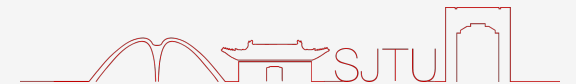


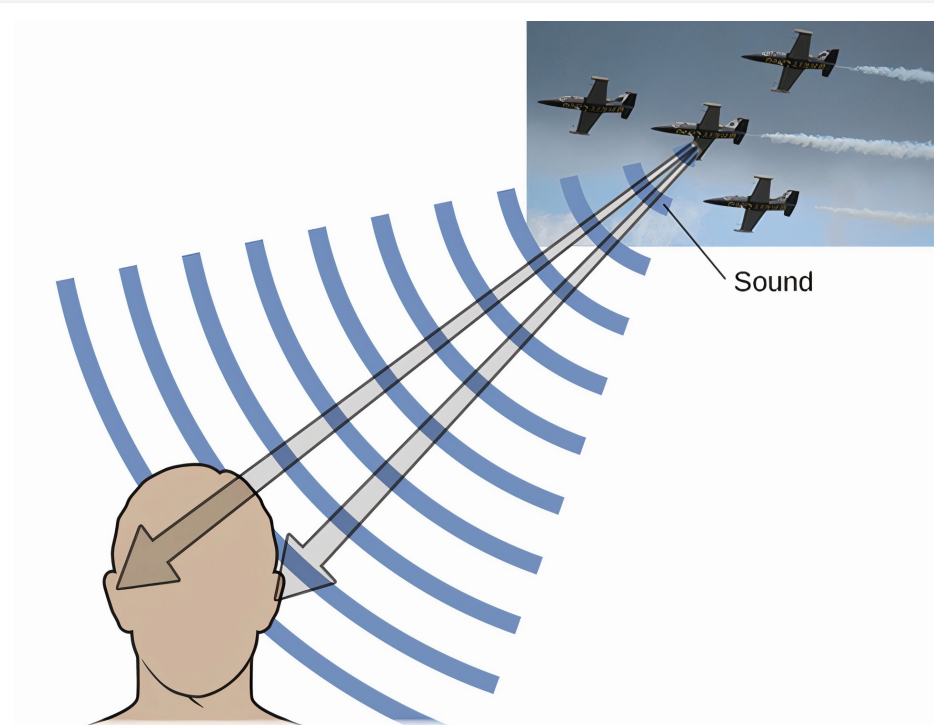
Visar: Projecting Virtual Sound Spots for Acoustic Augmented Reality Using Air Nonlinearity

**Juntao Zhou, Yijie Li, Yida Wang, Dian Ding, Yu Lu,
Yi-Chao Chen, Guangtao Xue**

Shanghai Jiao Tong University



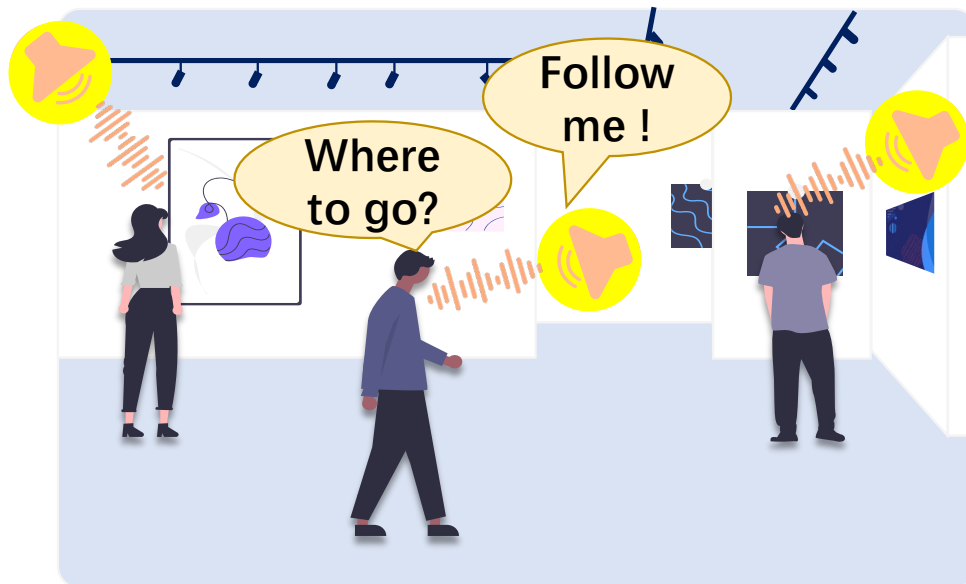
Binaural Spatial Hearing



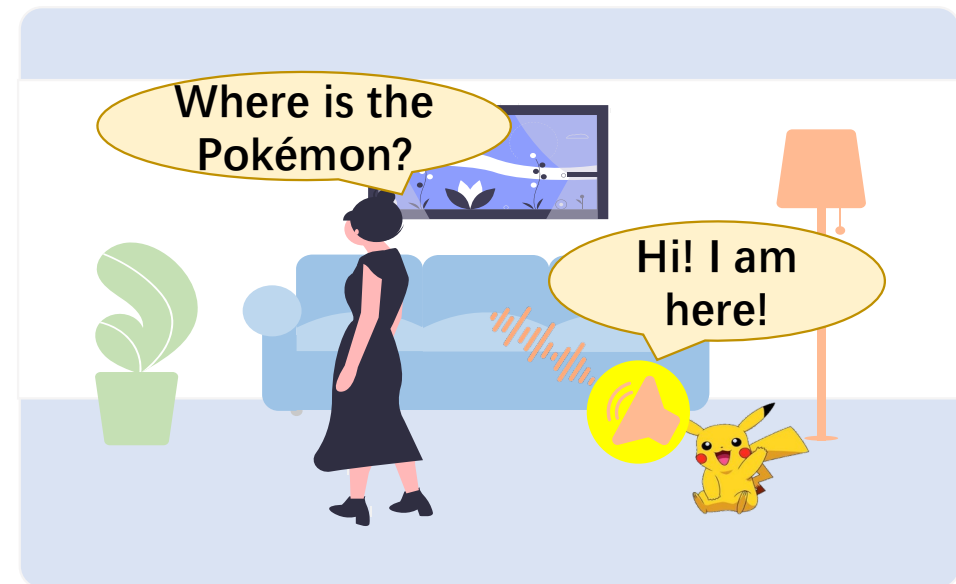
Binaural spatial hearing refers to the ability of humans to perceive the **direction** and **distance** of sounds using **both ears**.



Acoustic Augmented Reality Applications



Indoor Navigation



AR Game

Acoustic augmented reality focuses on enhancing real-world environments with **virtual soundscapes**.



Existing Solutions – Head Related Transfer Function



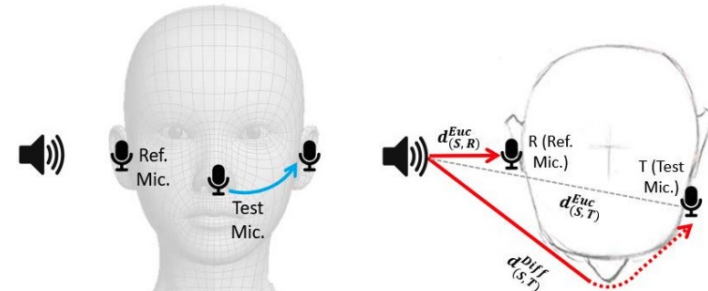
Spatial audio using earphones

✗ Almost all the work requires the aid of headphones.



[1] Yang, Zhijian, et al. "Ear-ar: indoor acoustic augmented reality on earphones." MobiCom 2020.

