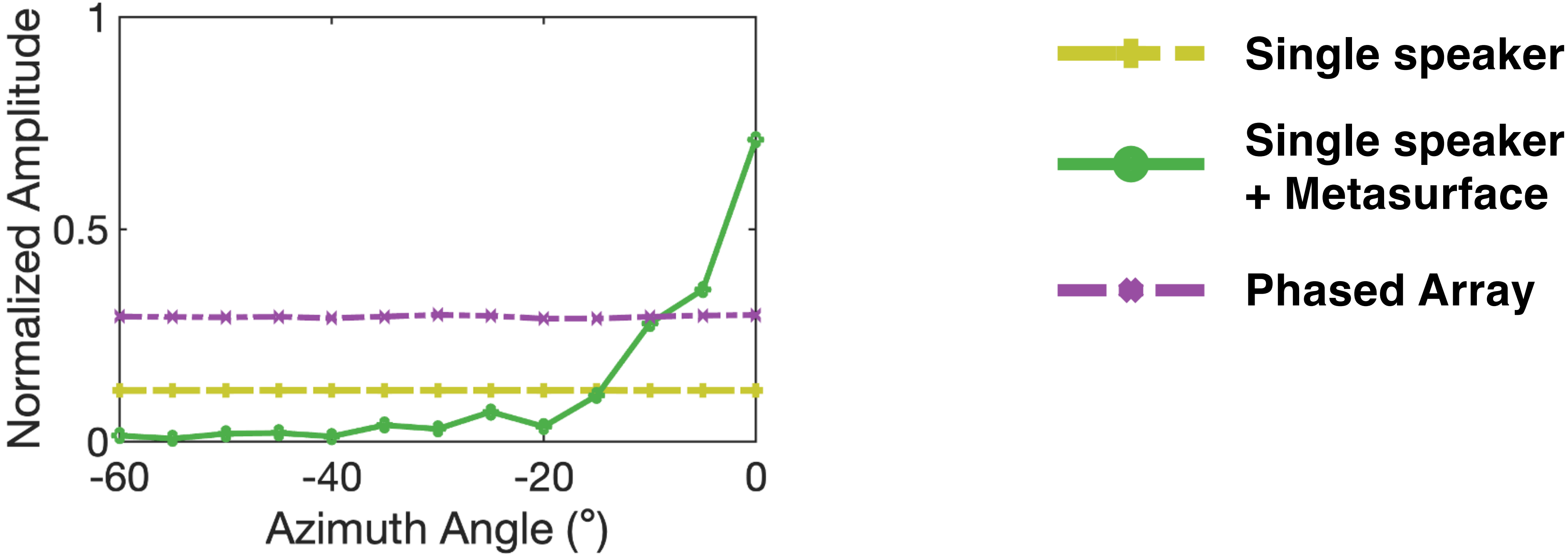
