


MobiCom 2023

Meta-Speaker: Acoustic Source Projection by Exploiting Air Nonlinearity

Weiguo Wang
Tsinghua University

Yuan He
Tsinghua University

Meng Jin
Shanghai Jiao Tong University

Yimiao Sun
Tsinghua University

Xiuzhen Guo
Zhejiang University



Magneto (Marvel Comics) can **generate and control magnetic fields.**


Can we Manipulate
Acoustic Field ?

Existing Approaches

Two perspectives to achieving **AFM** (Acoustic Field Manipulation):

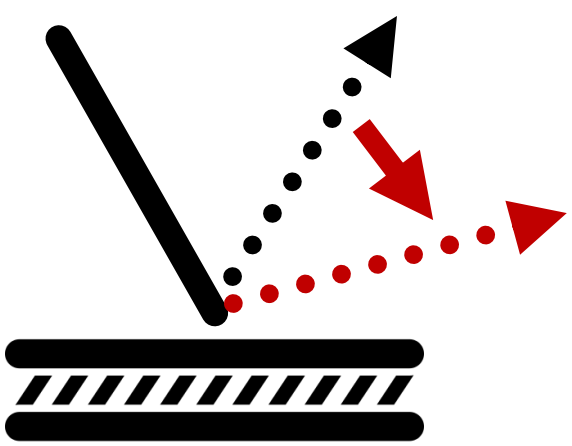
1. **Wave Propagation**

- The structure of the concert hall is well designed for good auditory experience.

Existing Approaches

Two perspectives to achieving AFM (Acoustic Field Manipulation):

1. **Wave Propagation**



redirect reflection

suppress scattering

- Recent advances in acoustic metamaterials allow us to control wave propagation **in a programmable way.**

Existing Approaches

Two perspectives to achieving AFM (Acoustic Field Manipulation):

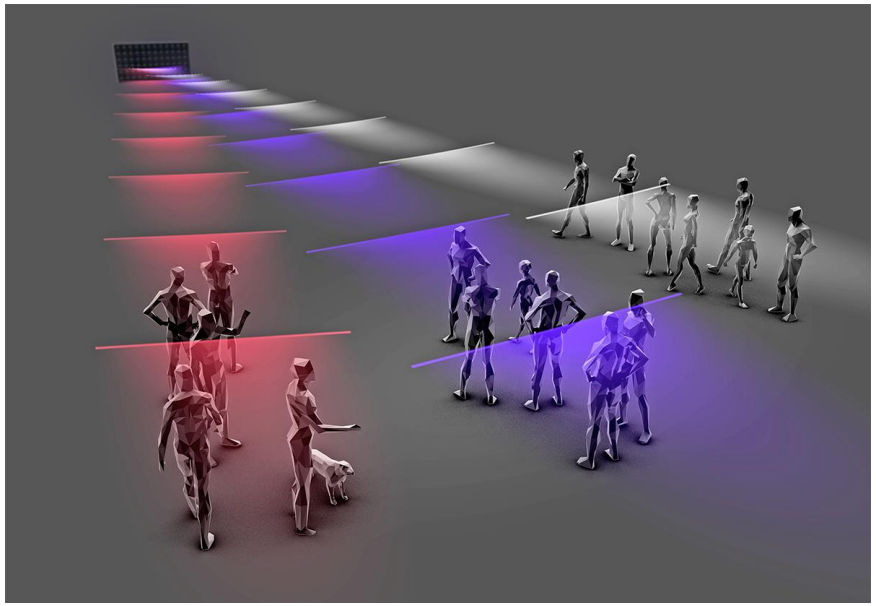
1. **Wave Propagation**
2. **Source Projection**

- By deploying multiple different in a room, Dolby Atomos allows sounds to move freely in 3D space.

Existing Approaches

Two perspectives to achieving AFM (Acoustic Field Manipulation):

1. **Wave Propagation**
2. **Source Projection**



- Directional Speakers can **divide and multiplex** acoustic channels spatially.

Meta-Speaker: A novel speaker that can project sounds with a high level of manipulability.

Sound Size can be manipulated

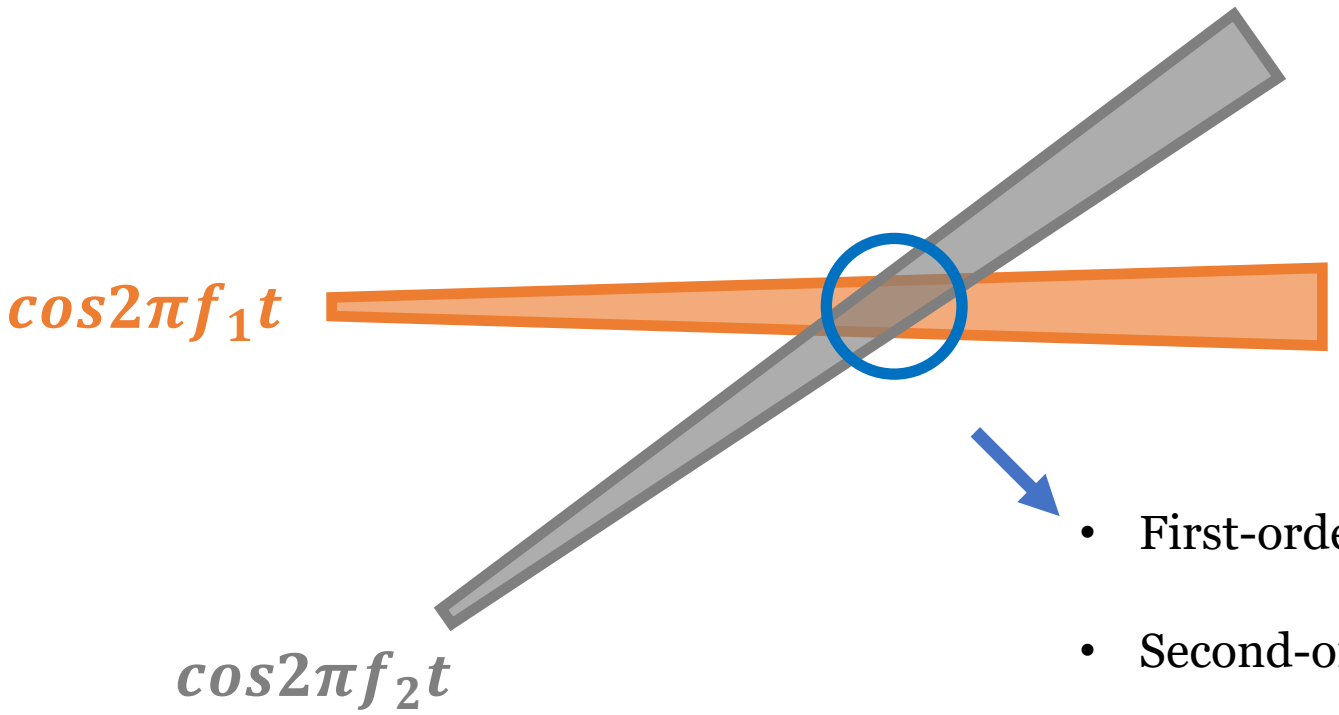
Sound Location can be manipulated

Spatial Audio for HCI

Air Nonlinearity

- The acoustic signal distributes the air medium unevenly, and makes it heterogeneous