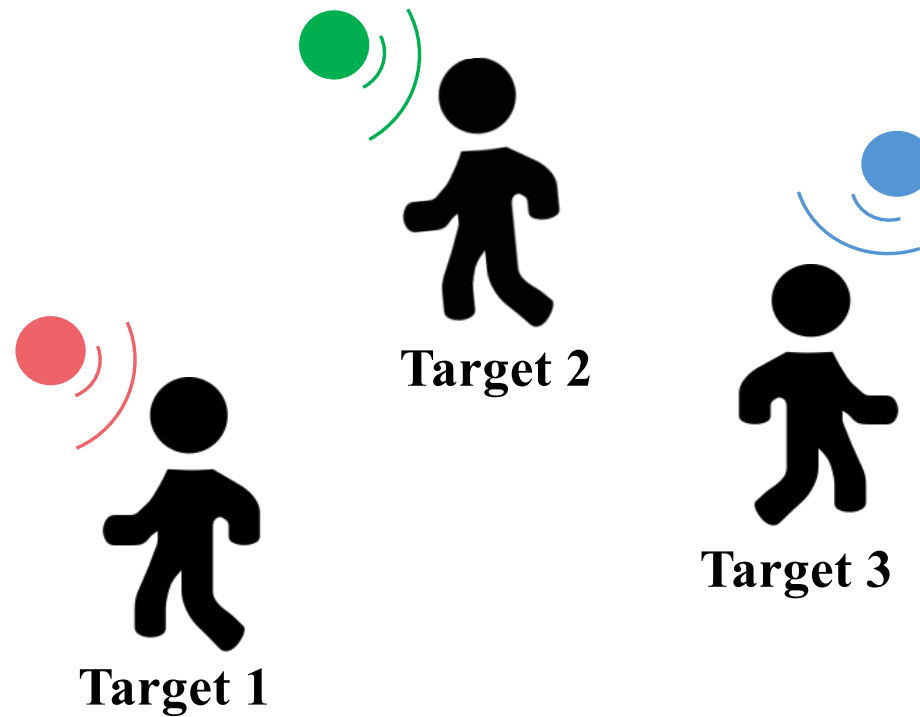
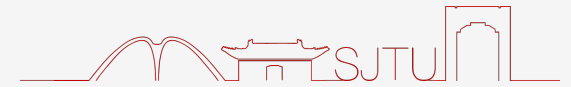
✗ Users need to put in extra effort to achieve personalization.



[2] Yang, Zhijian, and Romit Roy Choudhury. "Personalizing head related transfer functions for earables." SIGCOMM 2021.



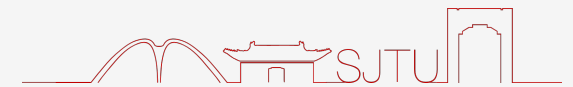
Parametric Array - Air Nonlinearity



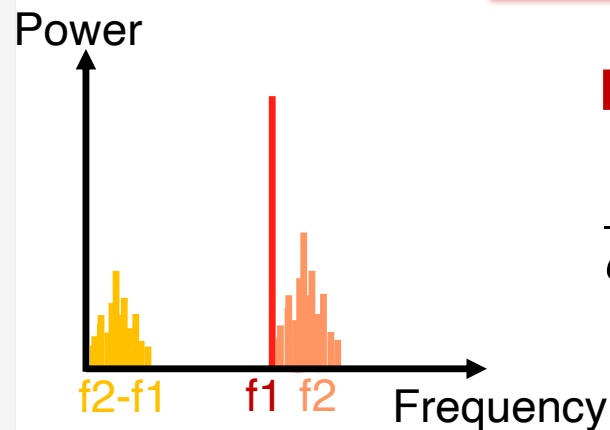
Virtual sound sources?



Parametric Array - Air Nonlinearity

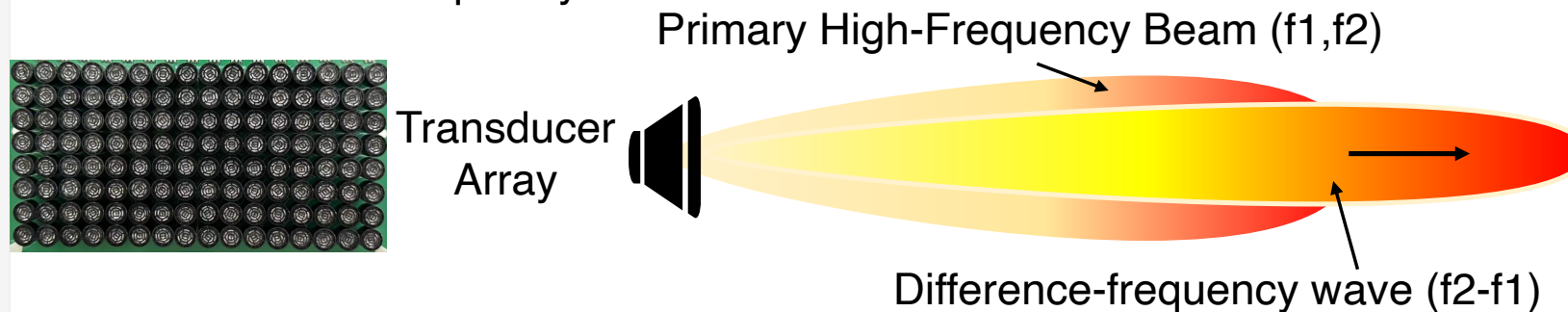


Air Nonlinearity



KZK Equation

$$\frac{\partial^2 p}{\partial z \partial \tau} = \frac{c_0}{2} \nabla_{\perp}^2 p + \frac{\delta}{2c_0^3} \frac{\partial^3 p}{\partial \tau^3} + \frac{\beta}{2\rho_0 c_0^3} \frac{\partial^2 p^2}{\partial \tau^2}$$



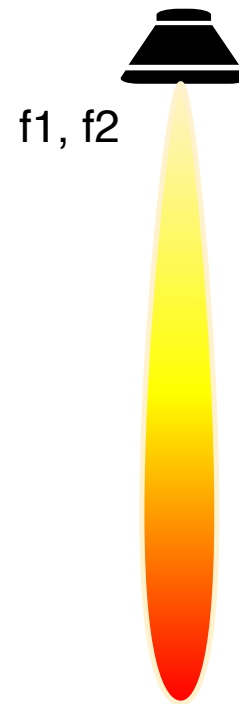
Air Nonlinearity can reproduce audible sounds from ultrasound.



