Exploiting an External Microphone to Improve Time-Difference-of-Arrival Estimates for Euclidean Distance Matrix-Based Source Localization

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Introduction

- Many source localization methods rely on estimated time-differences-of-arrival (TDOAs) between microphone pairs
- Accurate TDOA estimation in noisy and reverberant environments not straightforward
- We assume an external microphone is available in the vicinity of the source (capturing strong direct source component, relative to noise and reverberation)

What is an External Microphone?

An **additional microphone** to a main array, which is usually **spatially separated** and **has an unknown position**.

MAIN IDEAS

Exploit favourable acoustic conditions of external microphone near the source to

- improve reliability of estimated TDOAs
- improve accuracy of Euclidean distance matrix (EDM)-based source localization [1]

without requiring knowledge of external microphone position.

TDOA Estimation

Generalized Cross Correlation with Phase Transform (GCC-PHAT) Method [2]

Noisy and reverberant m-th microphone signal

$$Y_m(\omega) = \underbrace{X_{d,m}(\omega)}_{\text{direct}} + \underbrace{X_{r,m}(\omega)}_{\text{reverberation}} + \underbrace{N_m(\omega)}_{\text{noise}}$$

Frequency-domain GCC-PHAT function between i-th and j-th microphones

$$\psi_{i,j}(\omega) = \frac{\mathbb{E}\{Y_i(\omega)Y_j^*(\omega)\}}{|\mathbb{E}\{Y_i(\omega)Y_j^*(\omega)\}|}$$

Time-domain GCC-PHAT function

$$\xi_{i,j}(\tau) = \int_{-\omega_0}^{\omega_0} \psi_{i,j}(\omega)e^{j\omega\tau}d\omega$$