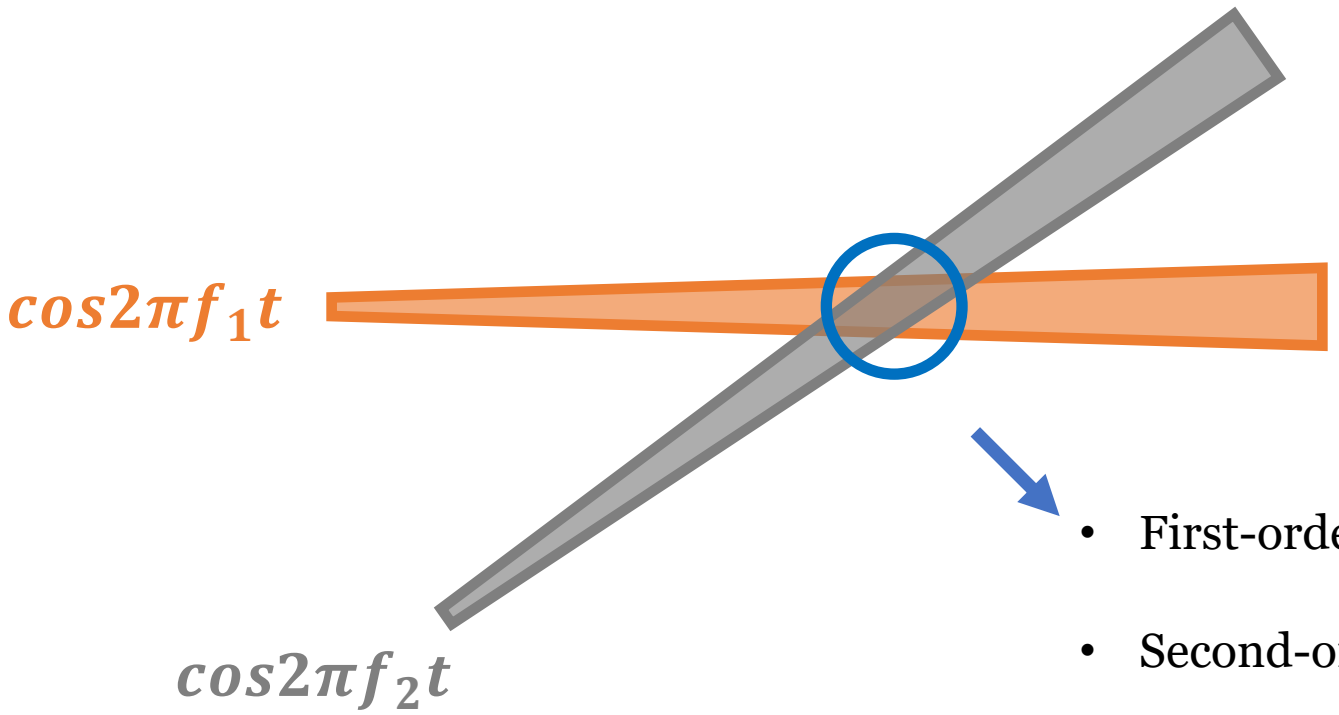
Air Nonlinearity



- The acoustic signal distributes the air medium unevenly, and makes it heterogeneous

- First-order: $A_1(s_1 + s_2) = cos2\pi f_1 t + cos2\pi f_2 t$
- Second-order: $A_2(s_1 + s_2)^2 = A_2 + 0.5A_2 cos2\pi 2f_1 t + 0.5A_2 cos2\pi 2f_2 t + A_2 cos2\pi(f_1 + f_2)t + A_2 cos2\pi(f_1 - f_2)t$
- Higher-orders .....

Sound from Silence

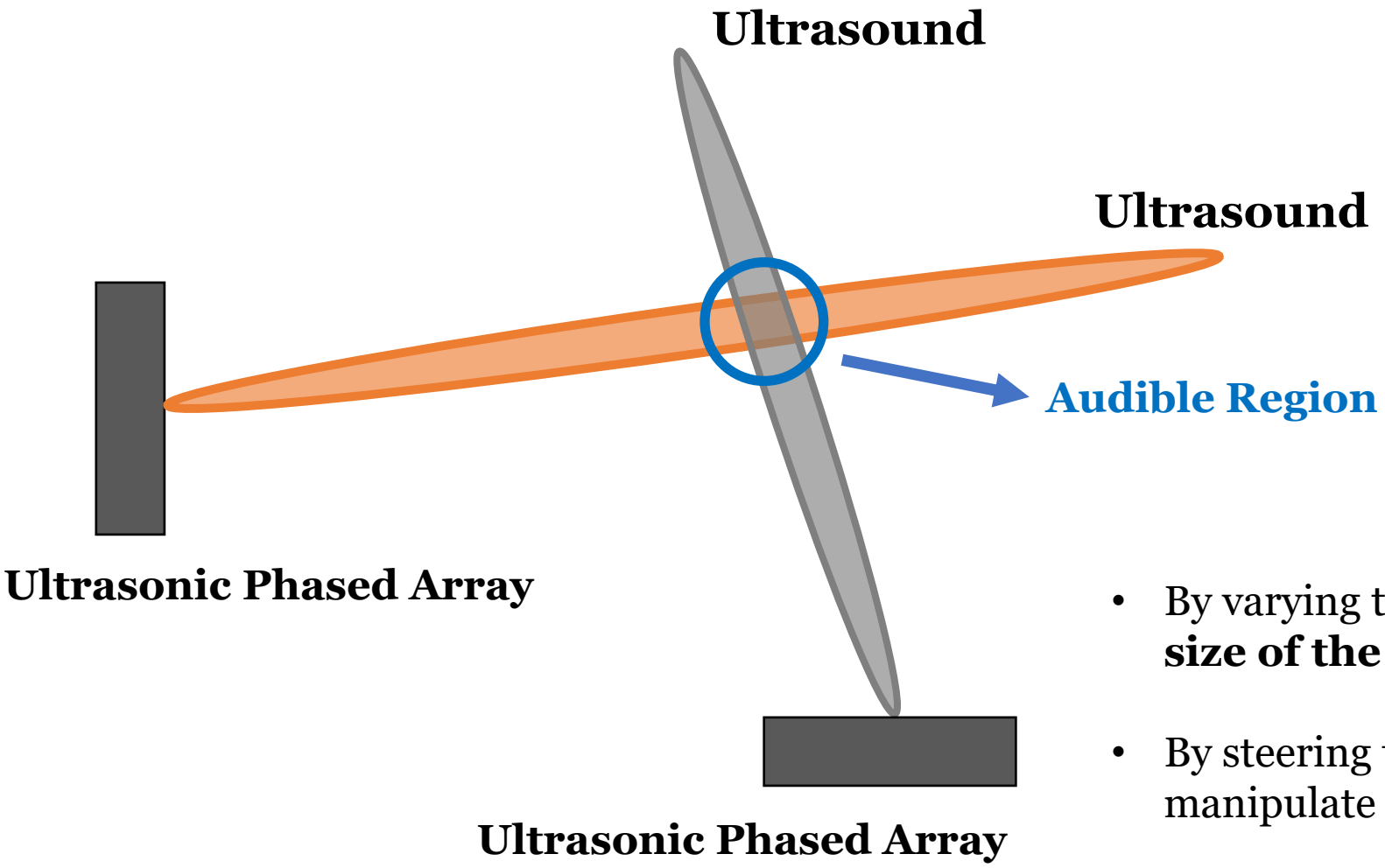


- The acoustic signal distributes the air medium unevenly, and makes it heterogeneous

- First-order: $A_1(s_1 + s_2) = \cancel{cos2\pi f_1 t + cos2\pi f_2 t}$
- Second-order: $A_2(s_1 + s_2)^2 = A_2 + \cancel{0.5A_2 cos2\pi 2f_1 t + 0.5A_2 cos2\pi 2f_2 t + A_2 cos2\pi(f_1 + f_2)t} + A_2 cos2\pi(f_1 - f_2)t$

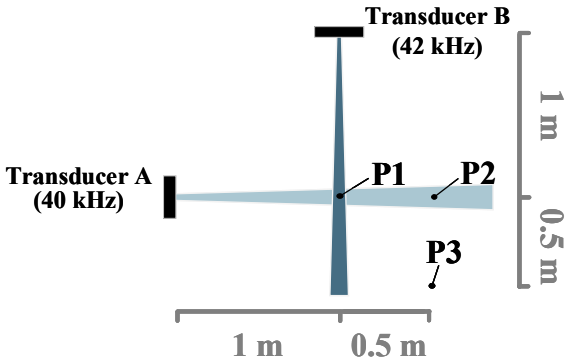
Air nonlinearity allows us to **reproduce audible sound** from ultrasounds.