Parametric Array - Air Nonlinearity



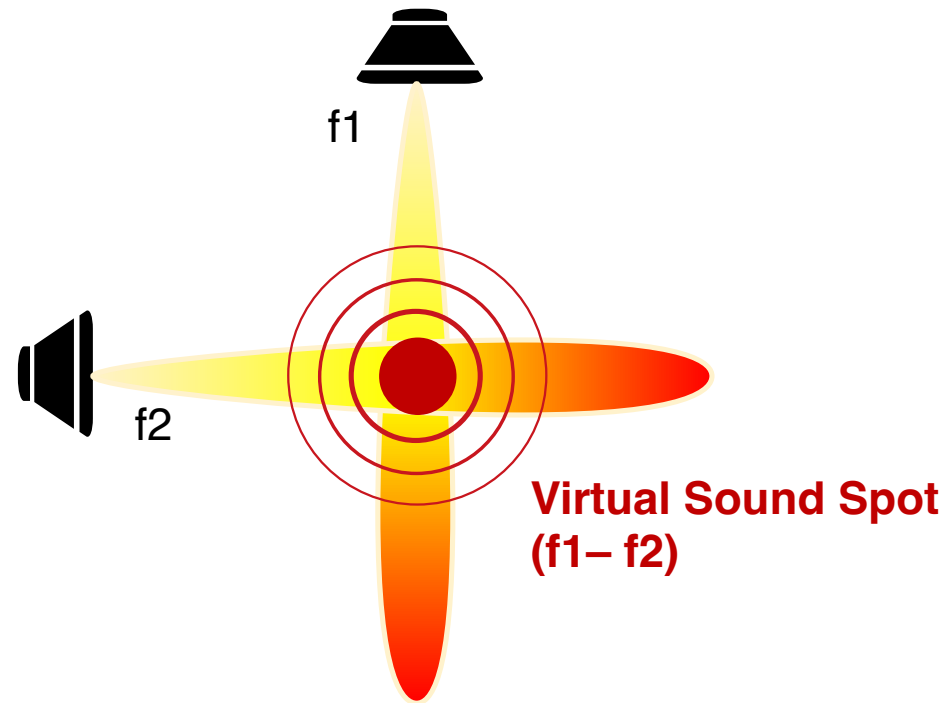
Virtual Sound Spot



Parametric Array - Air Nonlinearity



Virtual Sound Spot



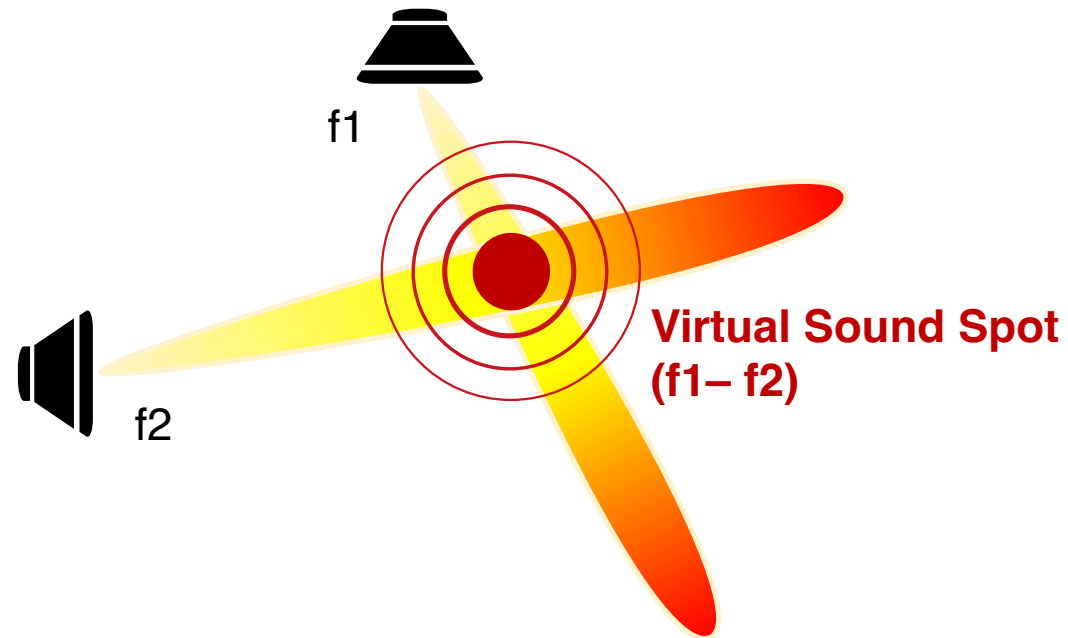
Separating high-frequency playback creates a sound source at the intersection spot.



Parametric Array - Air Nonlinearity



Virtual Sound Spot



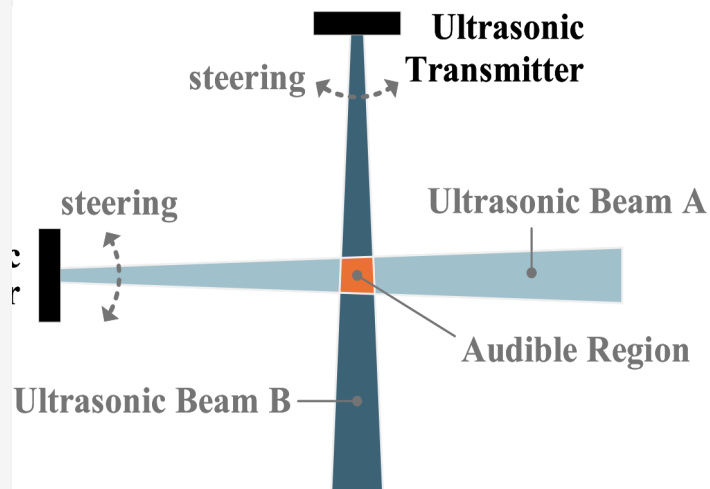
Controlling two speakers' directivity enables positioning of a virtual sound source.



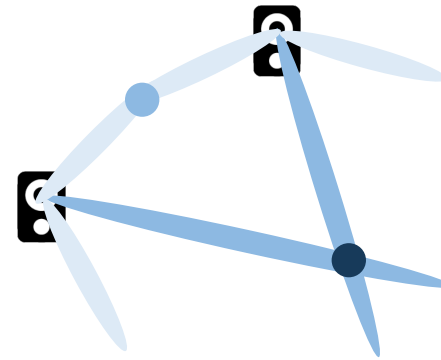
Parametric Array - Air Nonlinearity



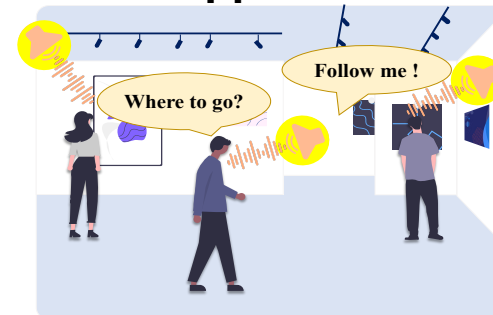
Virtual Sound Spot



❌ ■ Grating lobes



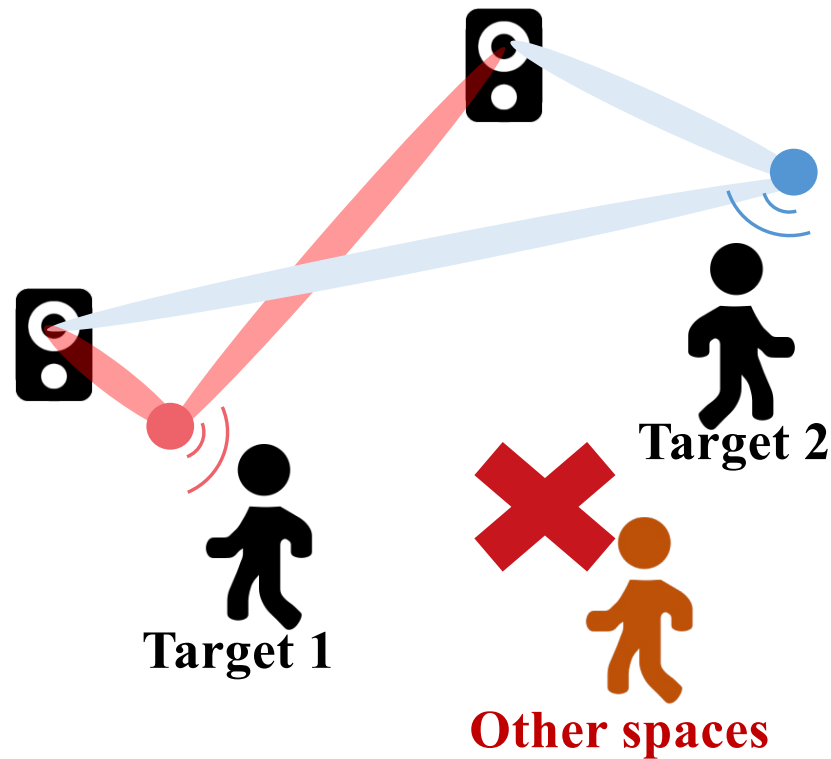
❌ ■ Cannot support multi-user



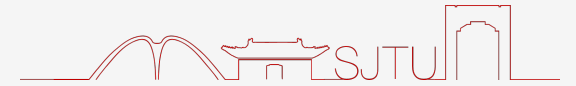
Visar – Multiple Virtual Sound Spots Projection



Visar Scheme



Challenges



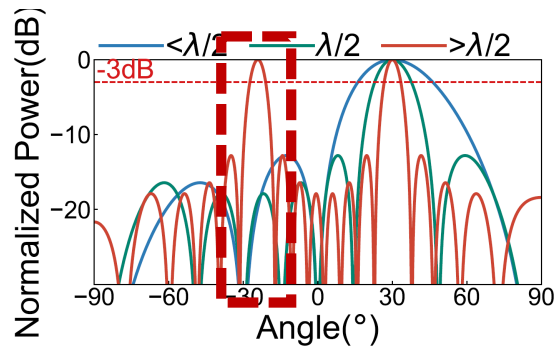
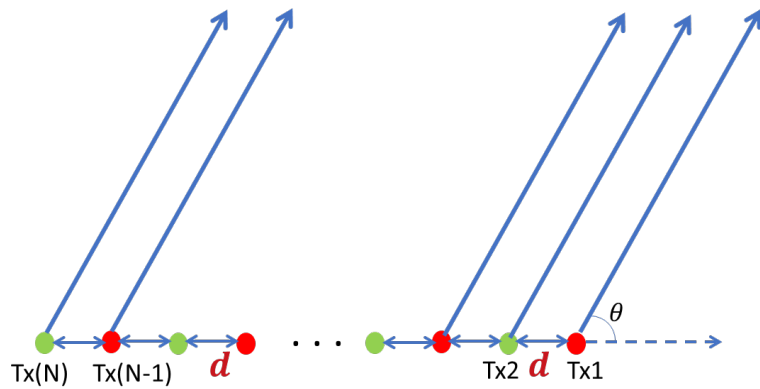
- 1) **Grating lobes** causing extraneous spots
- 2) **Mutual interference** due to multi-spot projection



