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Binaural beam-forming with dominant spatial cue preservation for hearing aids



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Overview

WHY PRESERVE
SPATIAL CUES?

OBJECTIVE

&

PROPOSED METHODS

RESULTS &
CONCLUSION

Introduction

- Hearing aids use beam-forming to enhance speech signals.
  - Binaural beam-forming estimates the target better than bilateral hearing aid configuration.

- Spatial cue preservation is necessary.
  - To help retain the spatial information of the auditory scene.
  - Spatial release from masking improves speech intelligibility [1].

- Major spatial cue [2]:
  - Interaural Time Difference (ITD)
  - Interaural Level Difference (ILD)
  - Interaural Coherence (IC)
  - Spectral Cues (Elevation Cues)

Lateralisation Cues [3]

Binaural Cues

- Binaural cues are frequency selective. [4]
  - ITD cues are dominant in f < 1.5 kHz
  - ILD cues are dominant in f ≥ 1.5 kHz

Signal Model

- Introduction
- Motivation
- Methods Proposed
- Results
- Conclusion

$$\mathbf{y} = \mathbf{a}s + \sum_{i=1}^{r} \mathbf{b}_i u_i + \mathbf{v} \quad \text{(In STFT domain)}$$

$\boldsymbol{a} = [a_1\ a_2\ \ldots\ a_M]^T$ - *ATF of the target signal w.r.t 'M' microphones*

$\boldsymbol{b}_i = [b_{i,1}\ b_{i,2}\ \ldots\ b_{i,M}]^T$ - *ATF of the i^{th} interfering signal w.r.t 'M' microphones*

$\boldsymbol{v} = [v_1\ v_2\ \ldots\ v_M]^T$ - *Additive microphone self noise at 'M' microphones*

$\boldsymbol{y} = [y_1\ y_2\ \ldots\ y_M]^T$ - *Measured signal at 'M' microphones*