Meta-Speaker Design

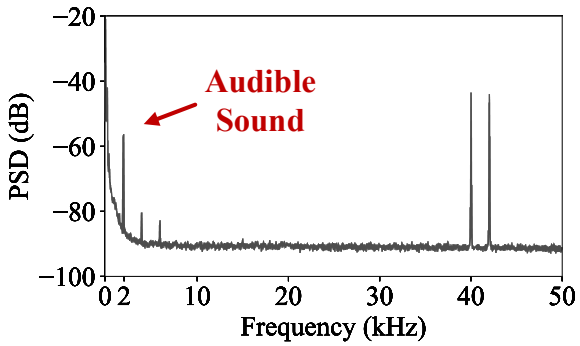


- By varying the beamwidth, we can manipulate **the size of the audible region**.
- By steering the the array orientation, we can manipulate **the location of the audible region**.

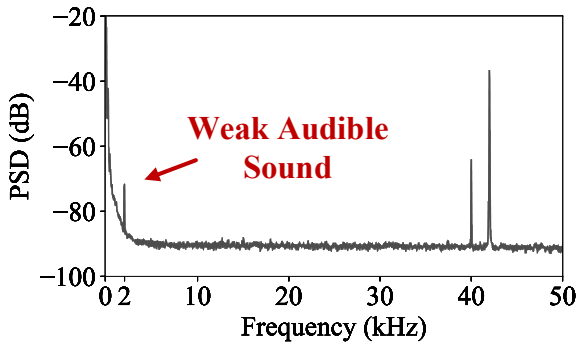
Quick Validations



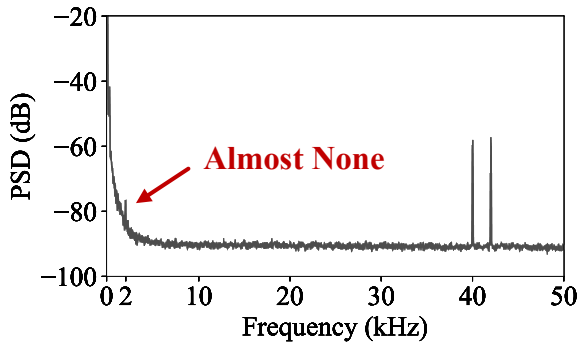
(a) Deployment



(b) P1



(c) P2

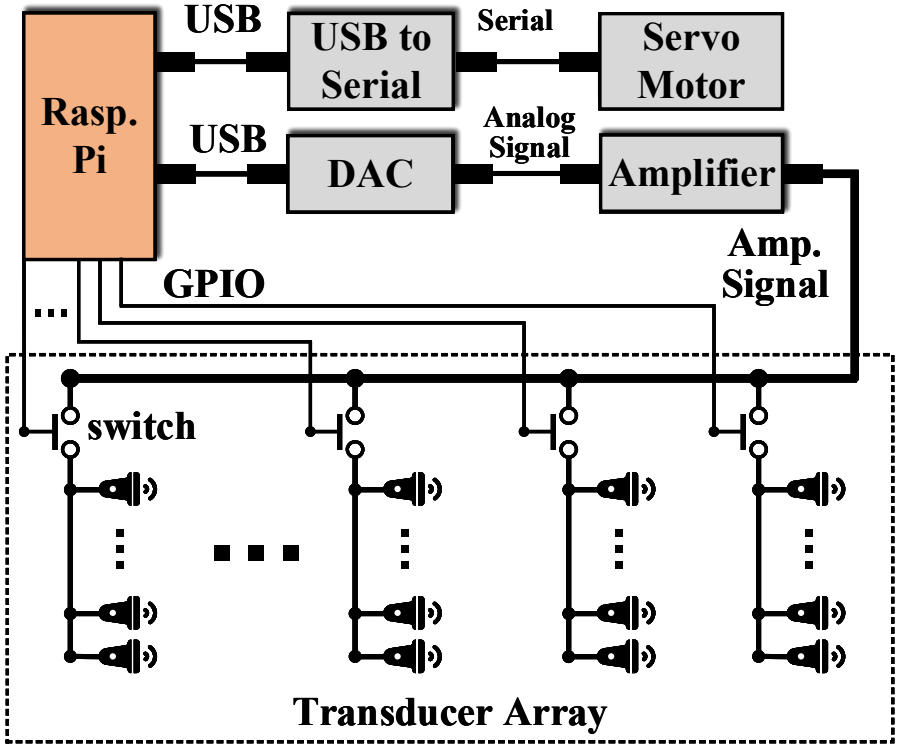


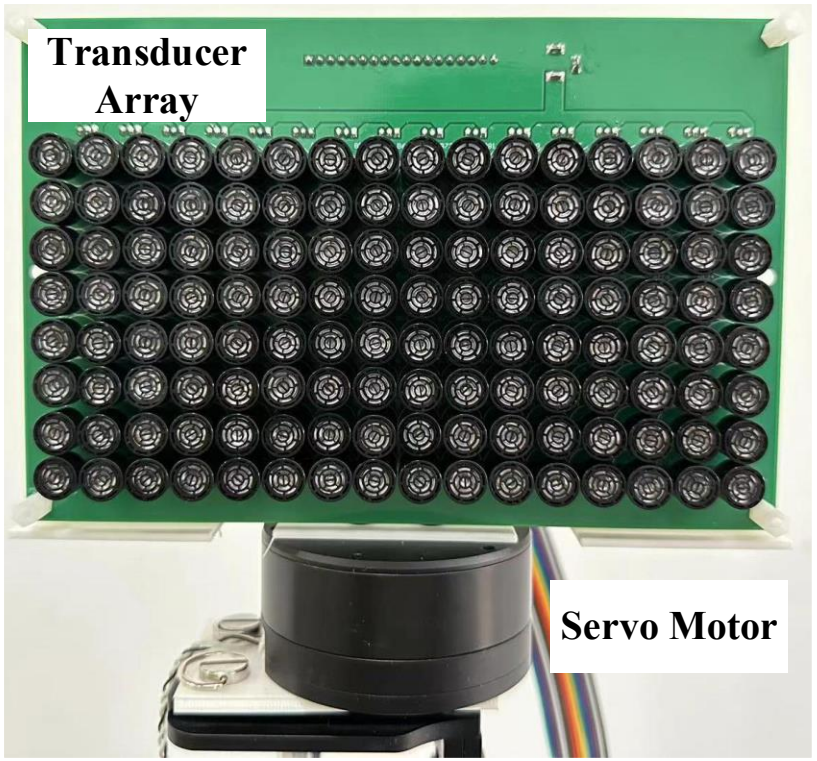
(d) P3

Expected audible frequency: **2 kHz**

- A distinct 2 kHz audio can be recorded at the intersection of beams, **P1**.
- The audio gets much weaker or almost disappears in **P2** and **P3**.

Implementation





(a) Hardware design of the transmitter. **(b) The array sits on top of a servo motor.**

- A Raspberry Pi 4B is used as the central controller
- A 24-bit DAC, with a sample rate of 96 kHz,
- The output from the DAC is amplified using a Class-D power amplifier
- The ultrasonic array consists of 16 x 8 transducers
- To steer the ultrasonic beam, the array is mounted on top of a servo motor.