Challenge 1: Grating lobes



Element Spacing $d > \lambda/2$



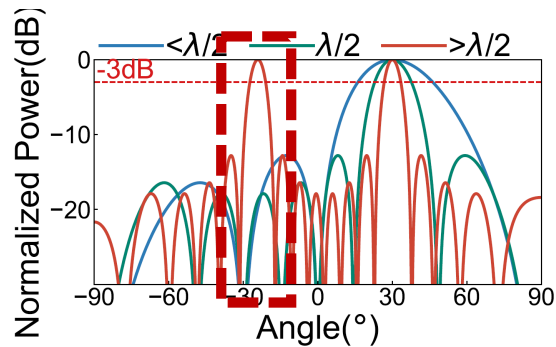
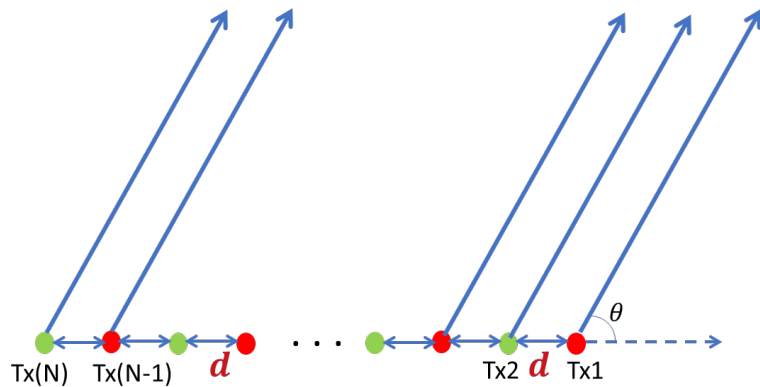
Grating lobe



Challenge 1: Grating lobes

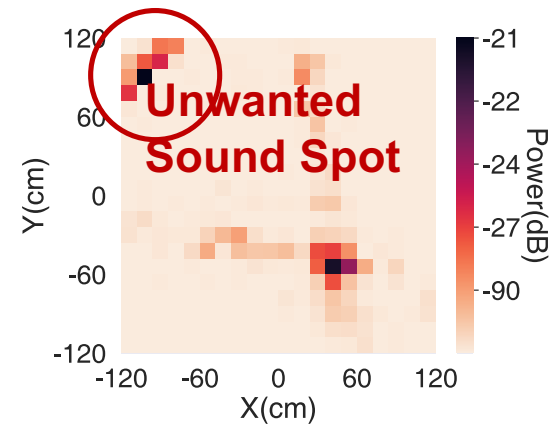
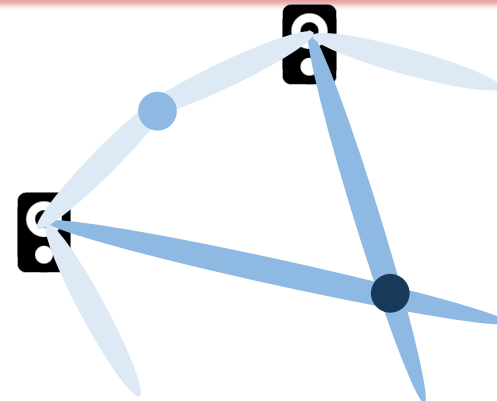