$M = 4$

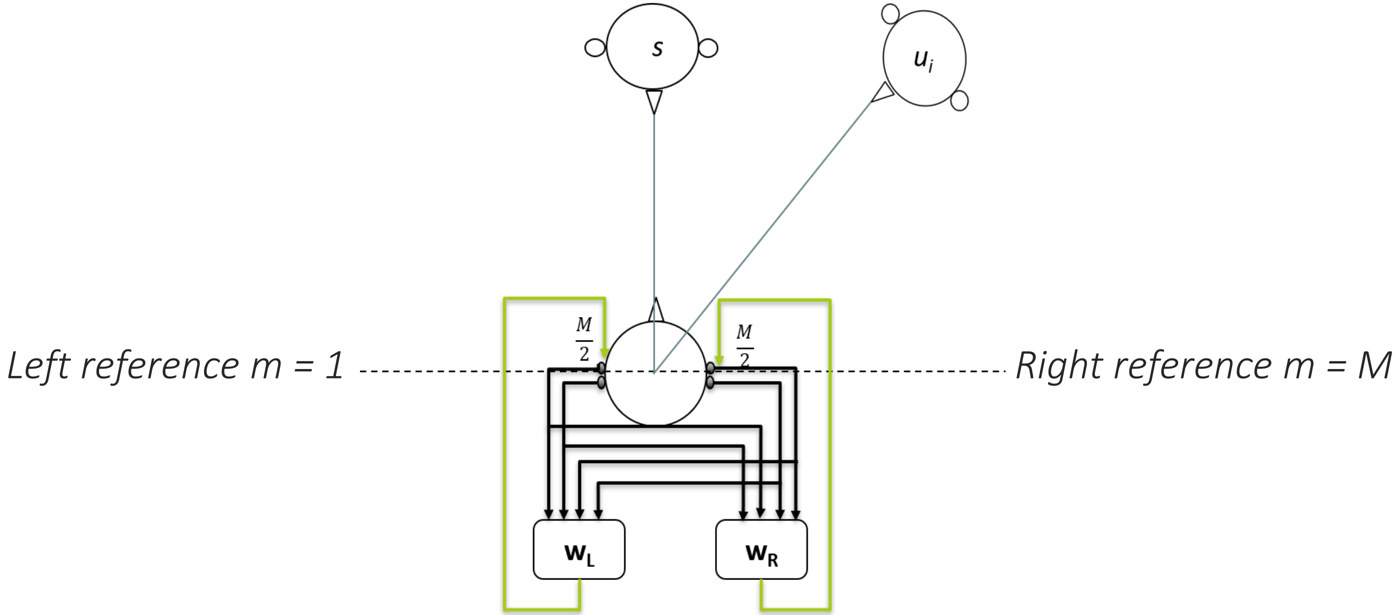

Figure: Binaural Hearing Aid Setup

Previous Work

- Introduction
- Motivation
- Methods Proposed
- Results
- Conclusion

Taking $\boldsymbol{w} = [\boldsymbol{w}_L^H \quad \boldsymbol{w}_R^H]^H \in \mathbb{C}^{2\text{M x 1}}$

BMVDR [5]	RBLCMV [6]	JBLCMV [7]
$min\ \boldsymbol{w}^H \widetilde{\boldsymbol{P}} \boldsymbol{w}$ s.t. $\mathbf{w}^{\mathrm{H}} \underbrace{\begin{bmatrix} \boldsymbol{a} & 0 \\ 0 & \boldsymbol{a} \end{bmatrix}}_{\boldsymbol{\Lambda}_A} = \underbrace{[a_1 \quad a_M]}_{\boldsymbol{f}_A^H}$	$min\ \boldsymbol{w}^H \widetilde{\boldsymbol{P}} \boldsymbol{w}$ s. t. $\boldsymbol{w}^{\boldsymbol{H}} \boldsymbol{\Lambda}_{\boldsymbol{A}} = \boldsymbol{f}_{\boldsymbol{A}}^{\boldsymbol{H}}$	$min\ \boldsymbol{w}^H \widetilde{\boldsymbol{P}} \boldsymbol{w}$ s.t. $\boldsymbol{w}^{\boldsymbol{H}} \boldsymbol{\Lambda}_{\boldsymbol{A}} = \boldsymbol{f}_{\boldsymbol{A}}^{\boldsymbol{H}}$
	$\left\| \frac{\boldsymbol{w}_L{}^H \boldsymbol{b}_i}{\boldsymbol{w}_R{}^H \boldsymbol{b}_i} - \frac{b_{i1}}{b_{iM}} \right\| \leq \varepsilon_i \; i = 1, \ldots, r$	$\boldsymbol{w}^H \begin{bmatrix} \boldsymbol{b}_1 b_{1M} & \ldots & \boldsymbol{b}_r b_{rM} \\ -\boldsymbol{b}_1 b_{11} & \ldots & -\boldsymbol{b}_r b_{r1} \end{bmatrix} = 0_{1xr}$

BMVDR:
- Best Noise Reduction
- Binaural Cues of Target preserved
- Interferers are co-located with the target

RBLCMV:
- Good Noise Reduction
- Binaural Cues of Target perfectly preserved
- Approximate interferer cue preservation

JBLCMV:
- Poor Noise Reduction
- Binaural Cues of Target & Interferers perfectly preserved

Objective

- Introduction
- **Motivation**
- Methods Proposed
- Results
- Conclusion

Will beam-forming with only the dominant binaural cue preservation of the noise components, help to improve the noise reduction performance, as opposed to the preservation of both the interaural level difference (ILD) and the interaural time difference (ITD) cues?

$$|\mathrm{ITF}_{u_i}{}^{in} - \mathrm{ITF}_{u_i}{}^{out}| \rightarrow |\mathrm{ITD}_{u_i}{}^{in} - \mathrm{ITD}_{u_i}{}^{out}| \quad f < 1.5\ \text{kHz}$$

$$|\mathrm{ITF}_{u_i}{}^{in} - \mathrm{ITF}_{u_i}{}^{out}| \rightarrow \boxed{|\mathrm{ILD}_{u_i}{}^{in} - \mathrm{ILD}_{u_i}{}^{out}|} \quad f \geq 1.5\ \text{kHz}$$

- Will preserving only ILD cues of the interferers in the higher frequencies help to improve the degrees of freedom available for noise reduction?