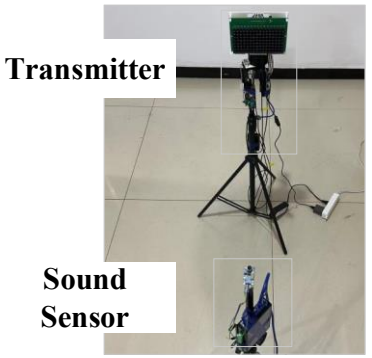
Profiling

Spatial Resolution

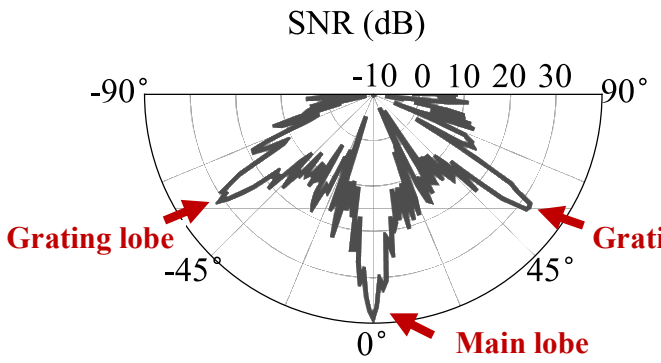
Energy Distribution

Frequency Response

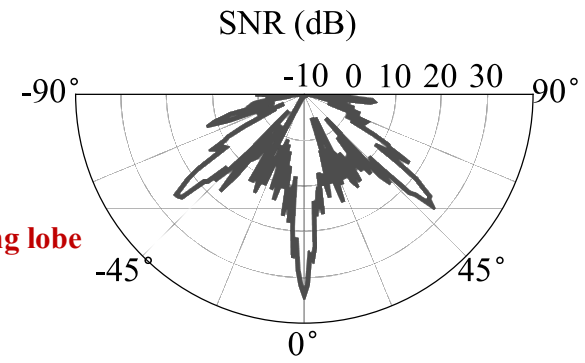
Profiling: Spatial Resolution



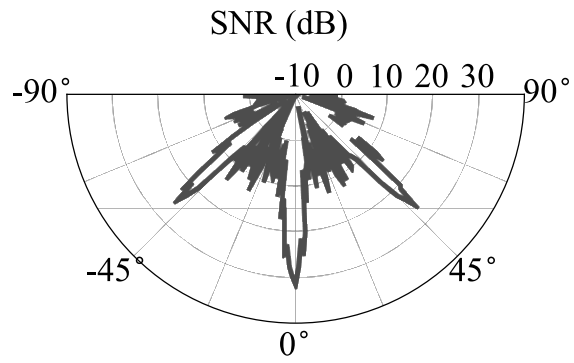
(a) Deployment



(b) 40 kHz (16x8 array)



(c) 42 kHz (16x8 array)

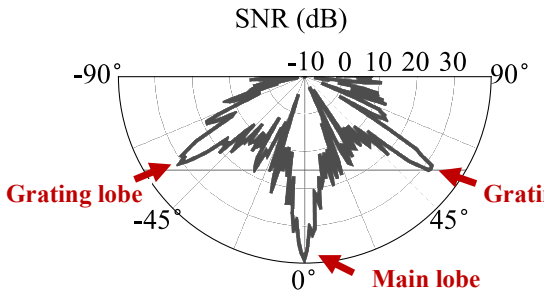


(d) 44 kHz (16x8 array)

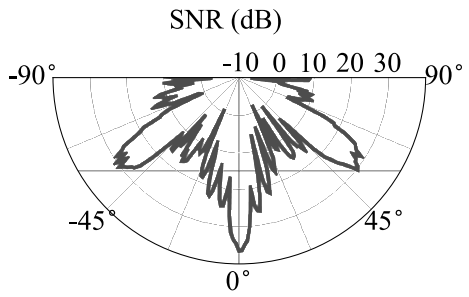
- The 3-dB beamwidths for the 40 kHz, 42 kHz, and 44 kHz ultrasound frequencies are found to be only **3.1, 2.7, and 2.4 degrees**, respectively

The transmitter can form **a sharp beam**, allowing it to pinpoint a direction precisely.

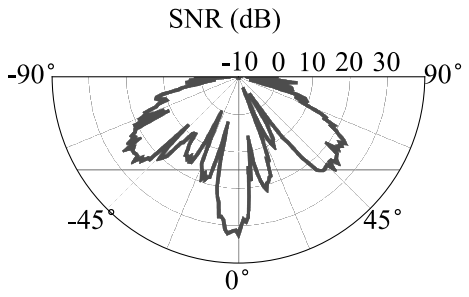
Profiling: Spatial Resolution



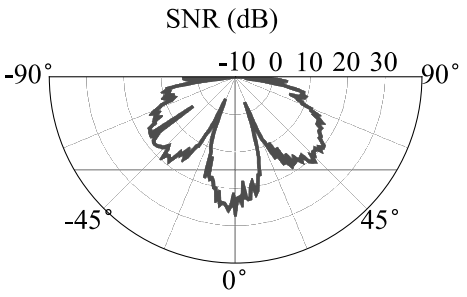
(a) 16 x 8 array



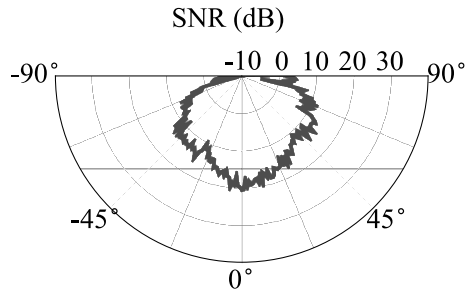
(a) 8 x 8 array



(a) 4 x 8 array



(a) 2 x 8 array

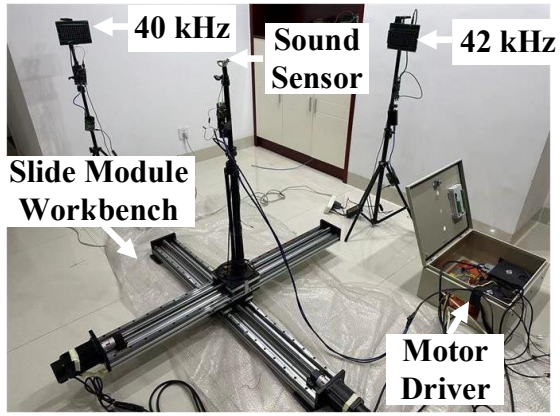


(a) 1 x 8 array

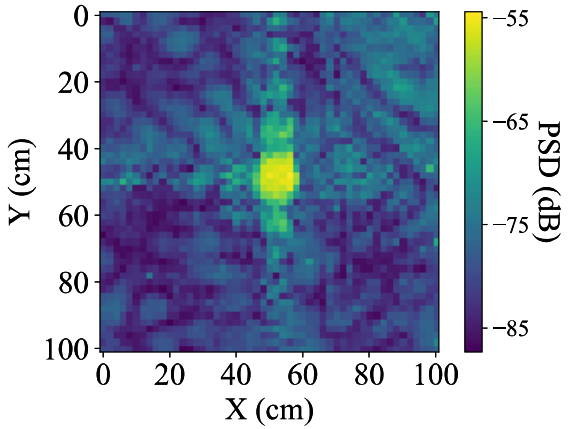
- The 3-dB beamwidths for the 40 kHz, 42 kHz, and 44 kHz ultrasound frequencies are found to be only **3.1, 2.7, and 2.4 degrees**, respectively

The transmitter offers **flexible manipulability over its spatial resolution** by enabling transducers selectively.