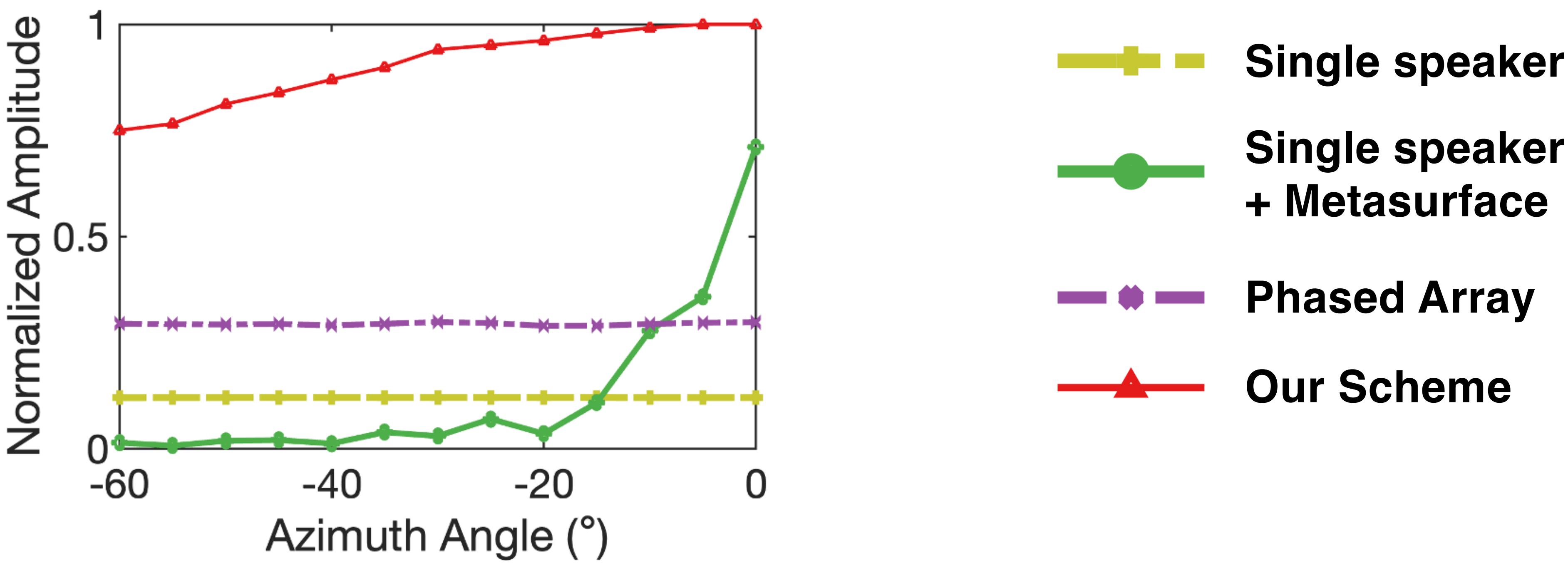
Evaluation: SNR Comparison