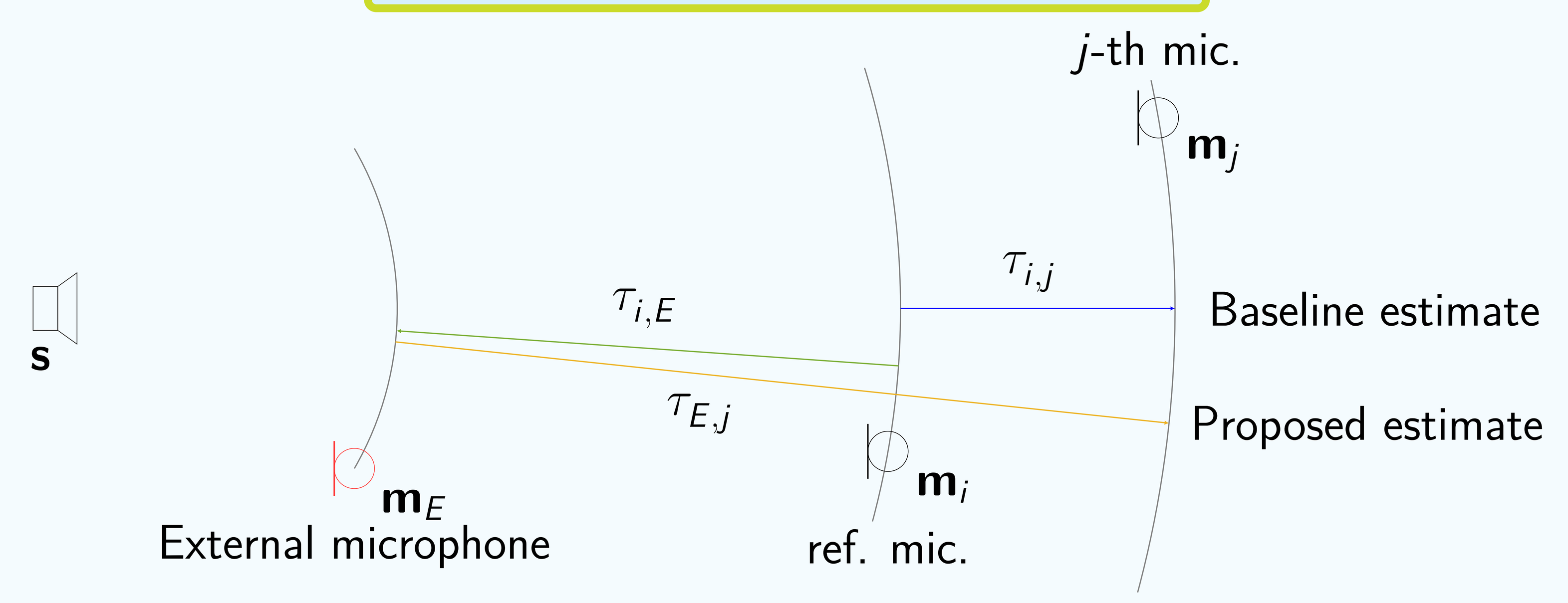
Conventional TDOA Estimation

$$\hat{\tau}_{i,j} = \underset{\tau}{\operatorname{argmax}} \; \xi_{i,j}(\tau)$$

GCC-PHAT Function Exploiting External Microphone

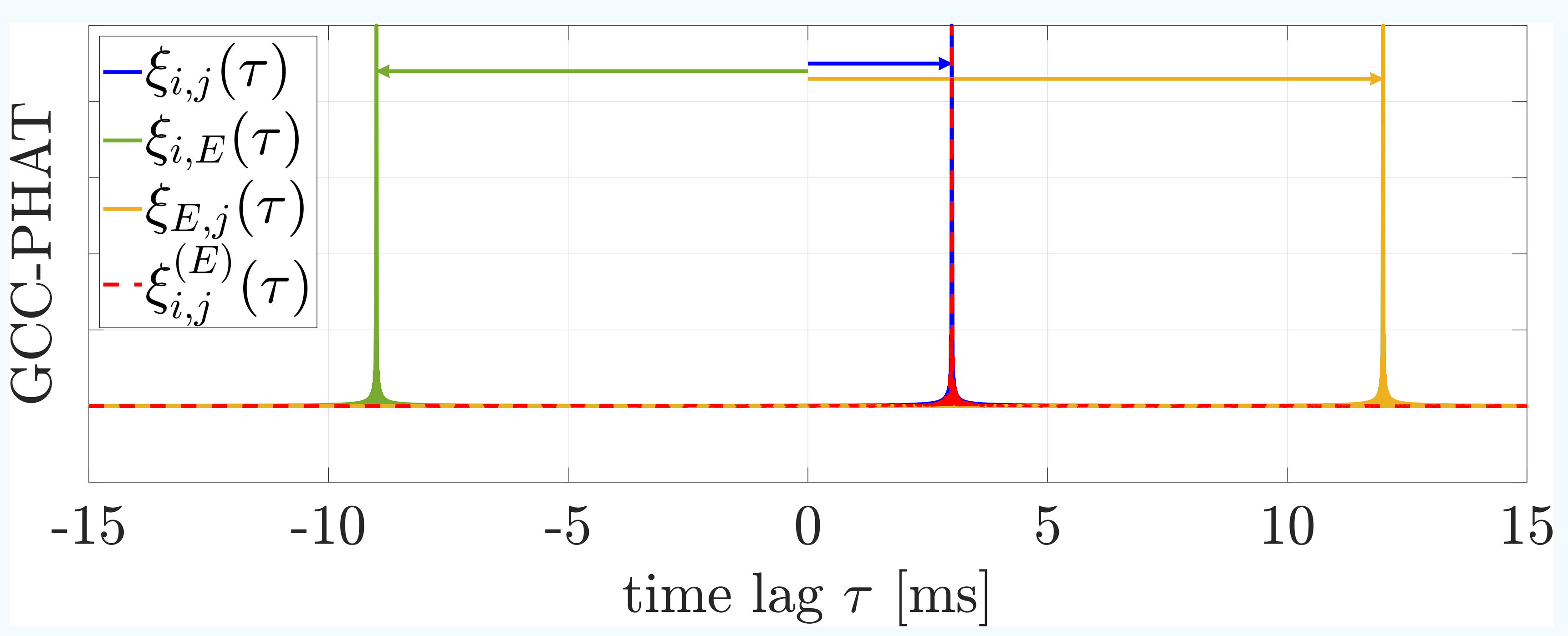
Exploit favourable acoustic conditions of external microphone by incorporating it in the GCC-PHAT function of microphones in main array

$$\xi_{i,j}^{(E)}(\tau) = \int_{-\infty}^{\infty} \xi_{i,E}(\tau')\xi_{E,j}(\tau-\tau')d\tau'$$