Element Spacing $d > \lambda/2$



Grating lobe

Causing extraneous spot



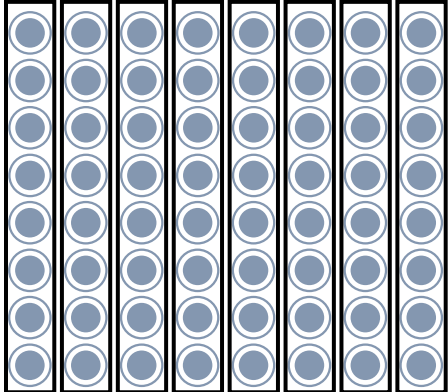
Optimization-based Beamforming



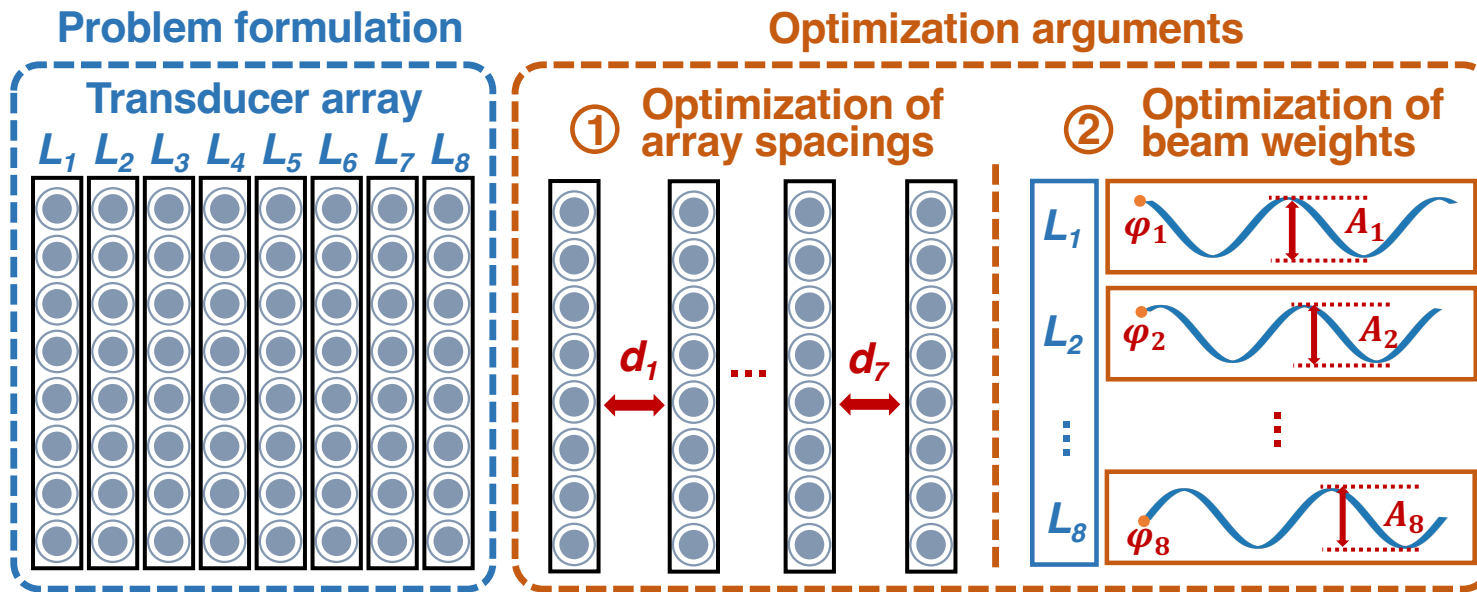
Problem formulation

Transducer array

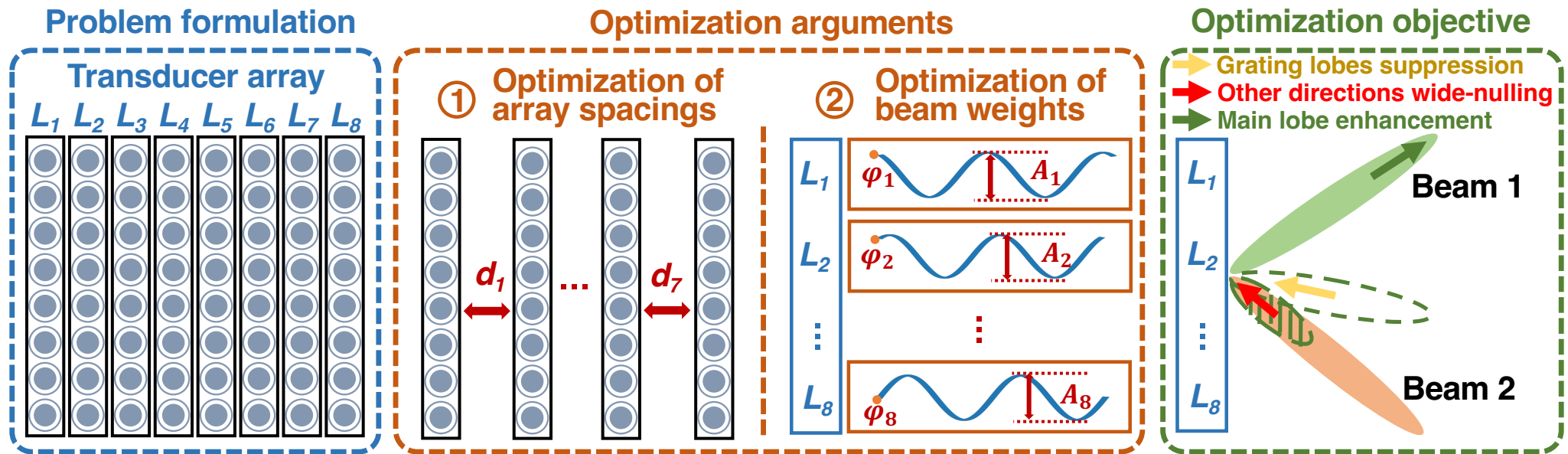
L_1 L_2 L_3 L_4 L_5 L_6 L_7 L_8



Optimization-based Beamforming



Optimization-based Beamforming

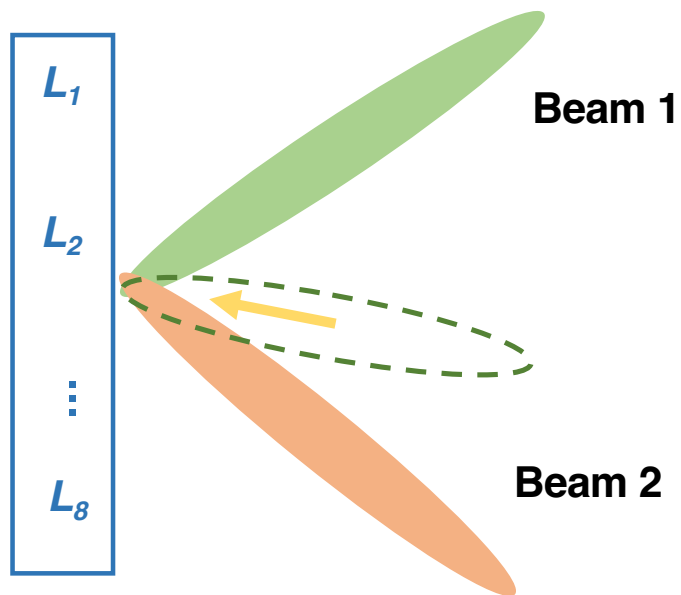


Optimization-based Beamforming



Optimization Objective

→ Grating lobes suppression



■ Grating lobes suppression

$$L_{grating} = \sum \mathcal{P}(\mathcal{PM}(\Theta_{grating}))$$



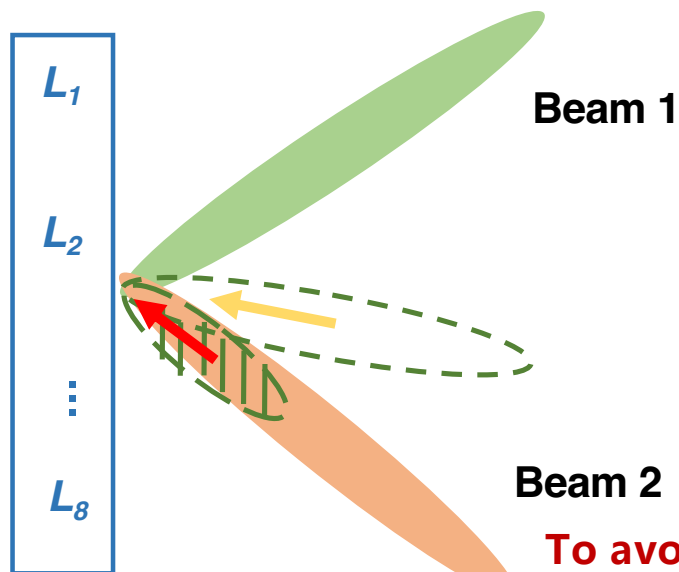
Optimization-based Beamforming



Optimization Objective

→ Grating lobes suppression

→ Other directions wide-nulling



■ Grating lobes suppression

$$L_{grating} = \sum \mathcal{P}(\mathcal{PM}(\Theta_{grating}))$$

■ Other directions wide-nulling

$$L_{other} = \sum \mathcal{PM}([\Theta_{other} - \gamma, \Theta_{other} + \gamma])$$

To avoid unintended acoustic outputs caused by interferences of multiple beams.



Optimization-based Beamforming

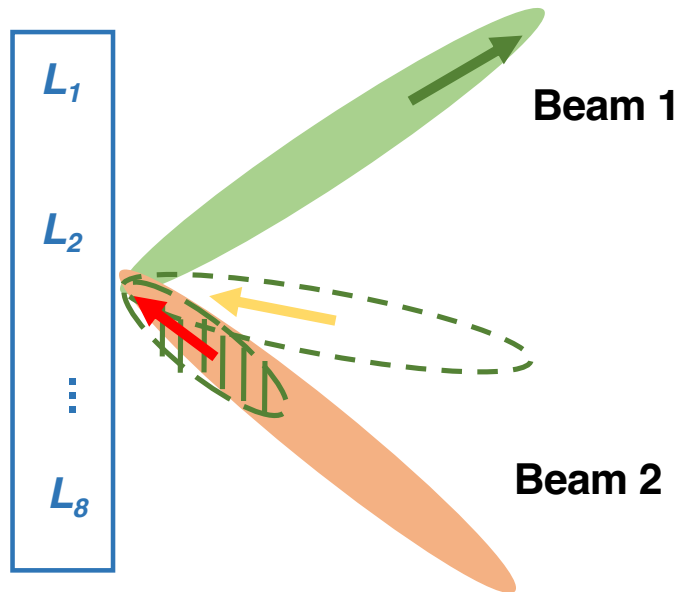


Optimization Objective

→ Grating lobes suppression

→ Other directions wide-nulling

→ Main lobe enhancement



■ Grating lobes suppression

$$L_{grating} = \sum \mathcal{P}(\mathcal{PM}(\Theta_{grating}))$$

■ Other directions wide-nulling

$$L_{other} = \sum \mathcal{PM}([\Theta_{other} - \gamma, \Theta_{other} + \gamma])$$

■ Main lobe enhancement

$$L_{main} = \sum \mathcal{PM}([\theta - \xi, \theta + \xi])$$



Optimization-based Beamforming

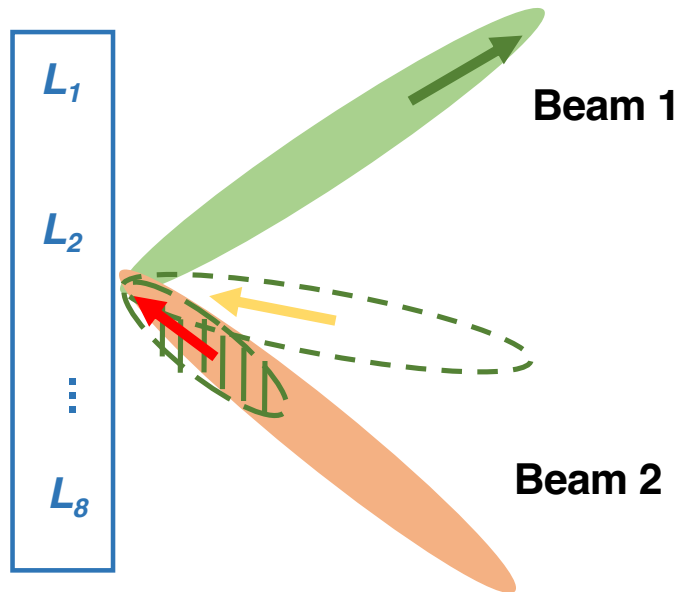


Optimization Objective

→ Grating lobes suppression

→ Other directions wide-nulling

→ Main lobe enhancement



■ Grating lobes suppression

$$L_{grating} = \sum \mathcal{P}(\mathcal{PM}(\Theta_{grating}))$$

■ Other directions wide-nulling

$$L_{other} = \sum \mathcal{PM}([\Theta_{other} - \gamma, \Theta_{other} + \gamma])$$