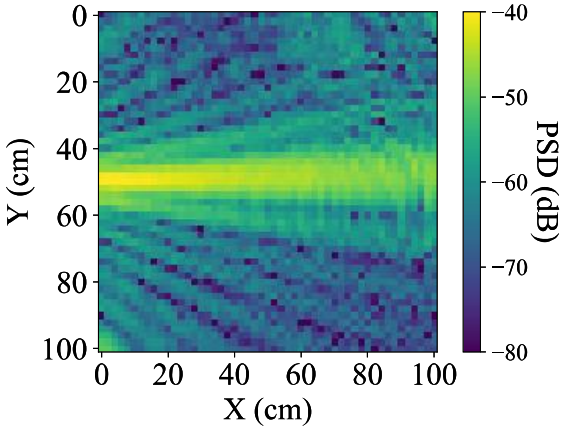
Profiling: Energy Distribution



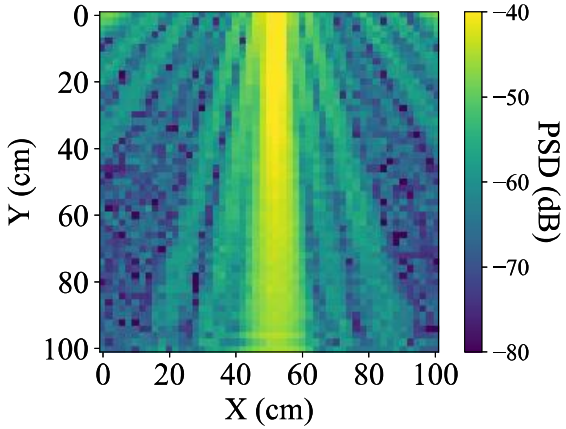
(a) Deployment



(b) 2 kHz



(c) 40 kHz

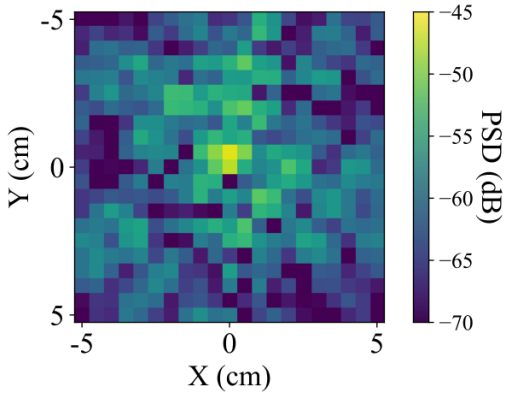


(d) 42 kHz

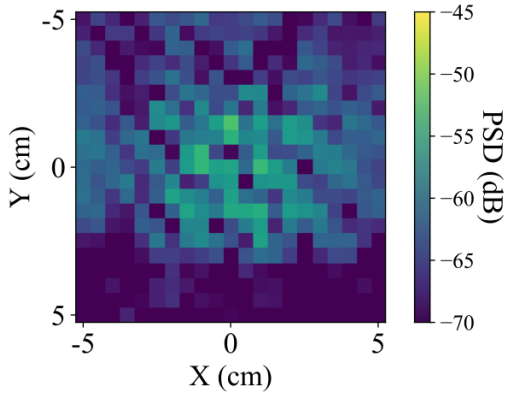
- A two-dimensional slide module workbench is used to carry the microphone to measure the signal energy across a 1m x 1m area with a grid size of 20 mm.

Meta-Speaker can reproduce **a point-wise audible source** at the intersection of two ultrasonic beams.

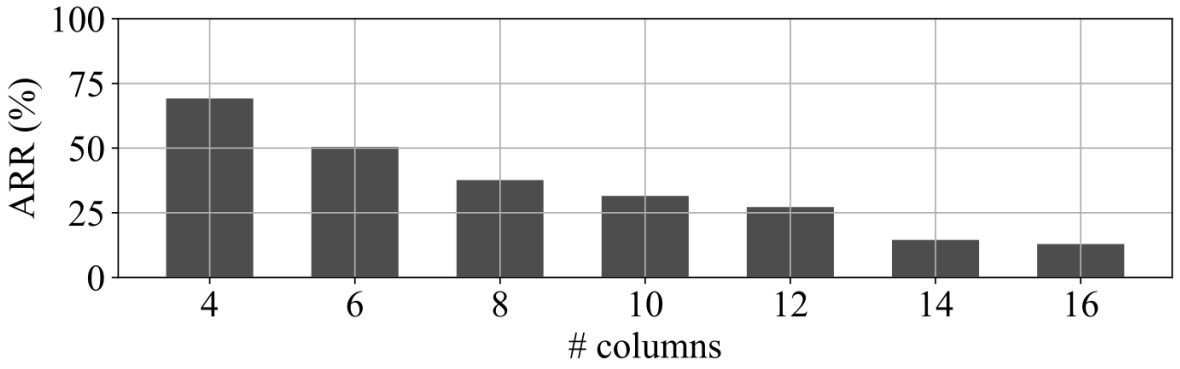
Profiling: Energy Distribution



(a) 16x8.



(b) 8x8.



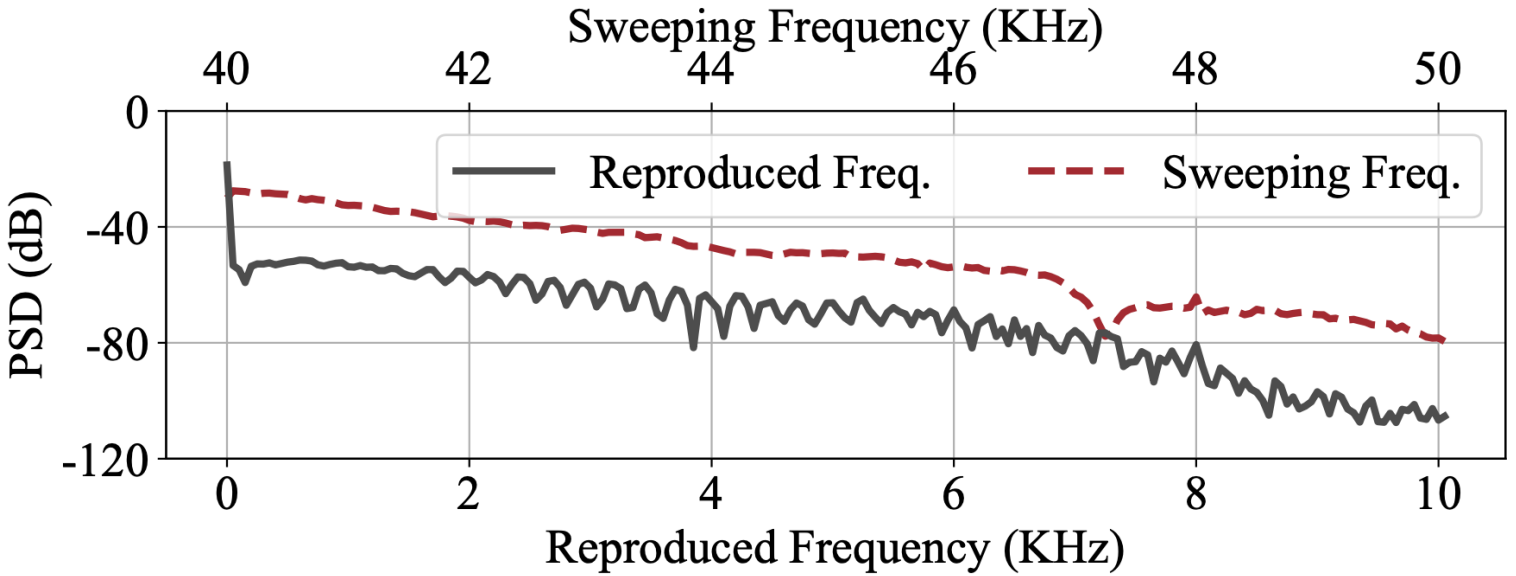
(c) ARR as a function of array column

The impact of array column on audible region size.

- As the number of columns increases, the beam becomes sharper and the audible region becomes finer.

The size of the audible region can be manipulated by adjusting the beamwidth of the transmitter.