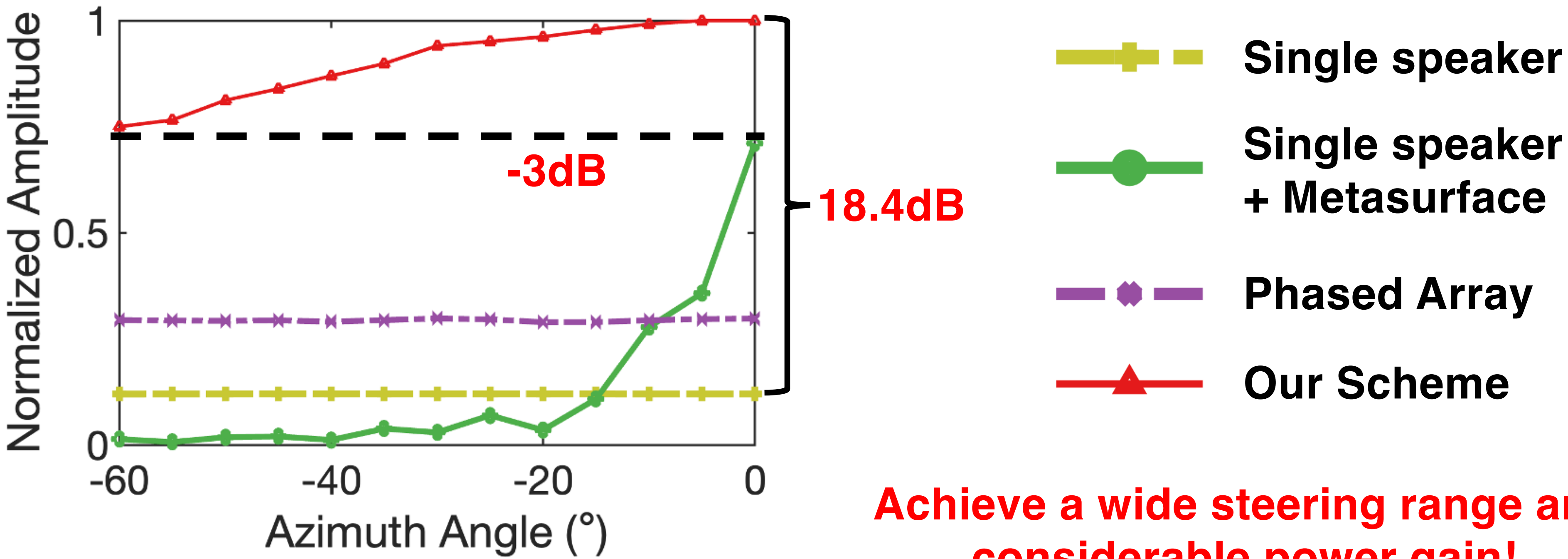
Power Gain At Different Steering Angles

Evaluation: SNR Comparison



Power Gain At Different Steering Angles

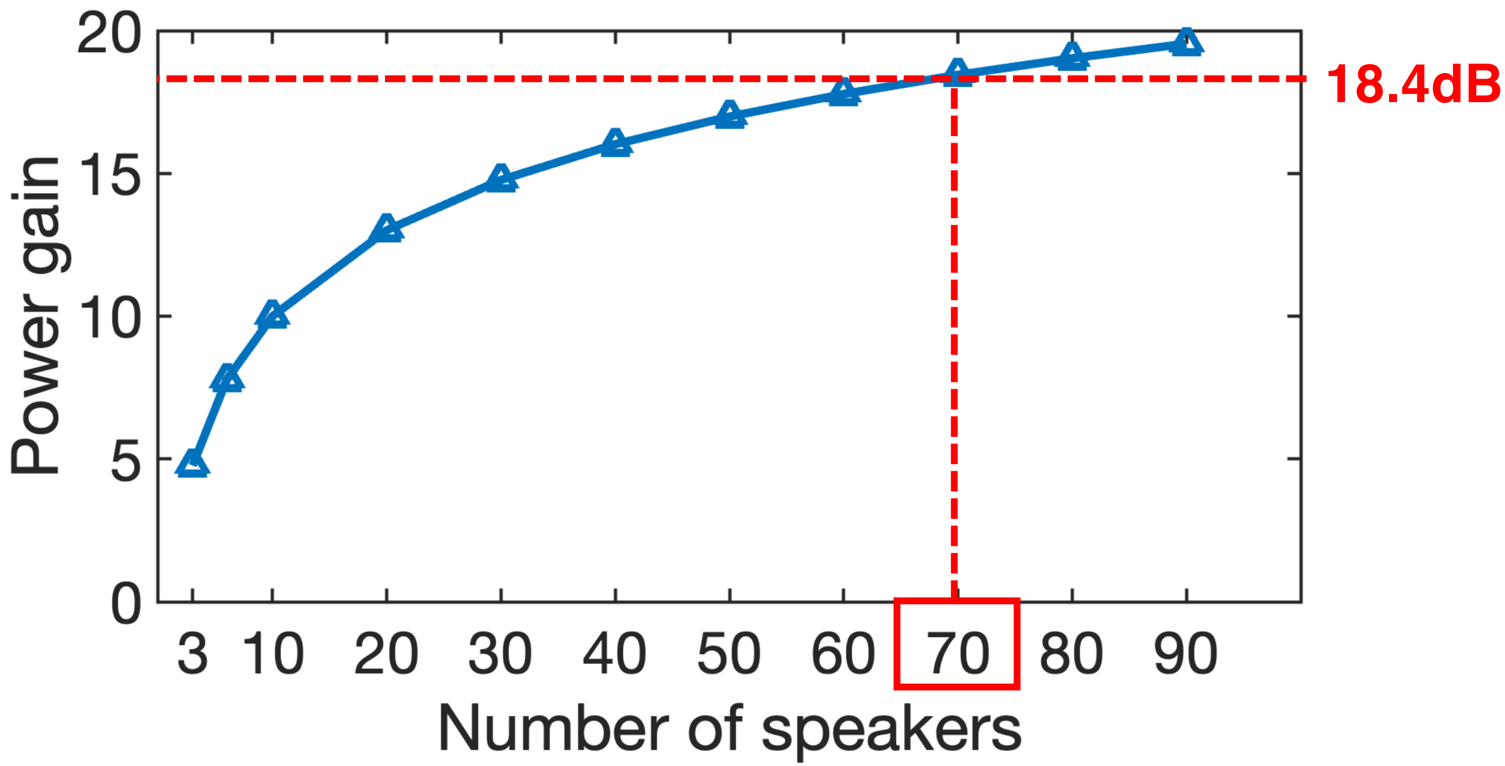
Evaluation: SNR Comparison