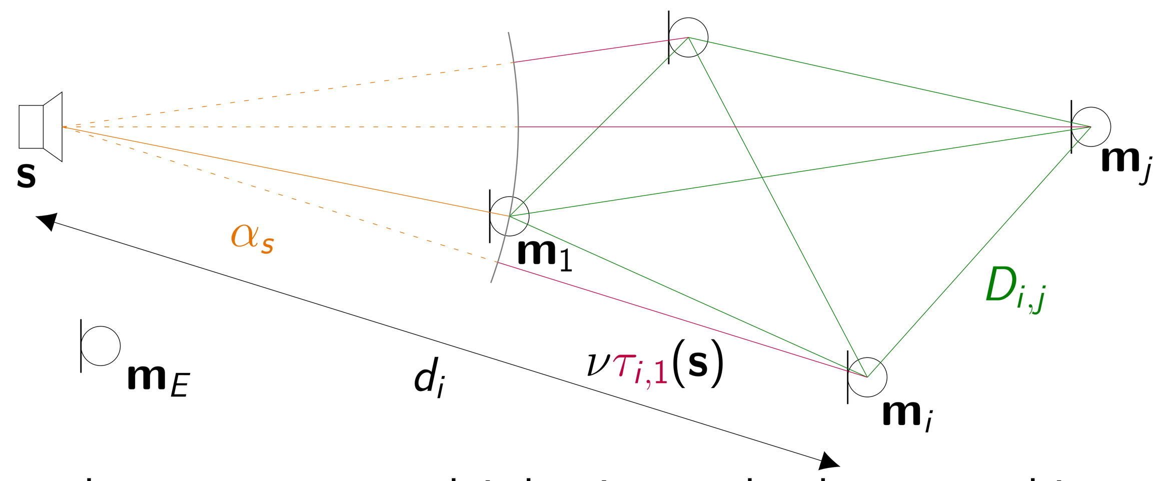
Anechoic case:

$$\xi_{i,j}^{(E)}(\tau) = \int_{-\infty}^{\infty} \delta\left(\tau' - \frac{\alpha_i - \alpha_E}{\nu}\right)\delta\left(\tau - \frac{\alpha_E - \alpha_j}{\nu} - \tau'\right) d\tau' = \delta(\tau - \tau_{i,j})$$



EDM-Based Source Position Estimation [1]

Given a distributed microphone array (DMA) with a known geometry



unknown distance between source and i-th mic. can be decomposed into two components

$$d_i = \underbrace{\alpha_s}_{\text{source to ref. mic.}} + \underbrace{\nu\,\tau_{i,1}(\mathbf{s})}_{\text{ref. mic. to } i\text{-th mic}}$$

Theory: Assuming that TDOAs $\tau_{i,1}(\mathbf{s})$ are available and defining

$$d_i(\alpha) = \alpha + \nu\,\tau_{i,1}(\mathbf{s})$$

with variable α, an EDM-based cost function $J(\alpha)$ can be used to compute α_s

$$\alpha_s = \underset{\alpha}{\operatorname{argmin}} \; J(\alpha) = \underset{\alpha}{\operatorname{argmin}} \sum_{i=3+1}^{M+1} |\lambda_i(\alpha)|$$

Practice: consider multiple TDOA estimates per microphone pair

$$\hat{\alpha}_s = \underset{\alpha, c_2, \ldots, c_M}{\operatorname{argmin}} \; J(\alpha, \hat{\tau}_{2,1}^{c_2}, \ldots, \hat{\tau}_{M,1}^{c_M})$$

Experimental Evaluation

Comparison of 3D source position estimation error $\varepsilon_s = ||\mathbf{s} - \hat{\mathbf{s}}||_2$ of EDM-based source position estimation method using TDOA estimates from:

- GCC-PHAT function $\xi_{i,j}(\tau)$ without external microphone
- External microphone-based GCC-PHAT function $\xi_{i,j}^{(E)}(\tau)$