Optimisation Problem-P-ILD

$$
\begin{aligned}
\underset{\mathbf{w}_L,\mathbf{w}_R\in\mathbb{C}^{M\times 1}}{\text{minimise}} \quad & \mathbf{w}_L^H\mathbf{P}\mathbf{w}_L + \mathbf{w}_R^H\mathbf{P}\mathbf{w}_R \\
\text{subject to} \quad & \mathbf{w}_L^H\mathbf{a} = a_1 \quad \mathbf{w}_R^H\mathbf{a} = a_M \\
& \underbrace{\left|\frac{\mathbf{w}_L^H\mathbf{b_i}}{\mathbf{w}_R^H\mathbf{b_i}}\right|^2}_{\mathrm{ILD}_{u_i}{}^{out}} - \underbrace{\left|\frac{b_{i,1}}{b_{i,M}}\right|^2}_{\mathrm{ILD}_{u_i}{}^{in}} = 0, \quad i = 1,\dots,r \leq r_{max}.
\end{aligned}
$$

→ Eq.(1)

Optimising jointly w.r.t. $\mathbf{w}_L$ and $\mathbf{w}_R$

$$
\begin{aligned}
(\mathrm{P}_1)\ \underset{\mathbf{w}\in\mathbb{C}^{2M\times 1}}{\text{minimise}}\ & \mathbf{w}^H \underbrace{\begin{bmatrix} \mathbf{P} & \mathbf{0}_{M\times M} \\ \mathbf{0}_{M\times M} & \mathbf{P} \end{bmatrix}}_{\tilde{\mathbf{P}}\in\mathbb{C}^{2M\times 2M}} \mathbf{w} \\
\text{subject to } & \mathbf{w}^H \underbrace{\begin{bmatrix} \mathbf{a} & \mathbf{0} \\ \mathbf{0} & \mathbf{a} \end{bmatrix}}_{\mathbf{\Lambda}_A\in\mathbb{C}^{2M\times 2}} = \underbrace{\begin{bmatrix} a_1 & a_M \end{bmatrix}}_{\mathbf{f}_A^H\in\mathbb{C}^{1\times 2}} \\
& \mathbf{w}^H \underbrace{\begin{bmatrix} \mathbf{b_i}\mathbf{b_i}^H|b_{i,M}|^2 & \mathbf{0}_{M\times M} \\ \mathbf{0}_{M\times M} & -\mathbf{b_i}\mathbf{b_i}^H|b_{i,1}|^2 \end{bmatrix}}_{\mathbf{M_i}\in\mathbb{C}^{2M\times 2M}} \mathbf{w} = 0, \quad i = 1,\dots,r \leq r_{max}.
\end{aligned}
$$

Quadratic Equality Constraint

→ Eq.(2)

Non-convex

Optimisation Problem – P-ILD

- Introduction
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1. Linearising with $\mathbf{W} = \mathbf{w}\mathbf{w}^H$
2. Relaxing the equivalence constraint $\mathbf{W} \succeq \mathbf{w}\mathbf{w}^H$
3. Using the reformulation-linearization technique [9].

$$\text{(SDR-RLT}_1\text{)} \quad \underset{\substack{\mathbf{W}\in\mathbb{C}^{2M\times 2M},\\ \mathbf{w}\in\mathbb{C}^{2M\times 1}}}{\text{minimise}} \ \operatorname{Tr}(\mathbf{W}\tilde{\mathbf{P}}) \quad (1)$$

$$\text{subject to } \mathbf{w}^H\mathbf{\Lambda}_A = \mathbf{f}_A^H$$

$$(1) \quad \operatorname{Tr}(\mathbf{W}\mathbf{M}_i) = 0, \quad i = 1, \dots, r \le r_{max},$$