Power Gain At Different Steering Angles

Achieve a wide steering range and considerable power gain!

Evaluation: SNR Comparison

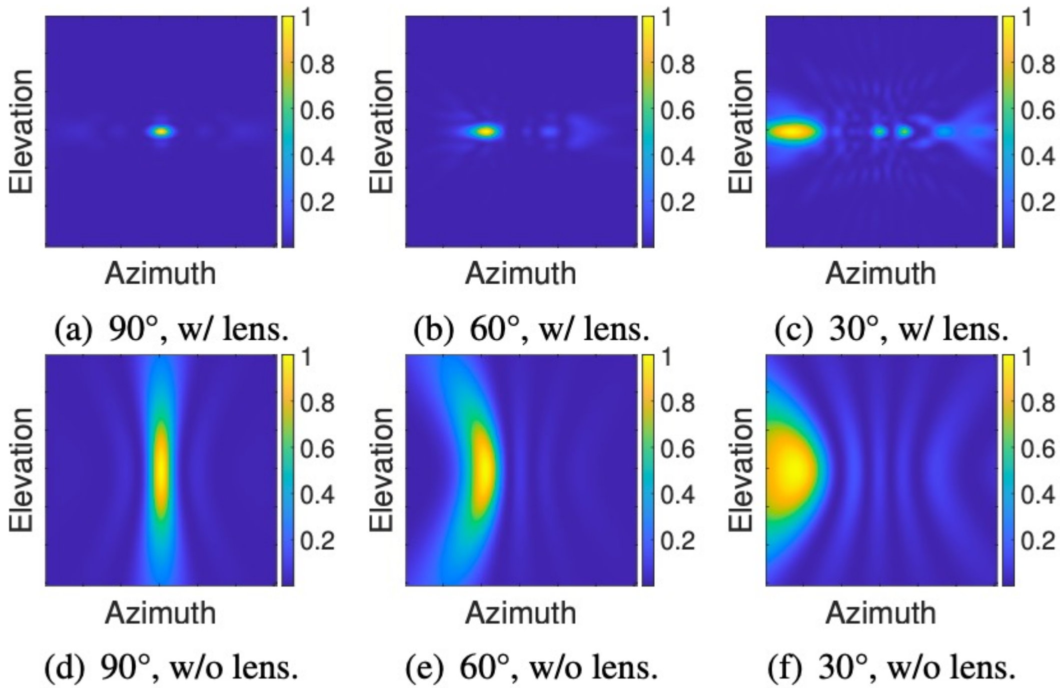


Comparable to 70 speakers in terms of power gain!

