Design and evaluation of binaural speech enhancement and cue preservation algorithms

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Introduction

- Hearing impaired suffer from a loss of speech understanding in adverse acoustic environments (“cocktail-party effect”)

Apply acoustic signal pre-processing techniques in order to improve speech intelligibility

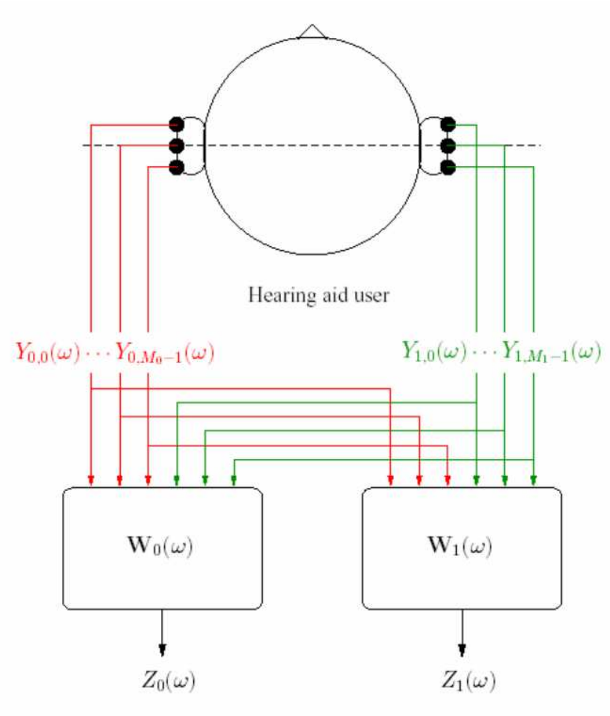
Introduction

- Digital hearing aids allow for advanced acoustical signal pre-processing
  - Multiple microphones available → spatial + spectral processing
  - Speech enhancement (noise reduction, beamforming), computational auditory scene analysis (source localisation, environment classification)

Monaural (2-3) *Binaural* *External microphones*

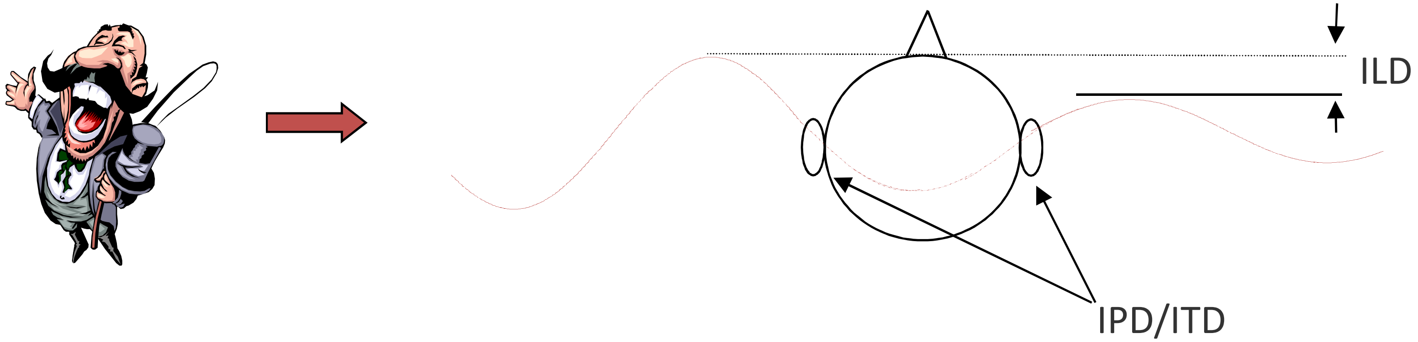
Introduction

- **This Presentation:**
  - Instrumental and subjective evaluation of recent binaural noise reduction algorithms based on MVDR/MWF
  - Two acoustic scenarios: diffuse noise and interfering speaker
- **Main Objectives:**
  - Improve speech intelligibility and avoid signal distortions
  - Preserve spatial awareness and directional hearing (binaural cues)