(3) Redundant constraints

$$\begin{cases} \mathbf{W}\mathbf{\Lambda}_A - \mathbf{w}\mathbf{f}_A^H = 0 \\ \operatorname{Tr}\left(\mathbf{W}\mathbf{\Lambda}_A\mathbf{\Lambda}_A^H\right) - \mathbf{w}^H\mathbf{\Lambda}_A\mathbf{f}_A - (\mathbf{\Lambda}_A\mathbf{f}_A)^H\mathbf{w} + \mathbf{f}_A^H\mathbf{f}_A = 0 \end{cases}$$

$$(2) \quad \begin{bmatrix} \mathbf{W} & \mathbf{w} \\ \mathbf{w}^H & 1 \end{bmatrix} \succeq 0.$$

Eq.(3)

[8] SDP Relaxation - Convex

Optimisation Problem – R-ILD

- Introduction
- Motivation
- Methods Proposed
- Results
- Conclusion

$$\begin{aligned}
&\underset{\mathbf{w}_L,\mathbf{w}_R\in\mathbb{C}^{M\times 1}}{\text{minimise}} && \mathbf{w}_L^H\mathbf{P}\mathbf{w}_L+\mathbf{w}_R^H\mathbf{P}\mathbf{w}_R\\
&\text{subject to} && \mathbf{w}_L^H\mathbf{a}=a_1 \quad \mathbf{w}_R^H\mathbf{a}=a_M\\
& && \left|\left|\frac{\mathbf{w}_L^H\mathbf{b_i}}{\mathbf{w}_R^H\mathbf{b_i}}\right|^2-\left|\frac{b_{i,1}}{b_{i,M}}\right|^2\right|\le\mathcal{E}_i, \quad i=1,\ldots,r\le r_{max}.
\end{aligned}$$

→ Eq.(4)

$$\mathcal{E}_i = c_i\underbrace{\left|\left|\frac{a_1}{a_M}\right|^2-\left|\frac{b_{i,1}}{b_{i,M}}\right|^2\right|}_{\epsilon_{u_i}^{\mathrm{BMVDR}}},$$

with $\quad 0\le c_i\le 1.$

Optimising jointly w.r.t. $\mathbf{w}_L$ and $\mathbf{w}_R$

$$(\mathrm{P}_2) \quad \underset{\mathbf{w}\in\mathbb{C}^{2M\times 1}}{\text{minimise}} \quad \mathbf{w}\tilde{\mathbf{P}}\mathbf{w}$$

$$\text{subject to} \quad \mathbf{w}^H\mathbf{\Lambda}_\mathbf{A}=\mathbf{f_A}^H$$

$$\mathbf{w}^H\underbrace{\begin{bmatrix}\mathbf{b_i}\mathbf{b_i}^H|b_{i,M}|^2 & \mathbf{0}_{M\times M}\\ \mathbf{0}_{M\times M} & -\mathbf{b_i}\mathbf{b_i}^H\left(|b_{i,1}|^2+\mathcal{E}_i|b_{i,M}|^2\right)\end{bmatrix}}_{\mathbf{M_{A,i}}\in\mathbb{C}^{2M\times 2M}}\mathbf{w}\le 0, \quad i=1,\ldots,r\le r_{max},$$

$$\mathbf{w}^H\underbrace{\begin{bmatrix}-\mathbf{b_i}\mathbf{b_i}^H|b_{i,M}|^2 & \mathbf{0}_{M\times M}\\ \mathbf{0}_{M\times M} & \mathbf{b_i}\mathbf{b_i}^H\left(|b_{i,1}|^2-\mathcal{E}_i|b_{i,M}|^2\right)\end{bmatrix}}_{\mathbf{M_{B,i}}\in\mathbb{C}^{2M\times 2M}}\mathbf{w}\le 0, \quad i=1,\ldots,r\le r_{max}.$$

Non- convex Quadratic Inequality Constraints

→ Eq.(5)