Evaluation: SNR Comparison

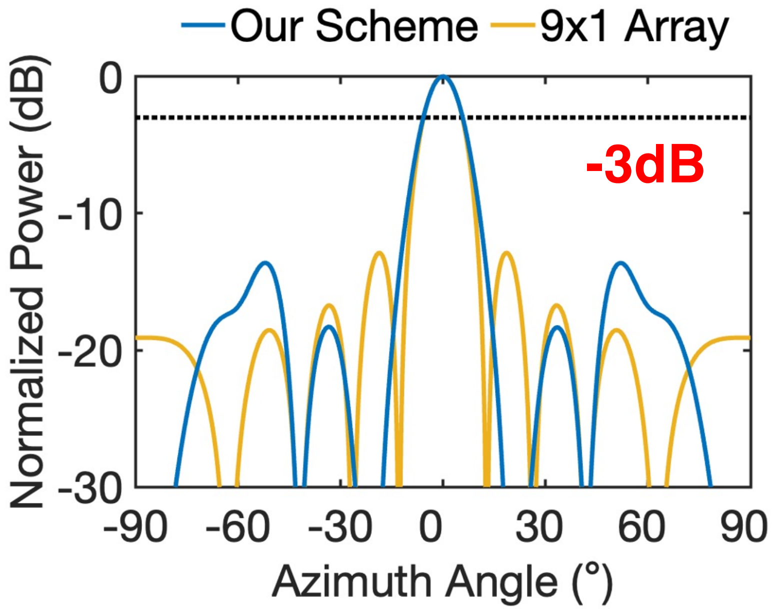
Our Scheme

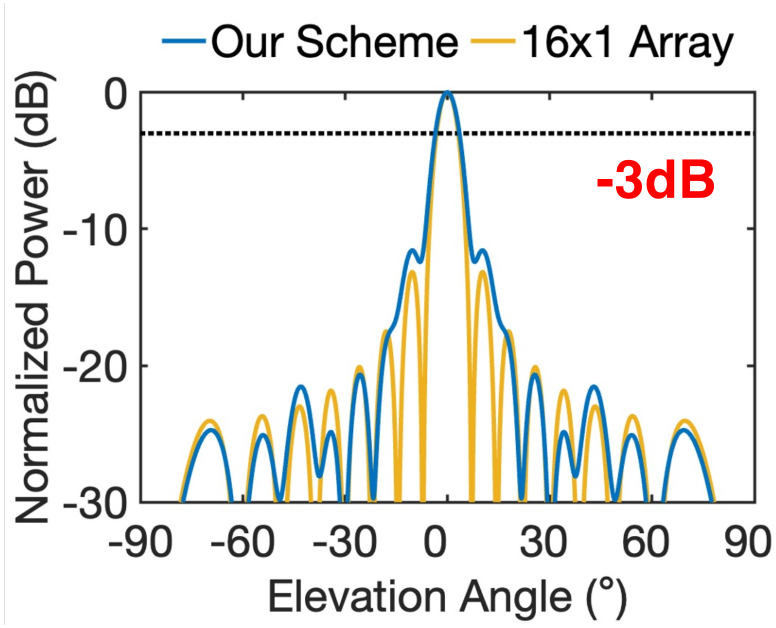
Phased Array



Focus beam in both azimuth and elevation!