■ Main lobe enhancement

$$L_{main} = \sum \mathcal{PM}([\theta - \xi, \theta + \xi])$$

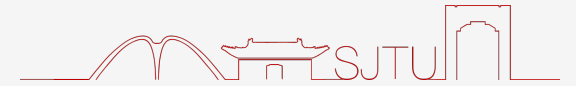
Objective Function

$$\min_{\omega, D} \lambda L_{grating} + \nu L_{other} - L_{main}$$

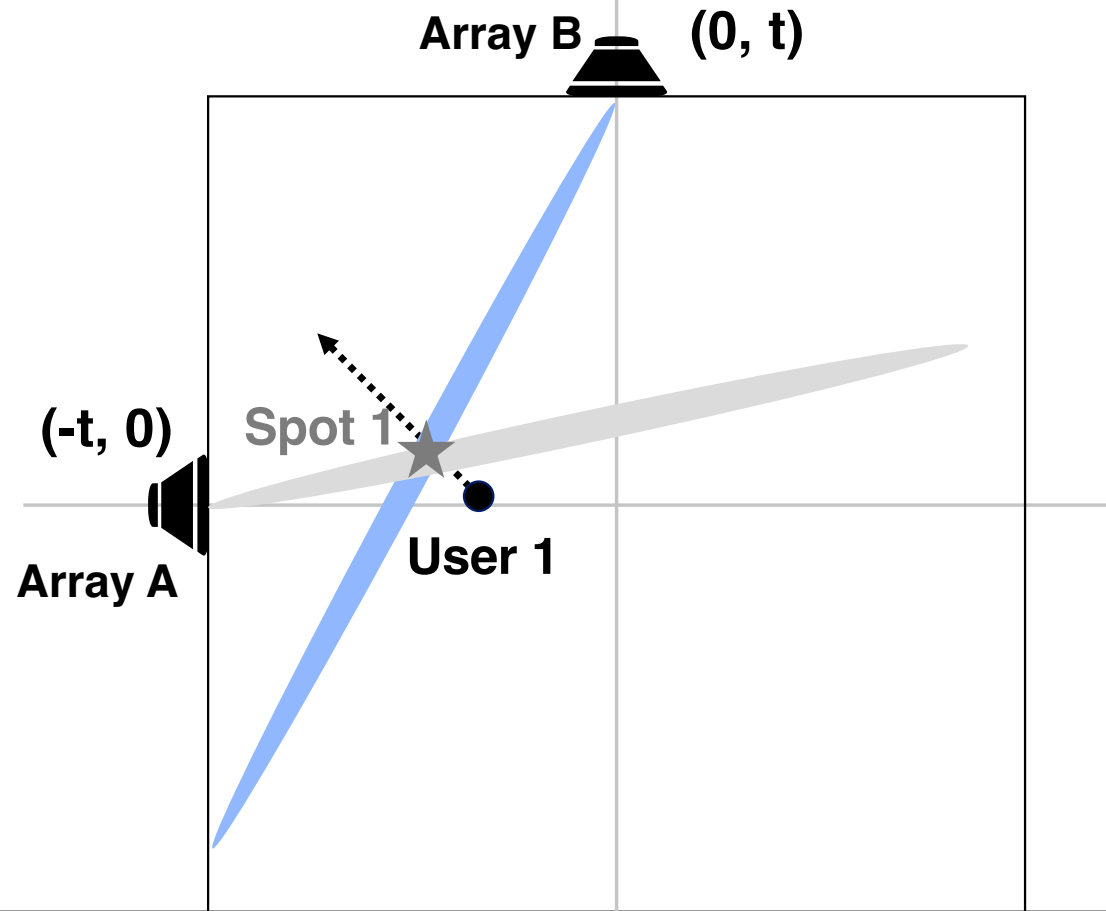
$$s.t. \quad \begin{cases} |\omega_\theta| \leq 1 & (\theta \in \Theta) \\ d_m \geq L & (1 \leq m \leq N - 1). \end{cases}$$