Non-convex

Optimisation Problem – R-ILD

- Introduction
- Motivation
- Methods Proposed
- Results
- Conclusion

1. Linearising with $\mathbf{W} = \mathbf{w}\mathbf{w}^H$
2. Relaxing the equivalence constraint
3. Introducing redundant constraints

$$
\begin{aligned}
(\text{SDR-RLT}_2)\ \underset{\substack{\mathbf{W}\in\mathbb{C}^{2M\times 2M},\\ \mathbf{w}\in\mathbb{C}^{2M\times 1}}}{\text{minimise}}\ & \text{Tr}(\mathbf{W}\tilde{\mathbf{P}}) \quad ① \\
\text{subject to } & \mathbf{w}^H\mathbf{\Lambda}_A = \mathbf{f}_A^H \\
& \text{Tr}\left(\mathbf{W}\mathbf{M}_{A,i}\right) \leq 0, \quad i = 1,\ldots,r \leq r_{max}, \\
& \text{Tr}\left(\mathbf{W}\mathbf{M}_{B,i}\right) \leq 0, \quad i = 1,\ldots,r \leq r_{max}, \\
③\ \text{Redundant constraints}\ \Bigg\{\ & \mathbf{W}\mathbf{\Lambda}_A - \mathbf{w}\mathbf{f}_A^H = 0 \\
& \text{Tr}\left(\mathbf{W}\mathbf{\Lambda}_A\mathbf{\Lambda}_A^H\right) - \mathbf{w}^H\mathbf{\Lambda}_A\mathbf{f}_A - \left(\mathbf{\Lambda}_A\mathbf{f}_A\right)^H\mathbf{w} + \mathbf{f}_A^H\mathbf{f}_A = 0 \\
② \ & \begin{bmatrix} \mathbf{W} & \mathbf{w} \\ \mathbf{w}^H & 1 \end{bmatrix} \succeq 0.
\end{aligned}
$$

→ Eq.(6)

SDP Relaxation - Convex

Experimental Setup

- Introduction
- Motivation
- Methods Proposed
- Results
- Conclusion

- Target - Speech signal – 30 seconds – F_s = 16 kHz
- Number of Interferers = 7 – Speech signals
- Microphones per ear = $\frac{M}{2} = 2$
- JBLCMV for f < 1.5 kHz + proposed method for f $\geq$ 1.5 kHz
- Anechoic and Office HRTF from the database in [11]
- BMVDR, JBLCMV, P-ILD, R-ILD (c = 0.2)