Binaural cues

- **Interaural Time/Phase Difference (ITD/IPD)**
  Interaural Level Difference (ILD)
  Interaural Coherence (IC)
  - ITD: f < 1500 Hz, ILD: f > 2000 Hz
  - IC: describes spatial characteristics, e.g. perceived width, of diffuse noise, and determines when ITD/ILD cues are *reliable*
- Binaural cues, in addition to spectro-temporal cues, play an important role in auditory scene analysis (source segregation) and speech intelligibility



Binaural cues

❑ Spatial release from masking (BMLD):

- ❑ *Localized noise source* : large effect for NH listeners (especially in free-field)
- ❑ *Diffuse noise* : about 2-3 dB

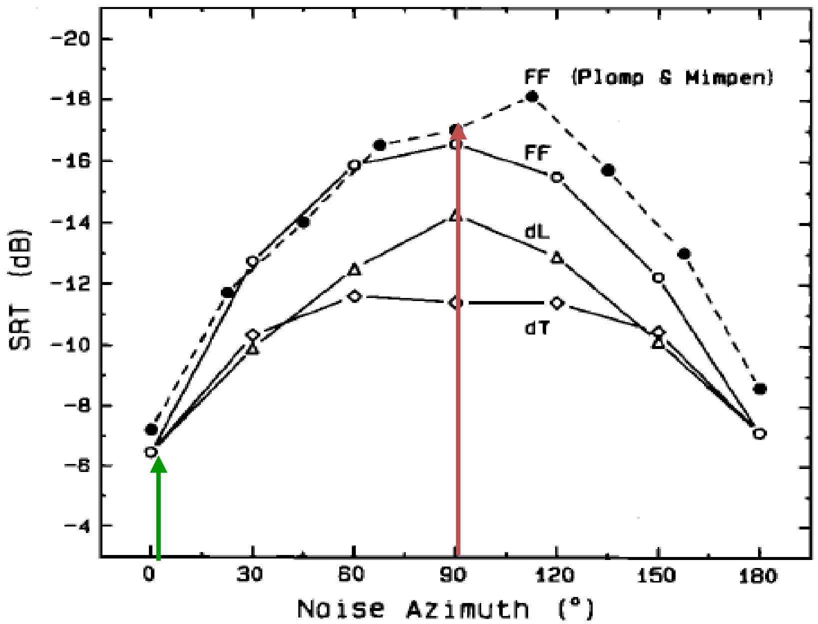
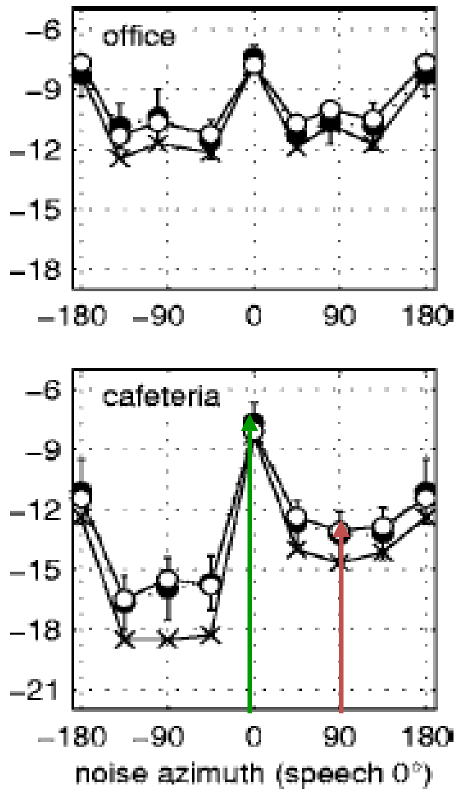


FIG. 5. Mean speech reception thresholds obtained in experiment I for three different noise types: FF (free field), dL (headshadow only), and dT (ITD only). The closed data points represent results of Plomp and Mimpen (1981) obtained in a free field.