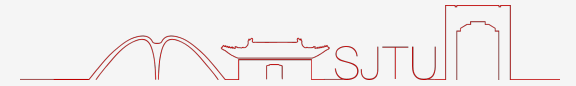
Challenge 2: Mutual Interference



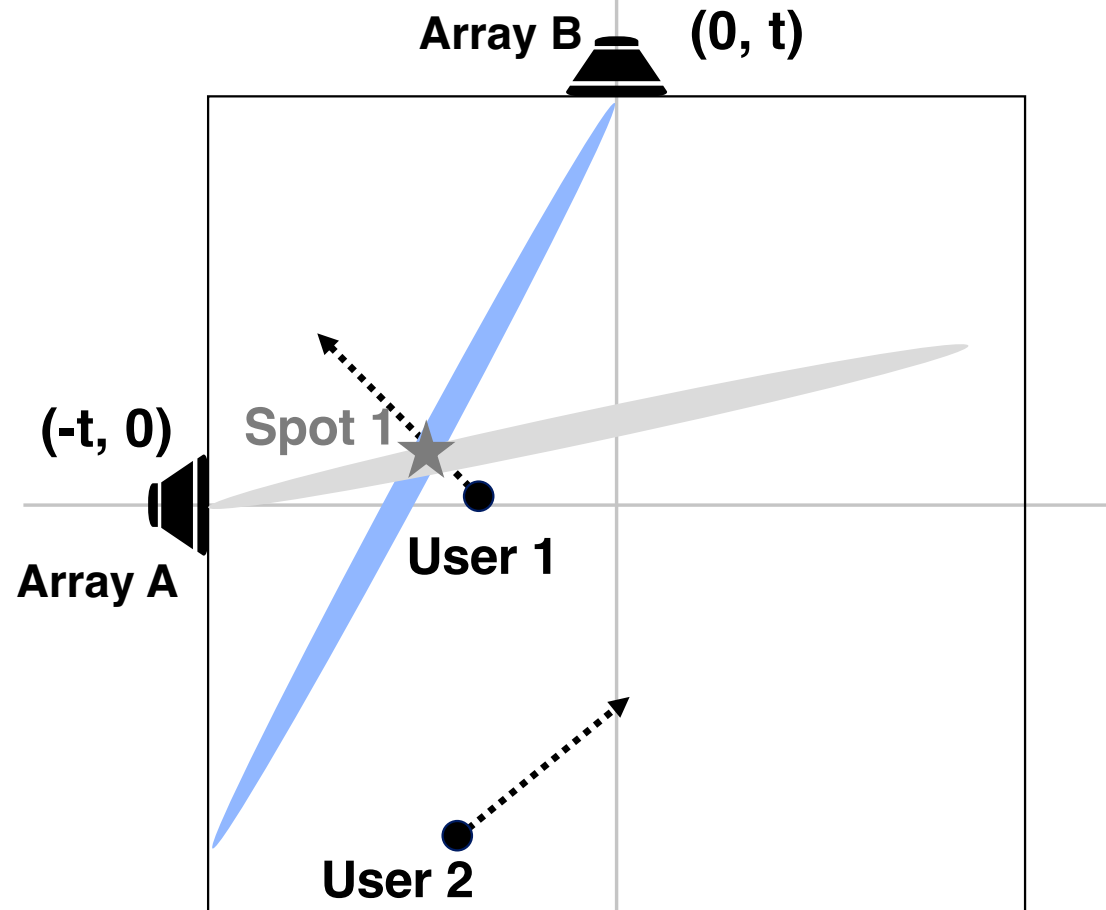
One User Scenario



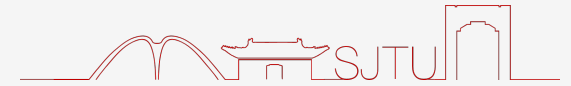
Challenge 2: Mutual Interference



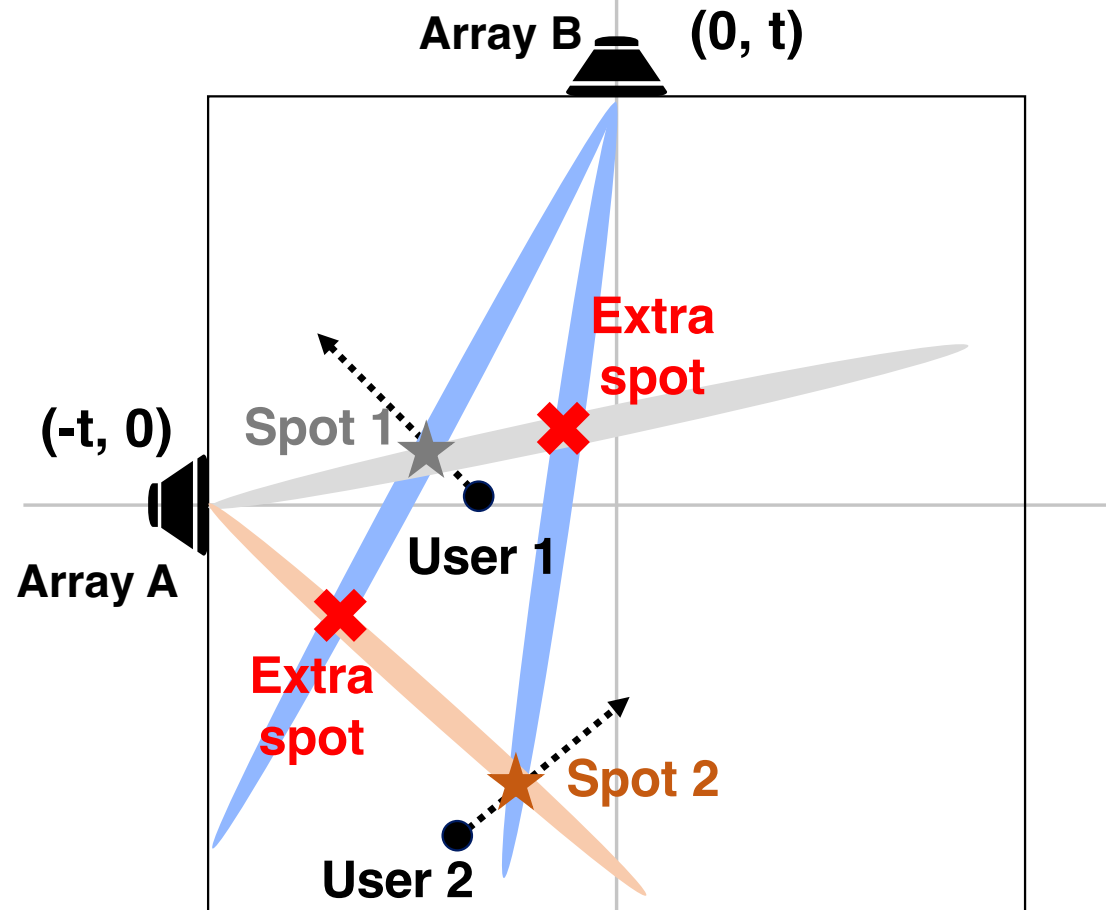
One User Scenario



Challenge 2: Mutual Interference



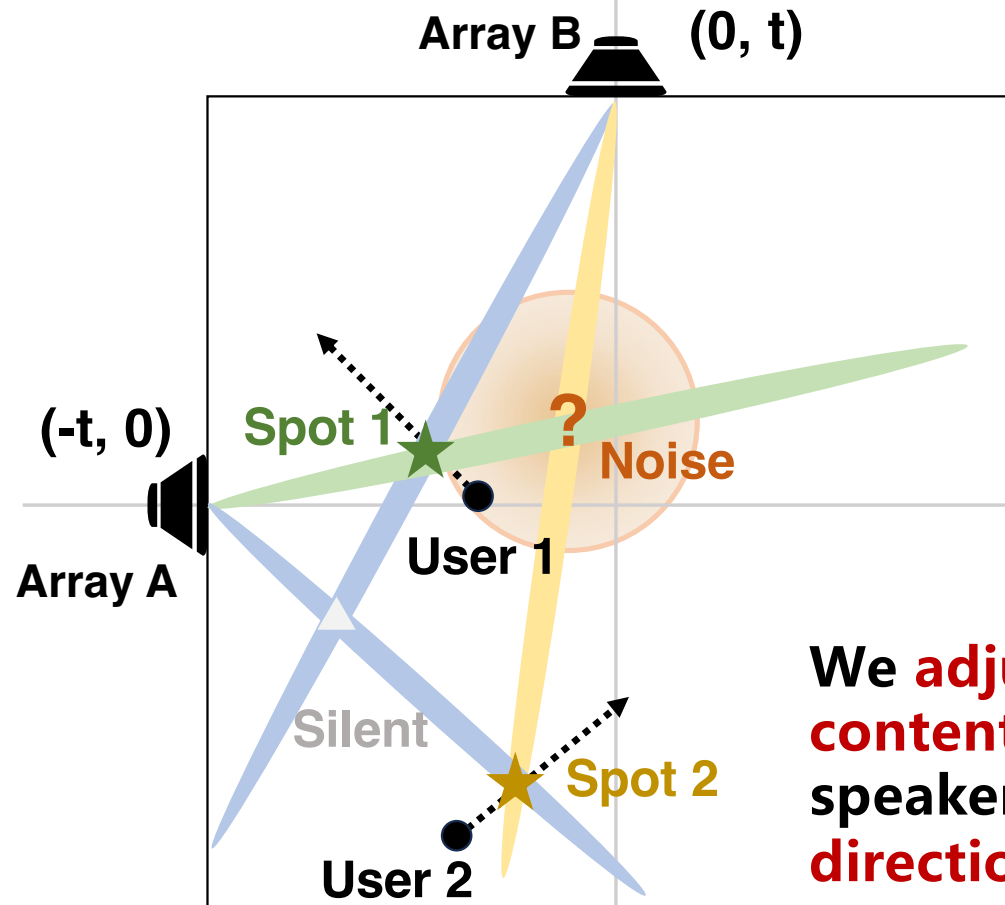
One User Scenario



Spot Scheduling



Transmission Content Redistribution



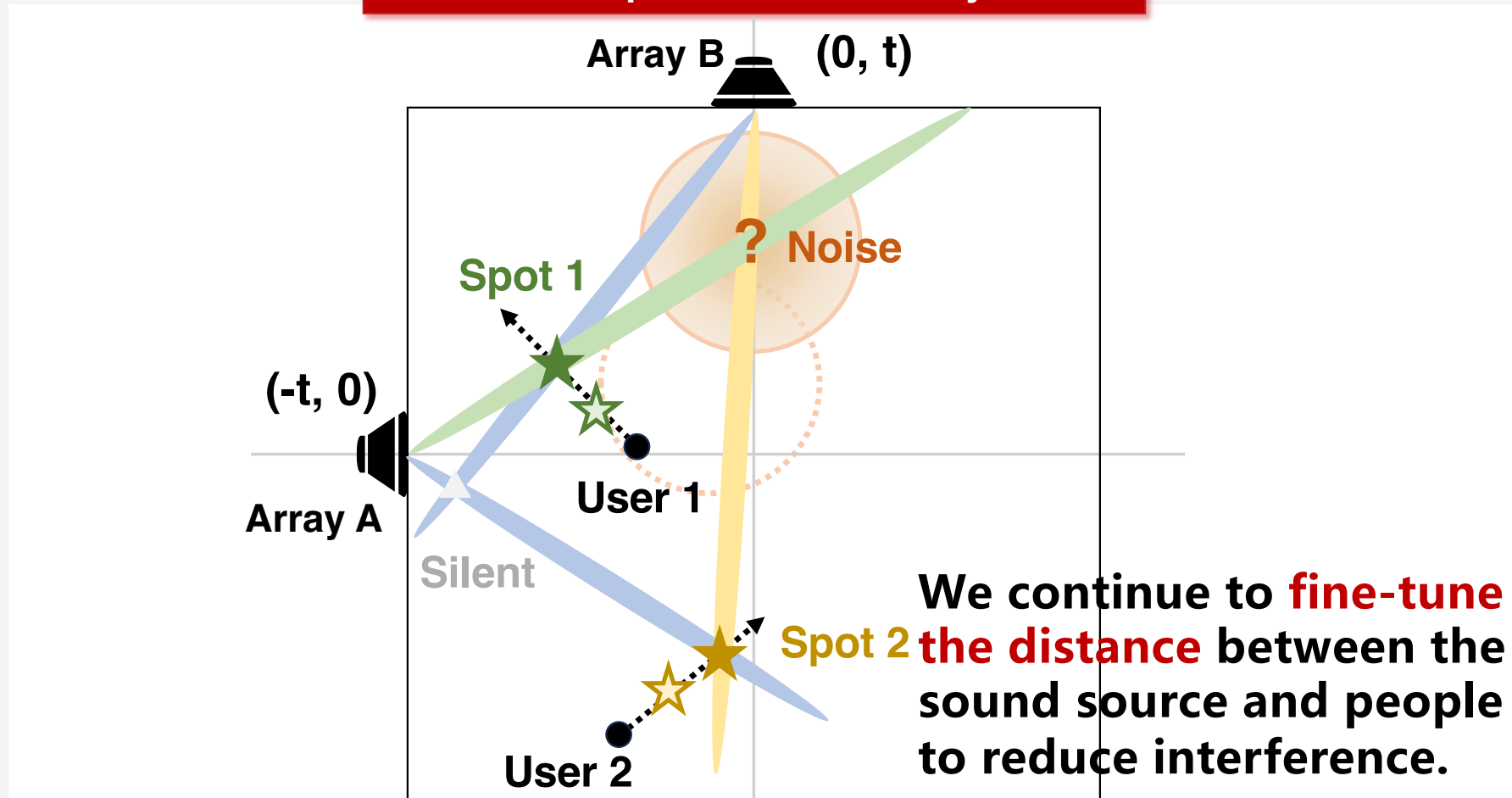
We **adjust the audio content** emitted by each speaker array in **different directions**.