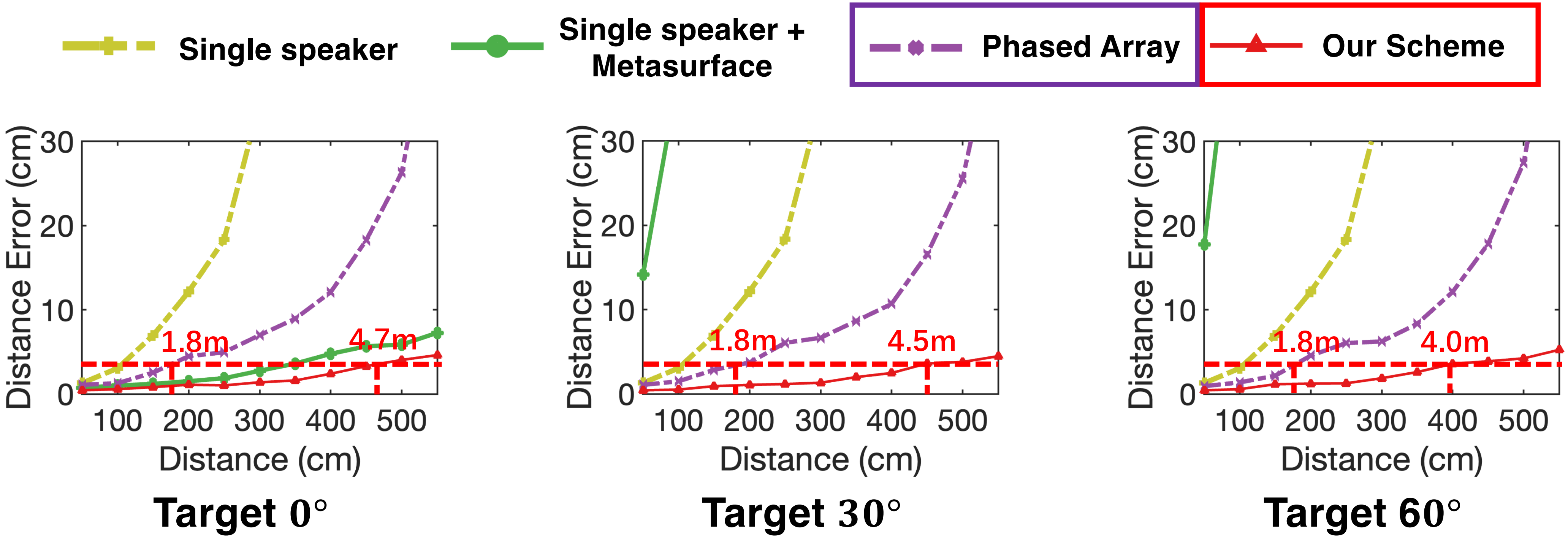
Evaluation: SNR Comparison





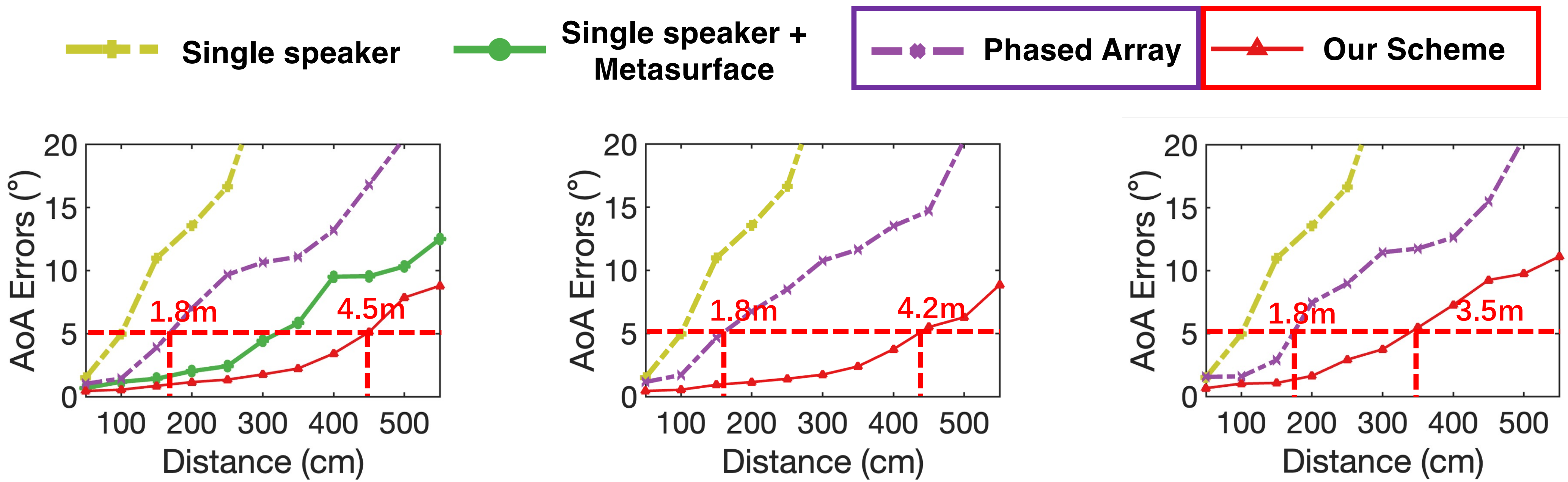
Comparable to 9×16 phased array in terms of beamwidth!