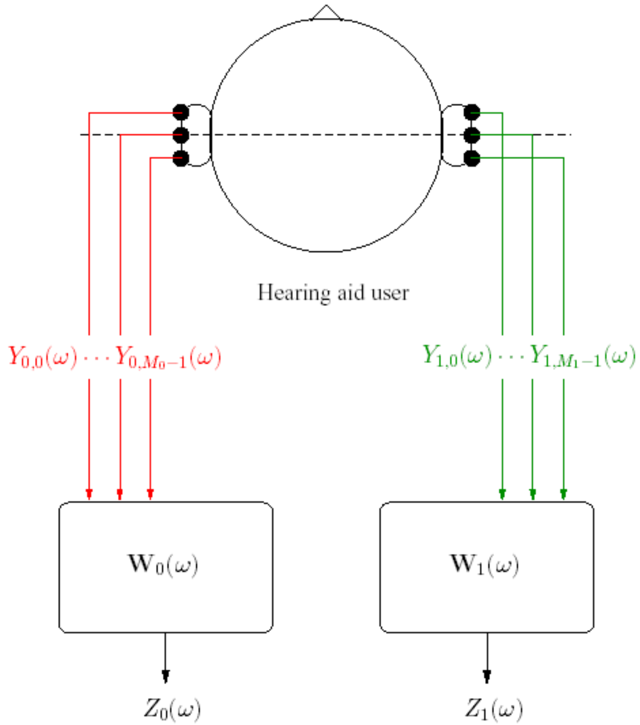
[Bronkhorst and Plomp, 1988]

[Beutelmann and Brand, 2006]

Binaural noise reduction algorithms

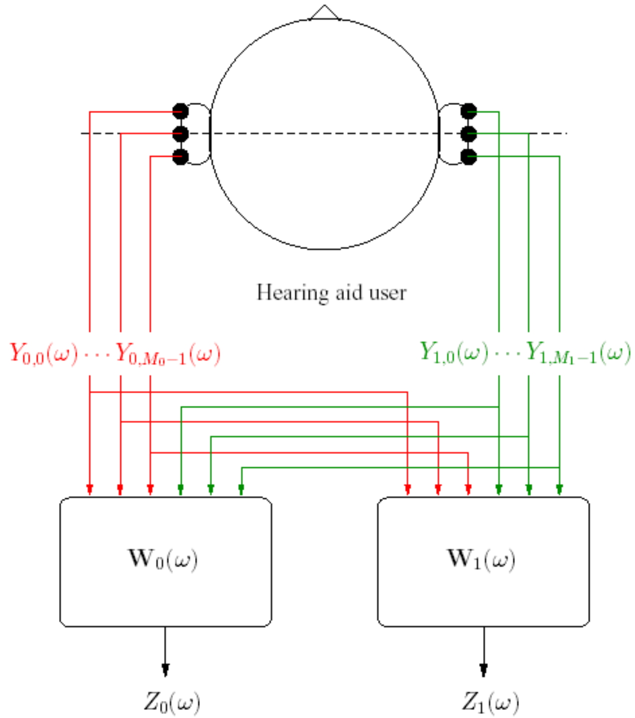
Binaural noise reduction: Configuration

Monaural/Bilateral system



⊖ **Independent** left/right processing:
- No cooperation (e.g. different environment classification)
- preservation of binaural cues ?