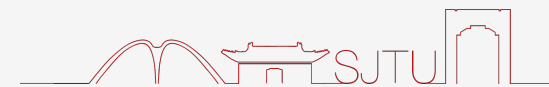
Spot Scheduling



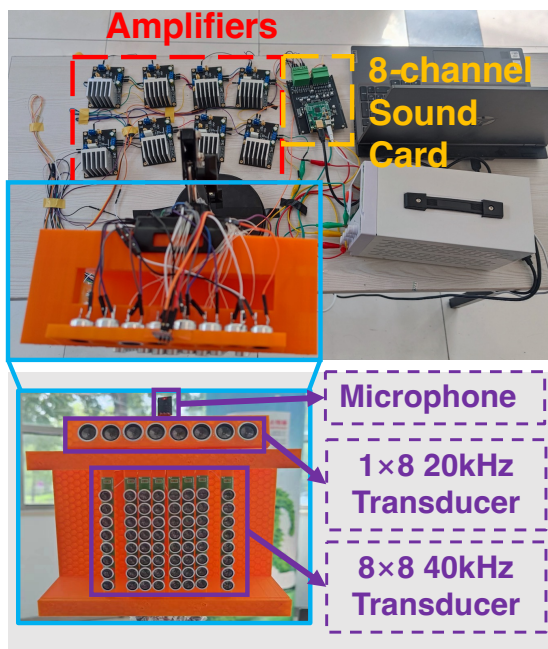
Extraneous Spots' Locations Adjustment



Experiment Setup



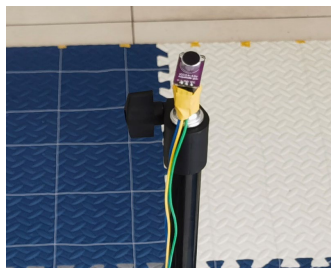
Transmitter



Receiver

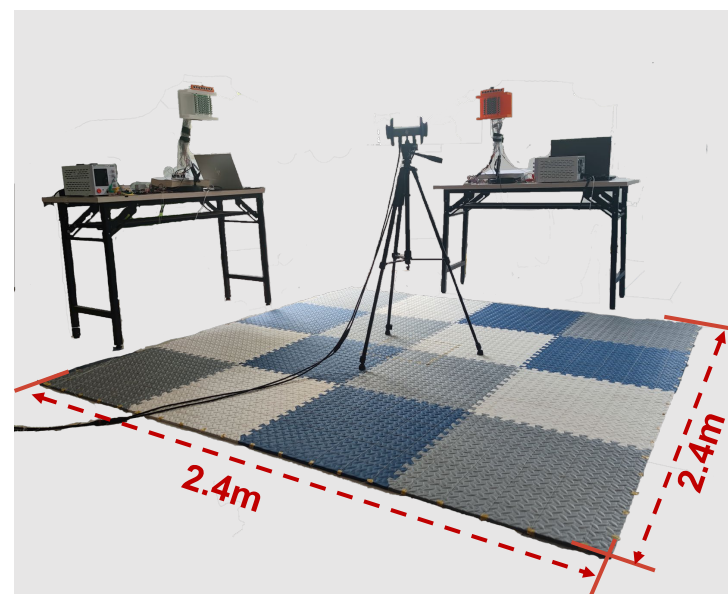


(1) Binaural Microphone

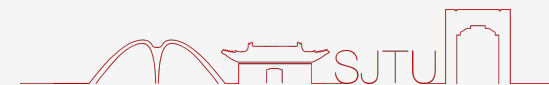


(2) Electret Condenser Microphone

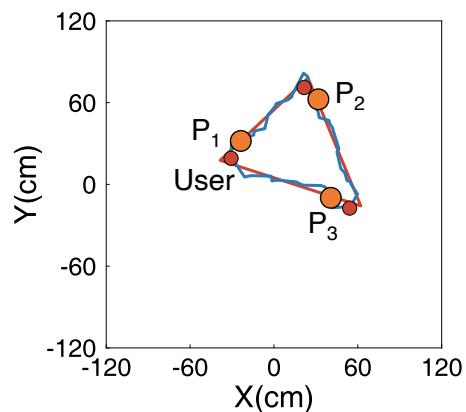
Test Scenario



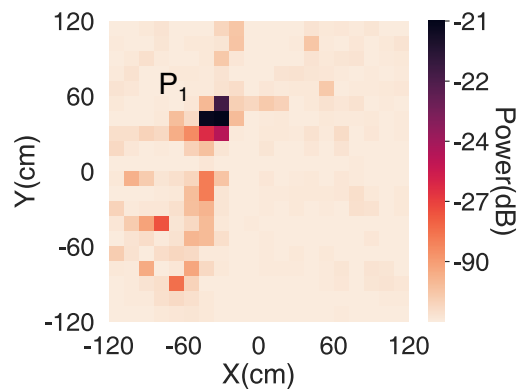
Performance



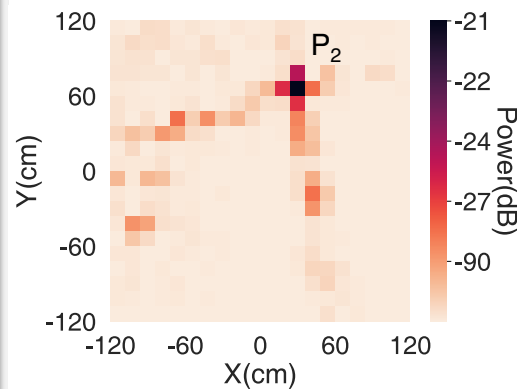
Trajectory



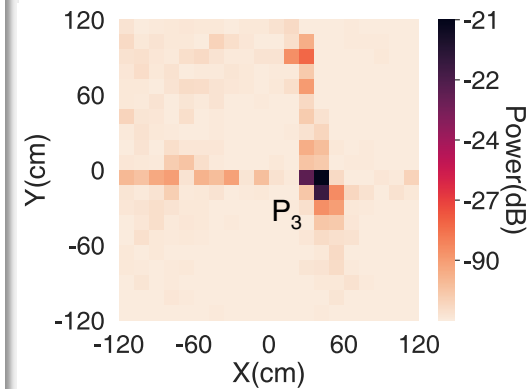
Heatmap at P₁



Heatmap at P₂



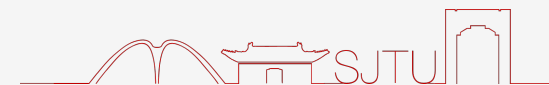
Heatmap at P₃



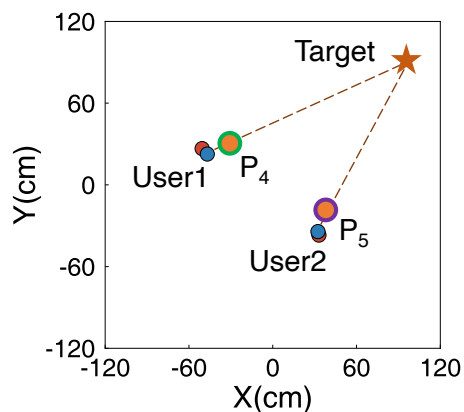
The system can project sound sources based on the user's position



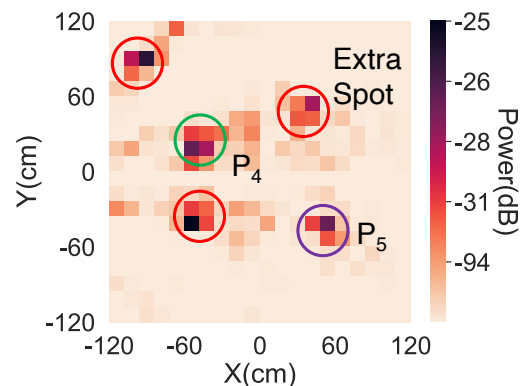
Performance



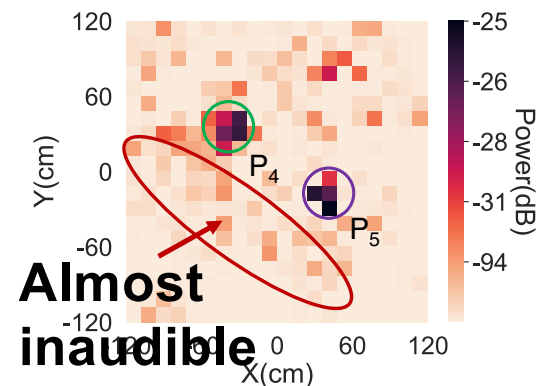
Guidance



Without Optimization



With Optimization



The system can reduce interference from extraneous spots in multi-user scenarios



Conclusion



- Proposed a Visar system for **multi-spot, multi-user** AAR applications.
- Developed an **optimization-based beamforming** method to reduce audio leakage from **grating lobes** and beam interference.
- Addressed **multi-spot scheduling** by adjusting content distribution and spot locations to **minimize interference**.





上海交通大學

SHANGHAI JIAO TONG UNIVERSITY

Thank You

飲水思源 愛國榮校