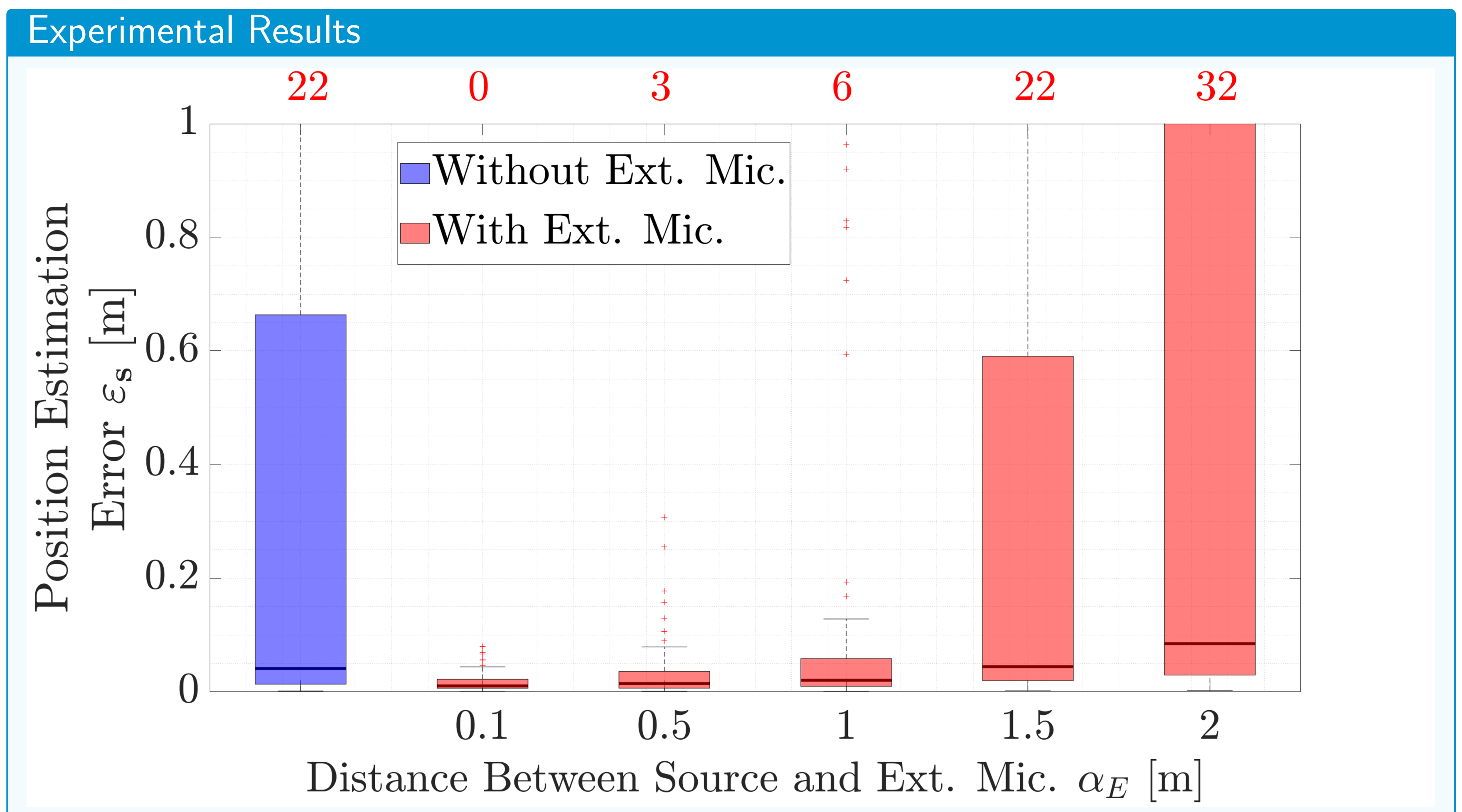
Framework and Acoustical Parameters

- $6 \times 6 \times 2.4$ m room simulated with RIR generator [3]
- $M = 6$ microphones randomly positioned within cube with cube length 2 m
- 100 acoustic scenarios (random 5 s speech signal, microphone array position & geometry, and speech source position (3 m away from centroid of DMA))
- Babble noise at average SNR = 0 dB across the microphones of the DMA
- Average direct-to-reverberant ratio (DRR) = 0 dB across the microphones of the DMA
- f_s = 16 kHz, 512 sample (32 ms) frame length, 50% overlap between frames, 1024 sample FFT-length

SNR and DRR for different external microphone positions between source and centroid of DMA

Distance between source and external microphone [m]	0.1	0.5	1	1.5	2
SNR in external microphone [dB]	23	9	5	2	1
DRR in external microphone [dB]	24	11	6	3	2

Experimental Results



3D position estimation error using EDM-based source position estimation method, where the TDOAs were estimated **without** and **with** an external microphone. The red numbers at the top indicate the number of results outside of the plotted range.

Conclusions and Outlook

- ✓ Incorporating **external microphone** for TDOA estimation **considerably improves accuracy of source position estimate**, particularly when the external microphone is located close to source.
- Further analysis of influencing parameters needed (SNR, DRR, external microphone position)

References

[1] K. Brümann and S. Doclo, "3D single source localization based on Euclidean distance matrices," in *Proc. International Workshop on Acoustic Echo and Noise Control (IWAENC)*. Bamberg, Germany: IEEE, 2022, pp. 1–5.

[2] C. Knapp and G. Carter, "The generalized correlation method for estimation of time delay," *IEEE Trans. on Audio, Speech, Language Processing*, vol. 24, no. 4, pp. 320–327, 1976.

[3] E. A. P. Habets, *RIR-Generator*, available at "https://github.com/ehabets/RIR-Generator".

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