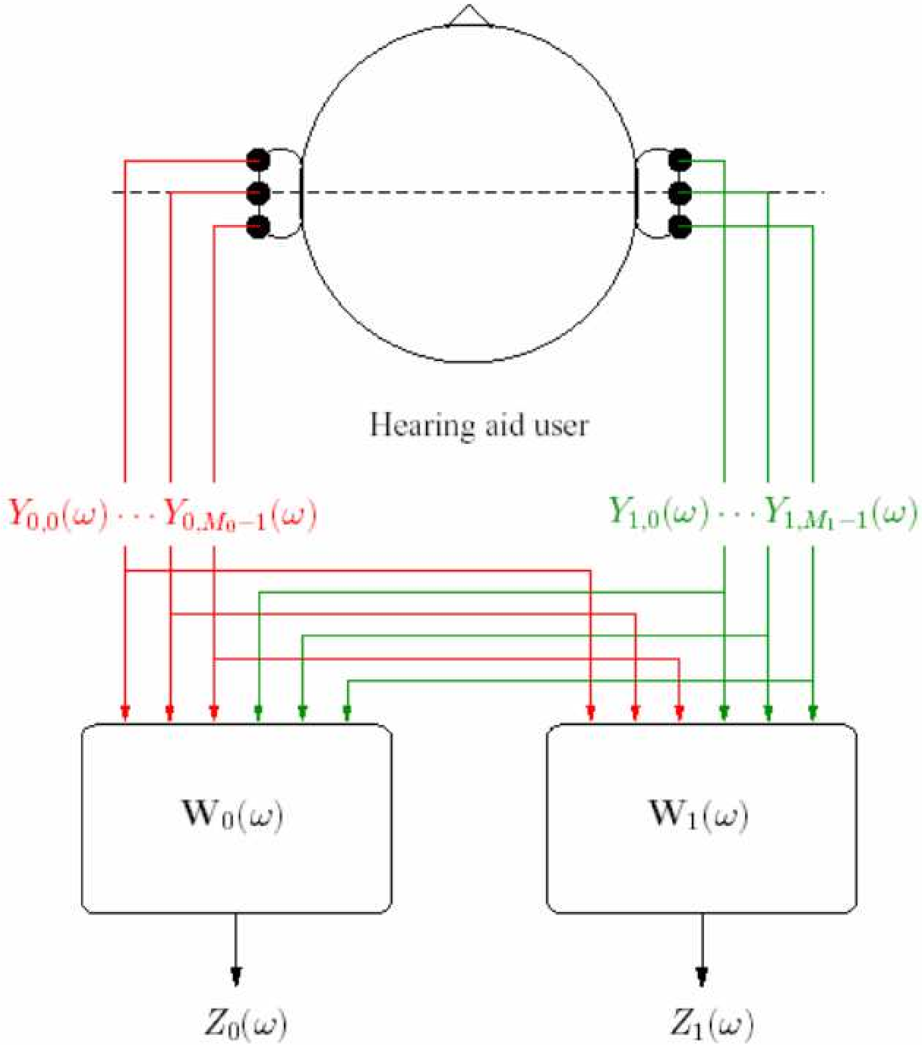
Binaural system



⊕ Exchange of:
- **parameters** (volume, environment)
- **signals** (cooperative processing for noise reduction, feedback, ...)

⊖ Need for wireless binaural link

Binaural noise reduction: Configuration



- Binaural hearing aid configuration:
  - Two hearing aids with in total *M* microphones
  - All microphone signals **Y** are assumed to be available at both hearing aids (perfect wireless link)
- Apply a filter $\mathbf{W}_0$ and $\mathbf{W}_1$ at the left and the right hearing aid, generating binaural output signals Z_0 and Z_1

$$Z_0(\omega) = \mathbf{W}_0^H(\omega)\mathbf{Y}(\omega), \quad Z_1(\omega) = \mathbf{W}_1^H(\omega)\mathbf{Y}(\omega)$$