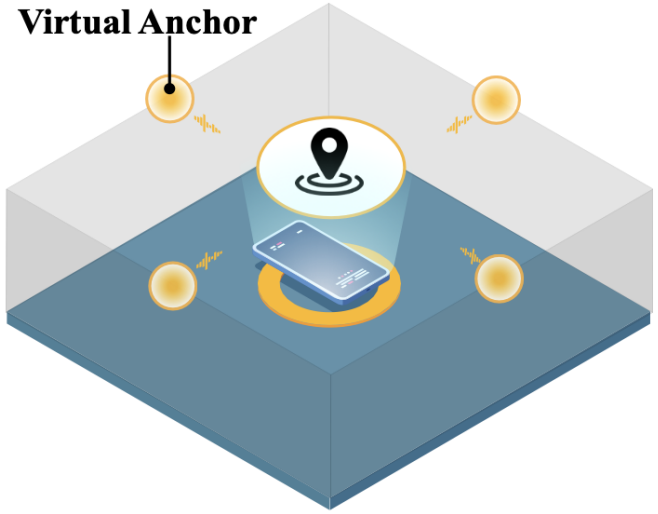
Profiling: Frequency Response



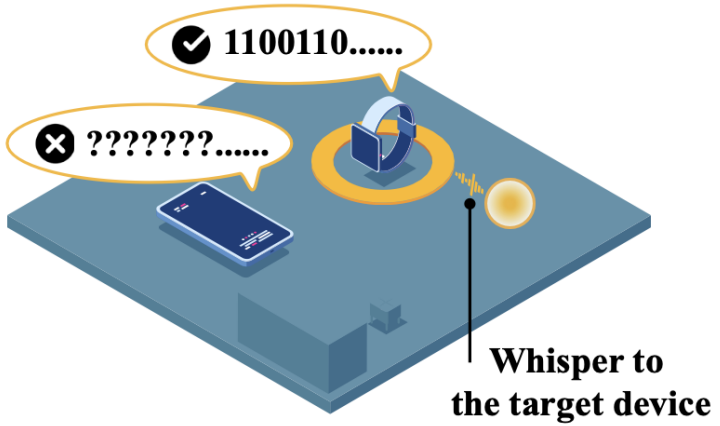
Reproduced frequency vs. sweeping frequency

The bandwidth of Meta-Speaker is approximately **3.8 kHz**.

Applications



(a) Anchor-Free Localization

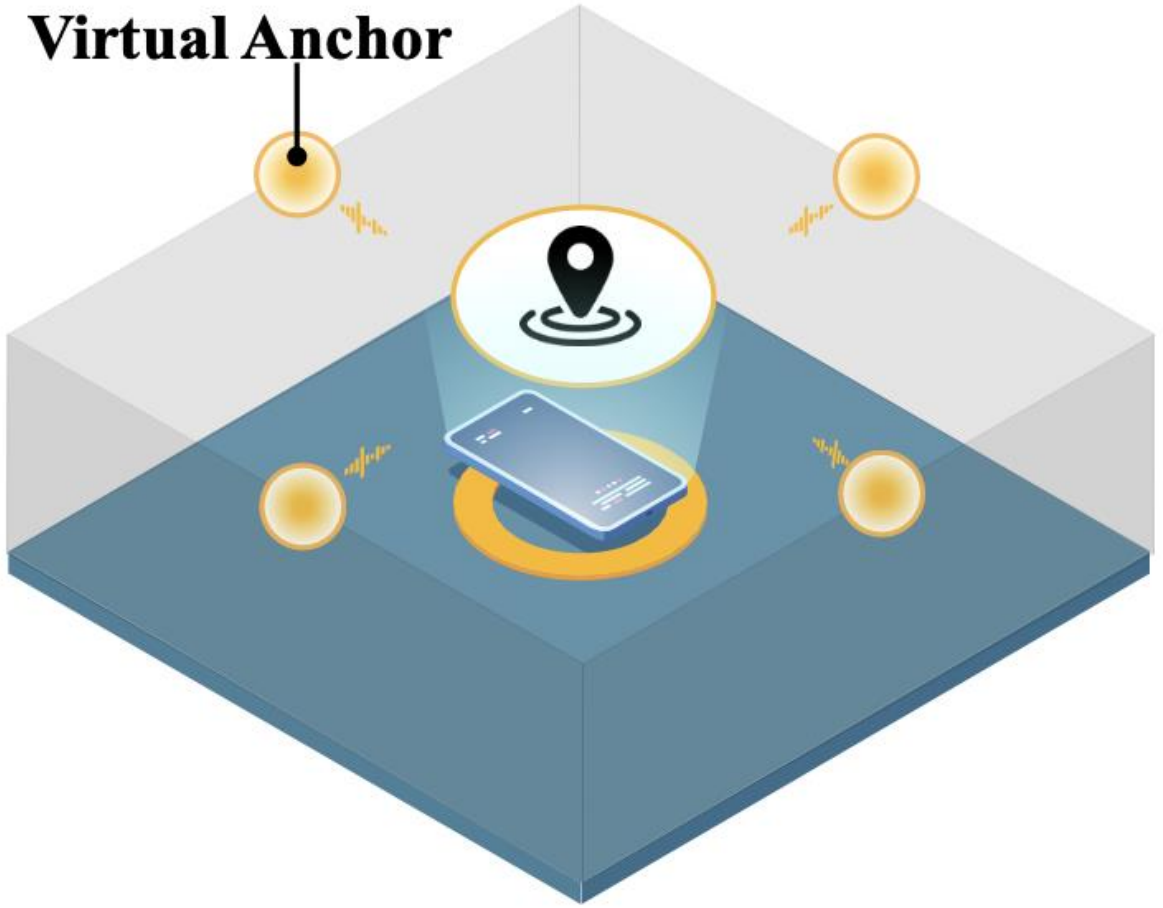


(b) Location-aware Communication

(c) Acoustic Augmented Reality

..... and more possible applications !

Application 1: Anchor-Free Localization



Meta-Speaker can create **multiple virtual anchors** that broadcast acoustic beacons, by projecting audible sources at different locations

Application 1: Anchor-Free Localization

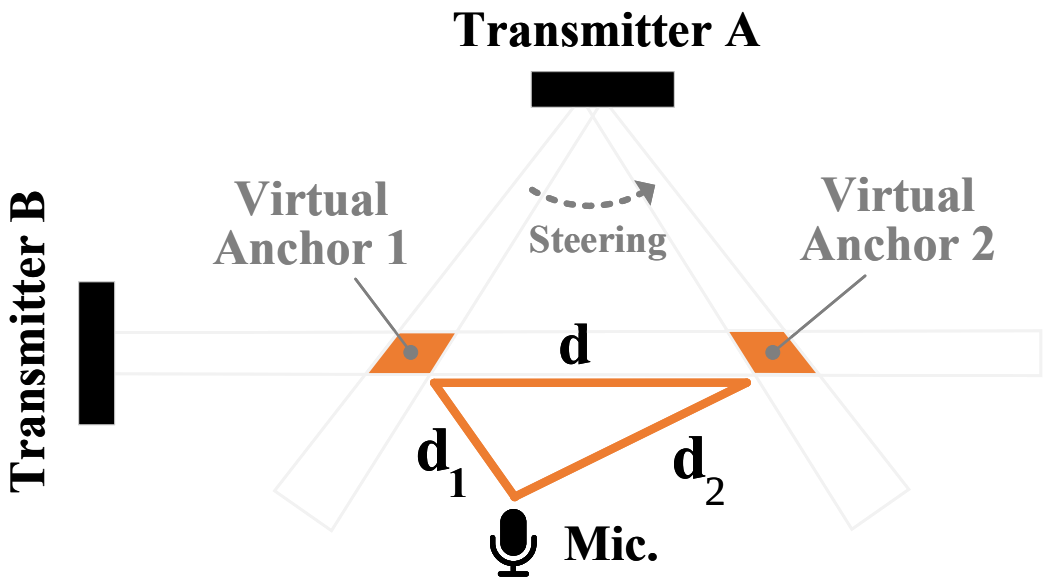
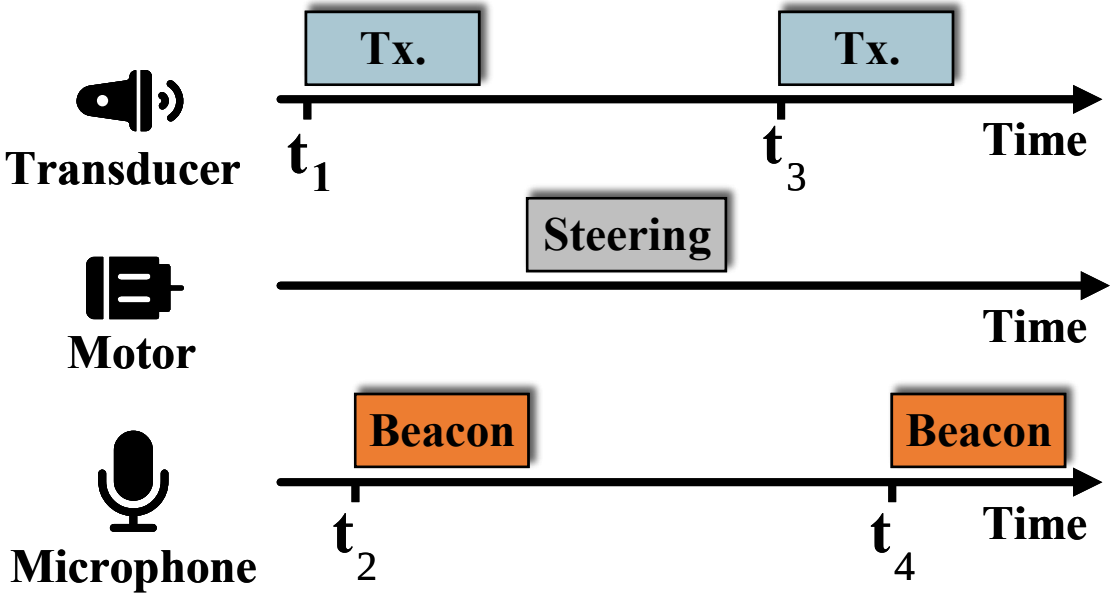