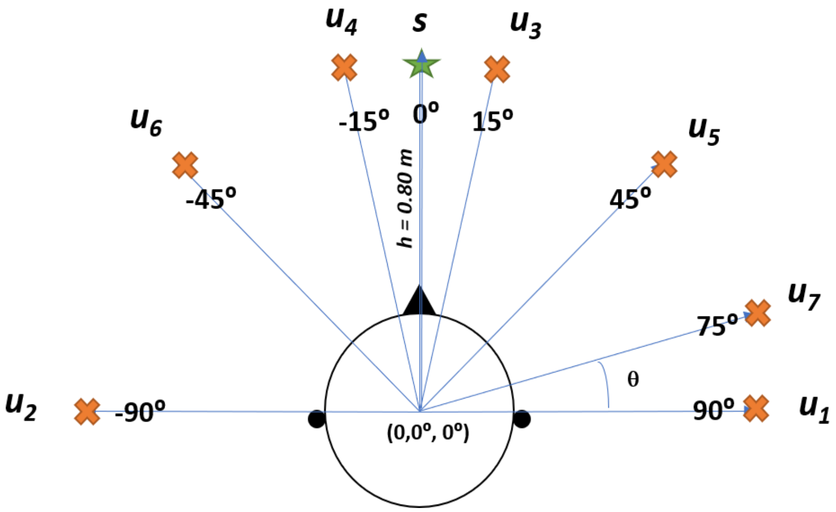

Figure: Acoustic Environmental Setup

Results

- Introduction
- Motivation
- Methods Proposed
- Results
- Conclusion

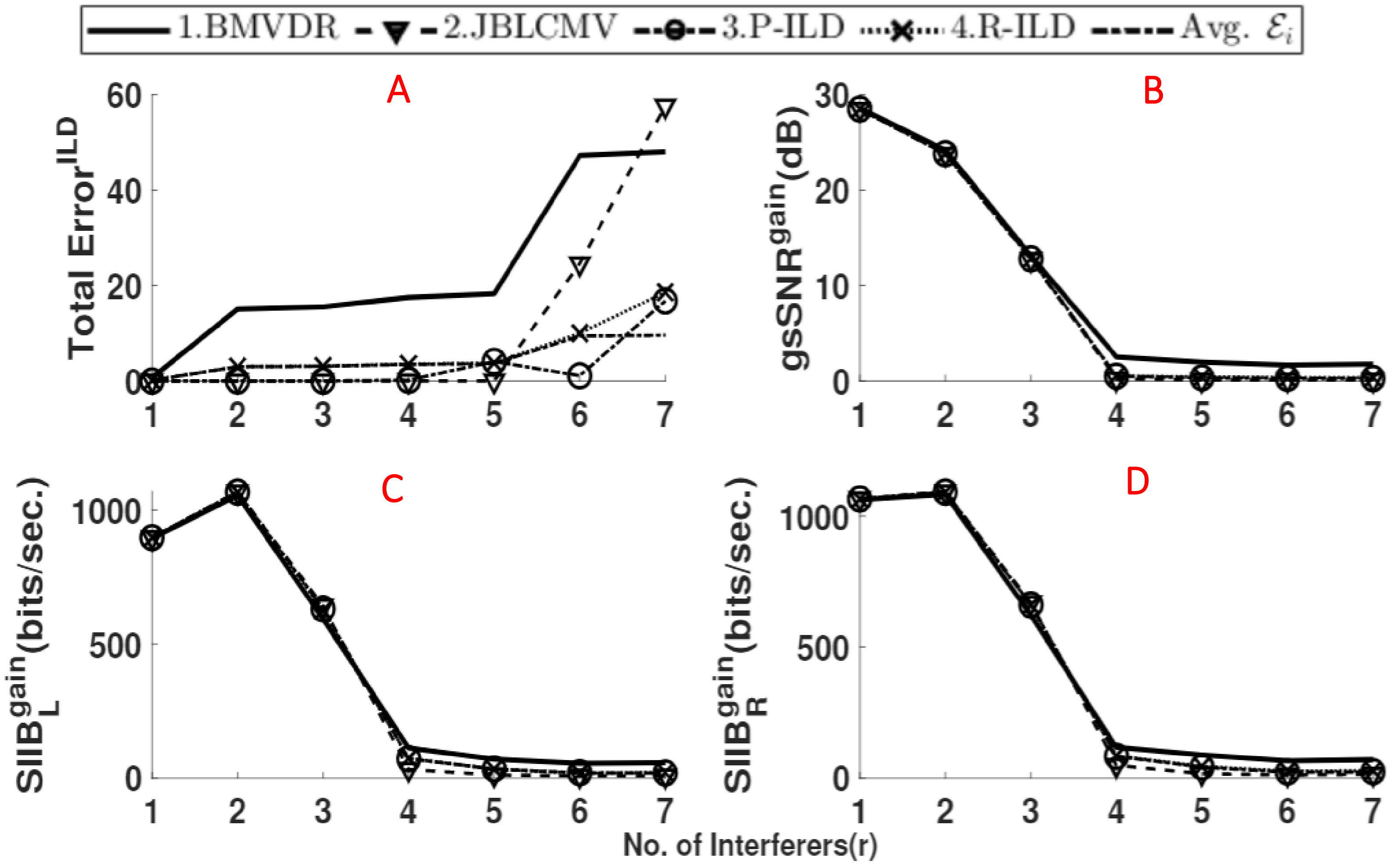

Fig. 1. Anechoic : ILD error, gsSNR^{gain} and SIIB^{gain} vs. No. of Interferers.