Evaluation: Sensing Performance (Distance Estimation)



Increase sensing range to 2.2x ~ 2.6x

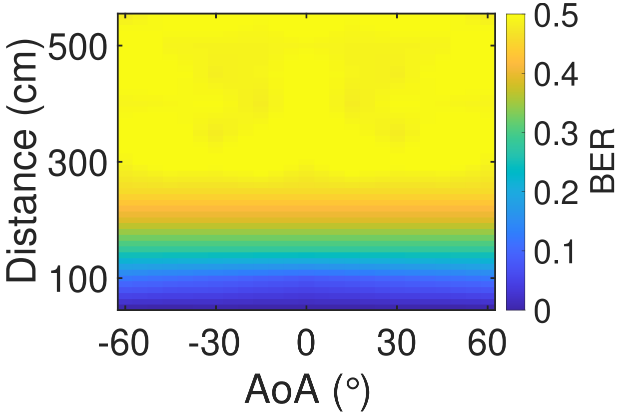
Evaluation: Sensing Performance (AoA Estimation)



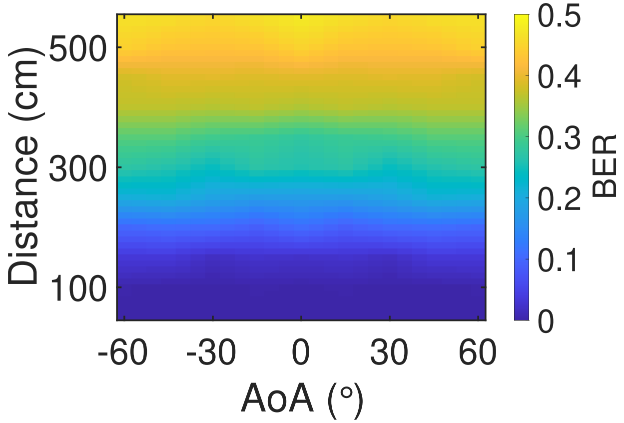
Target 0° **Target 30°** **Target 60°**

Increase sensing range to 1.9x ~ 2.5x

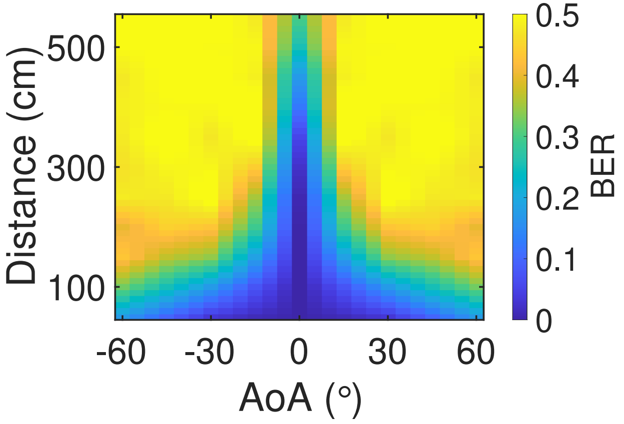
Evaluation: Communication Performance (BER)