Illustration of Virtual Anchors



The timelines of beacon transmission and reception

- Estimate Direction of Arrival from distance difference:

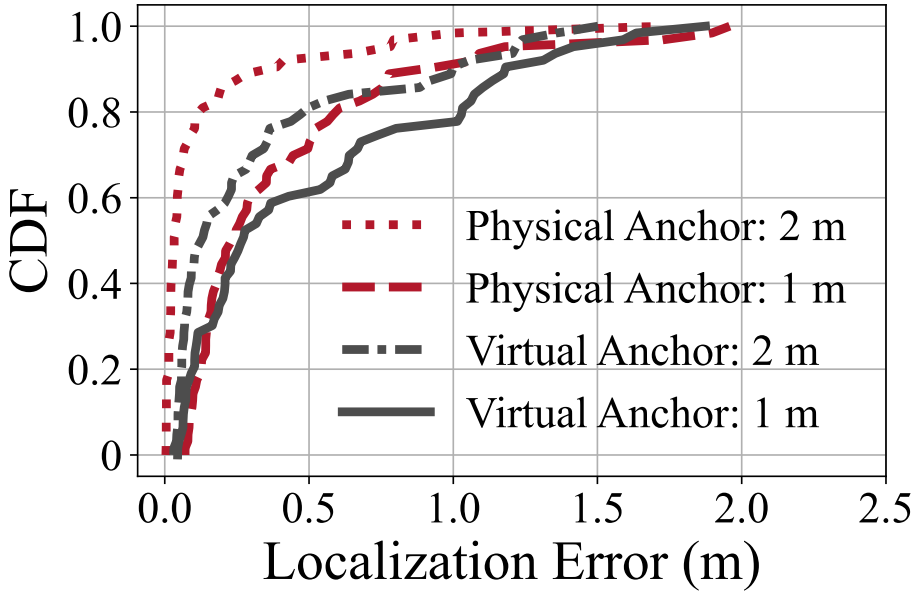
$$\theta = \arccos\left(\frac{\Delta d}{d}\right) = arccos\left(\frac{d2 - d1}{d}\right)$$

- Estimate distance difference from time difference:

$$d2 - d1 = \frac{t4 - t3}{c} - \frac{t2 - t1}{c} = \frac{t4 - t2}{c} - \frac{t3 - t1}{c}$$

constant

Application 1: Anchor-Free Localization

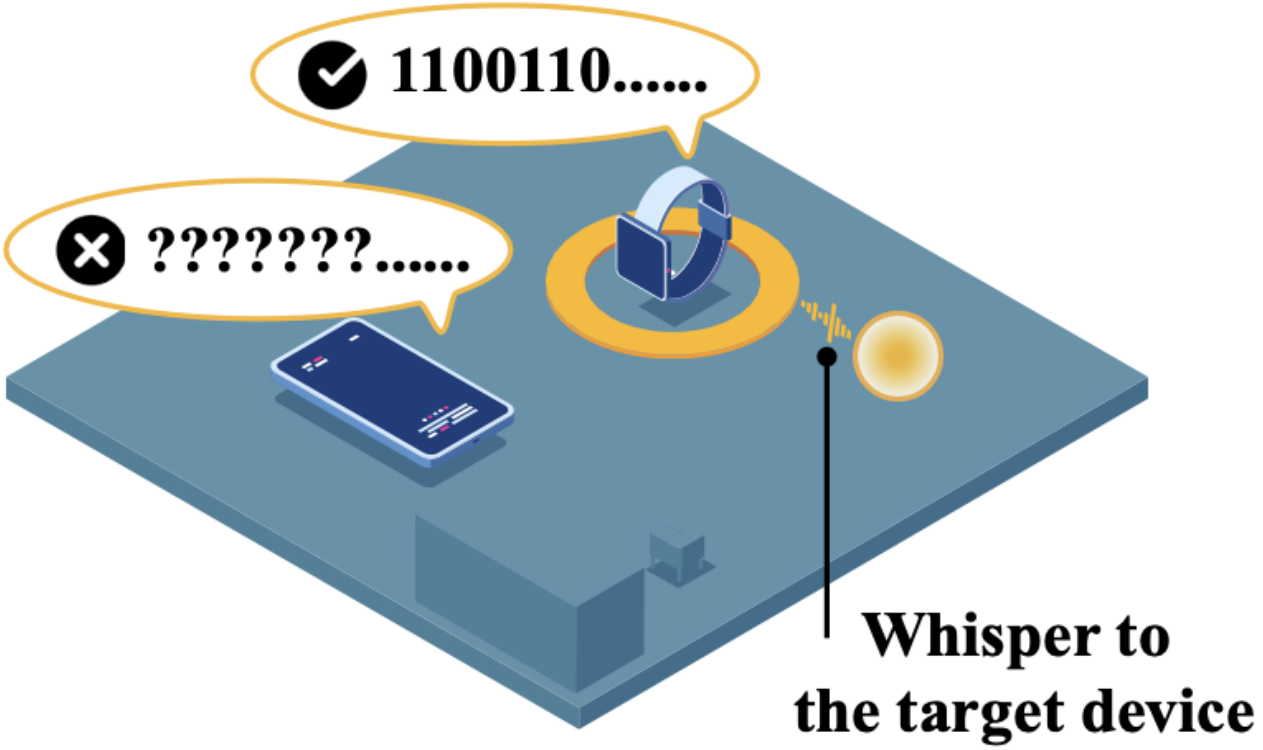


Physical Anchors vs. Virtual Anchors

- As increasing the inter-anchor distance from 1m to 2m, the median errors decreases
  - from **0.27 m** to **0.13 m** for the virtual anchors,
  - and from **0.23 m** to **0.03 m** for the physical anchors.