Results

- Introduction
- Motivation
- Methods Proposed
- **Results**
- Conclusion

Table: Listening Test Scenario

Scene	Target	Interferer 1	Interferer 2	Interferer 3	Microphone Noise	Environment
Signals	Female Speech	Male Speech	Music	HF Signal	WGN	
A	0°	90°	-60°	30°	Yes	Anechoic
B	0°	-75°	-15°	45°	Yes	Office

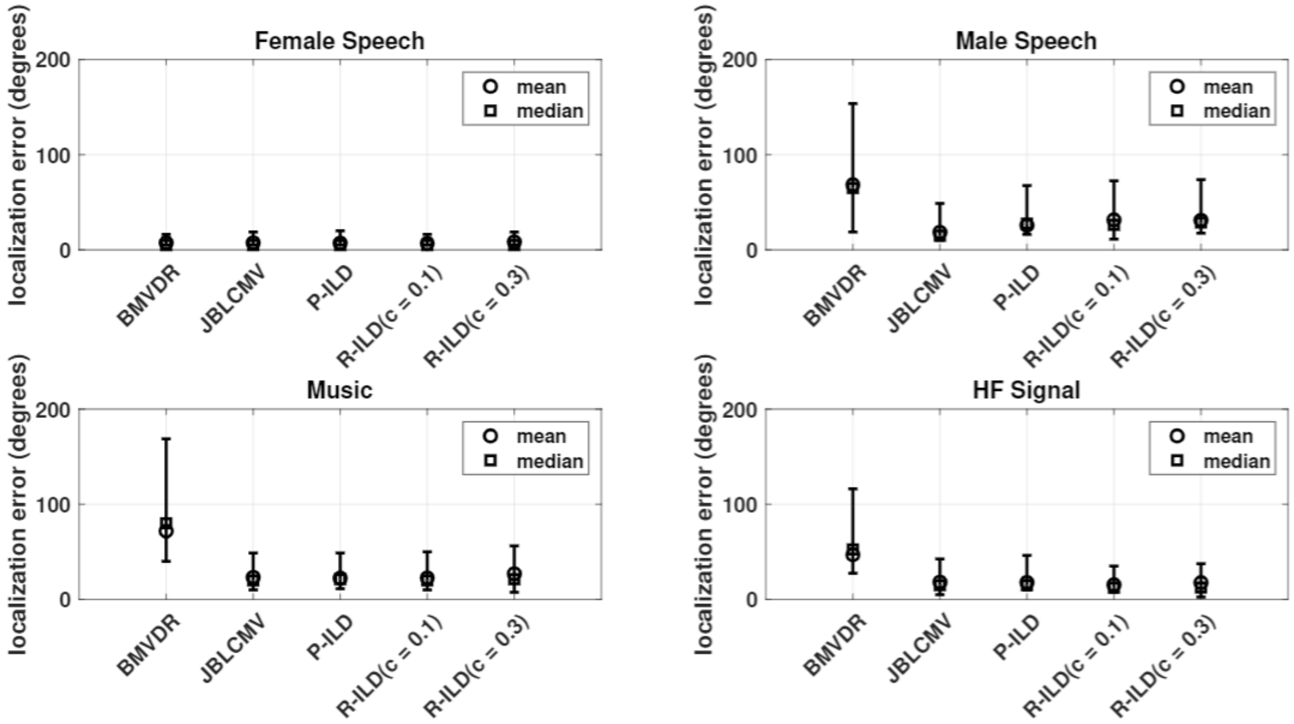

Fig. 2. Anechoic : localization error for each source across the proposed and reference methods.

Conclusion

- Introduction
- Motivation
- Methods Proposed
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- Conclusion

• Preserve only the ILD cues of the interferers in the higher frequencies

- Two methods were proposed

• Assess the localization Vs. noise reduction performance

- Expected localization performance for lower number of interferers
  - Localization performance was validated through listening tests
- Lower ILD errors compared to the JBLCMV for higher interferers
- A gain in SNR of less than 0.5 dB with higher number of interferers present.

Future Work:

- The methods can be used for lower frequency ILD cue preservation.
- *Effects of age and hearing loss can affect the sensitivity to low frequency ITDs [10].*

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