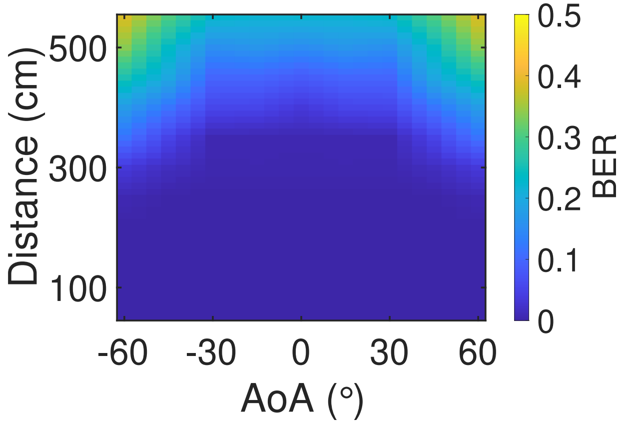
Single speaker



Phased Array

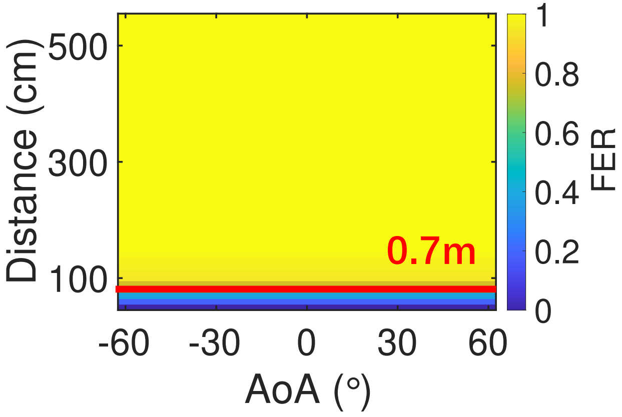


Single speaker + Metasurface

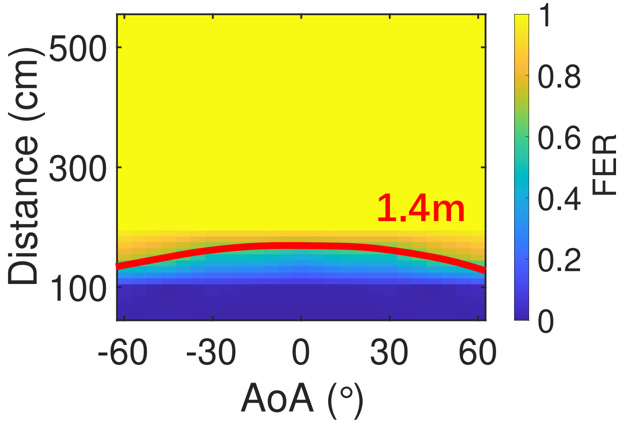


Our Scheme

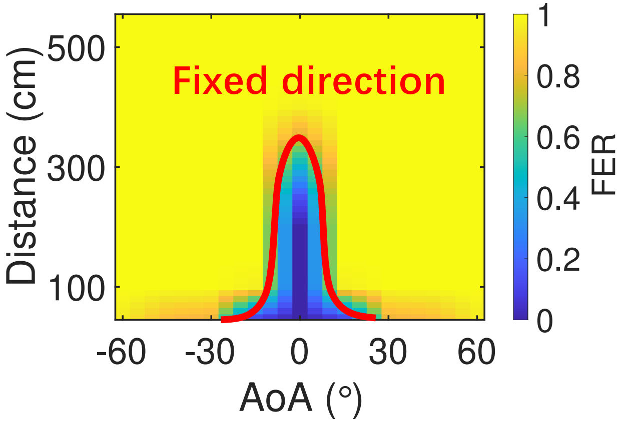
Evaluation: Communication Performance (FER)



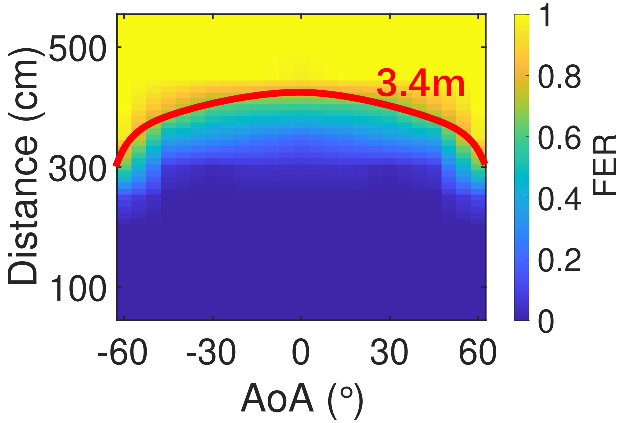
Single speaker



Phased Array



Single speaker + Metasurface



Our Scheme

Increase average communication range to 2.4x

Conclusion

- A small phased array + a passive metasurface
  - achieves a large phased array at low cost
- A joint optimization algorithm to realize dynamic and fine-grained beam-steering.
- A practical system with large improvement in SNR, sensing, and communication ranges.

Thank you!

Acoustic Sensing and Communication Using Metasurface

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