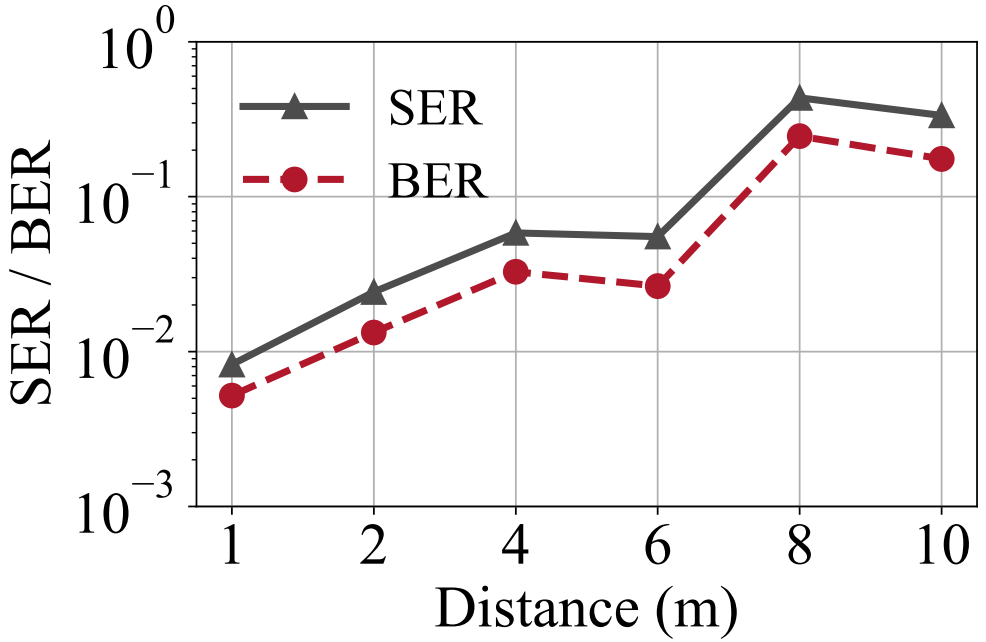
Meta-Speaker can further improve the localization performance by manipulating the locations of virtual anchors.

Application 2: Location-aware Communication

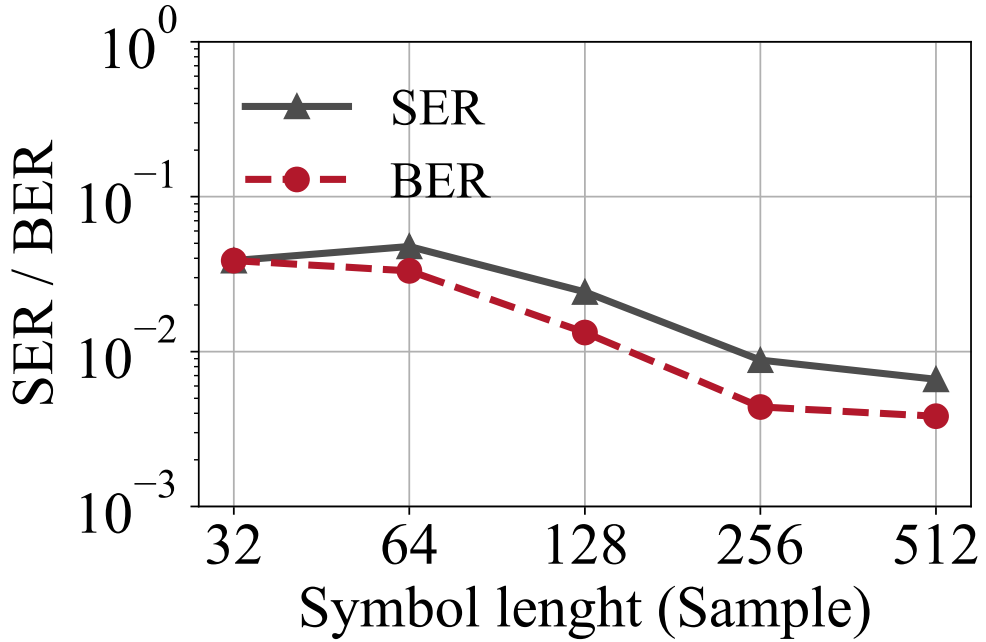


Acoustic messages can be transmitted solely to a targeted device, while devices located elsewhere cannot perceive such messages.

Application 2: Location-aware Communication



Impact of projection distance on SER and BER



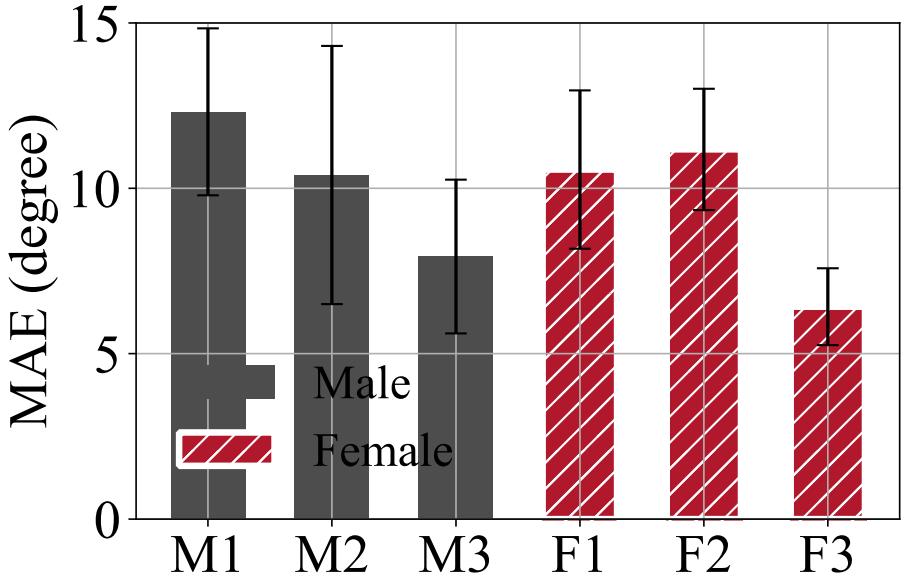
Impact of symbol length on SER and BER

- The projection distance is about 6 m
- The communication throughput is up to 1.28 kbps.

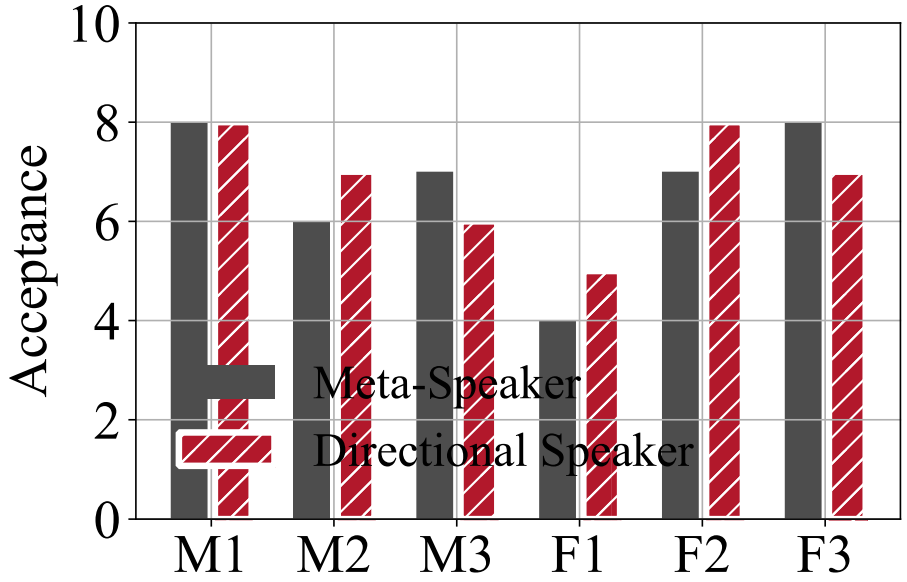
Application 3：Acoustic Augmented Reality

The physical presence of the reproduced audio in space allows humans to hear it spatially. This feature enables Meta-Speaker to interact directly with humans.

Application 3: Acoustic Augmented Reality



Direction Estimation Accuracy



Acceptance Score

The sounds that can be spatially perceived by humans with reasonable accuracy and acceptance.

Summary

- We propose a new tool for AFM, and demonstrate the feasibility of projecting audible sources with separated ultrasonic beams.

- We present the design and implementation of Meta-Speaker. We conduct thorough analysis on its fundamental properties.

- Meta-Speaker will enable diverse applications. We showcase three examples:
  - anchor-free localization
  - location-aware communication
  - acoustic augmented reality.
  - .....

Thank You!