Binaural noise reduction: Acoustic scenario

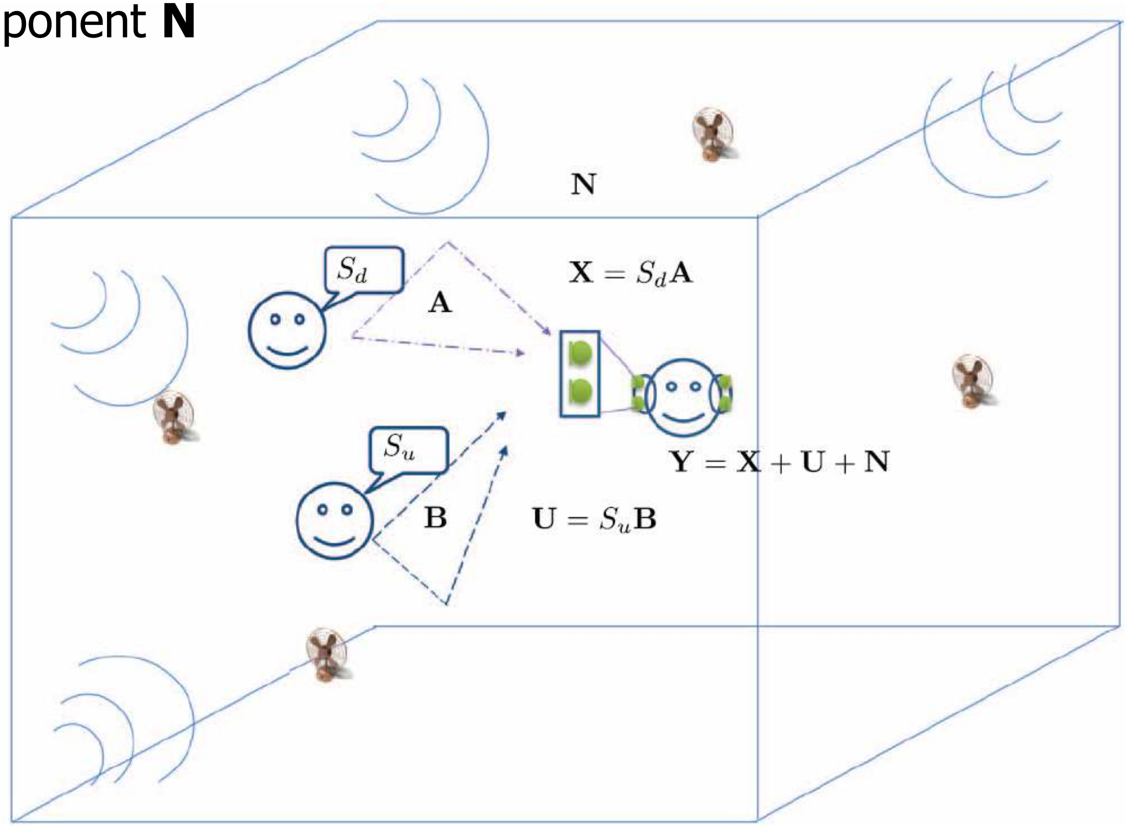
Acoustic Transfer Functions (ATFs)

- The microphone signals **Y** are composed of
  - (desired) speech component $\mathbf{X} = S_d \mathbf{A}$
  - (undesired) directional interference component $\mathbf{U} = S_u \mathbf{B}$
  - (undesired) background noise component **N**
- Correlation matrices:

$$\mathbf{R}_y = \mathbf{R}_x + \underbrace{\mathbf{R}_u + \mathbf{R}_n}_{\mathbf{R}_v}$$

$$\mathbf{R}_x = \mathcal{E}\left\{\mathbf{X}\mathbf{X}^H\right\} = P_s \mathbf{A}\mathbf{A}^H$$
$$\mathbf{R}_u = \mathcal{E}\left\{\mathbf{U}\mathbf{U}^H\right\} = P_u \mathbf{B}\mathbf{B}^H$$
$$\mathbf{R}_n = \mathcal{E}\left\{\mathbf{N}\mathbf{N}^H\right\},$$

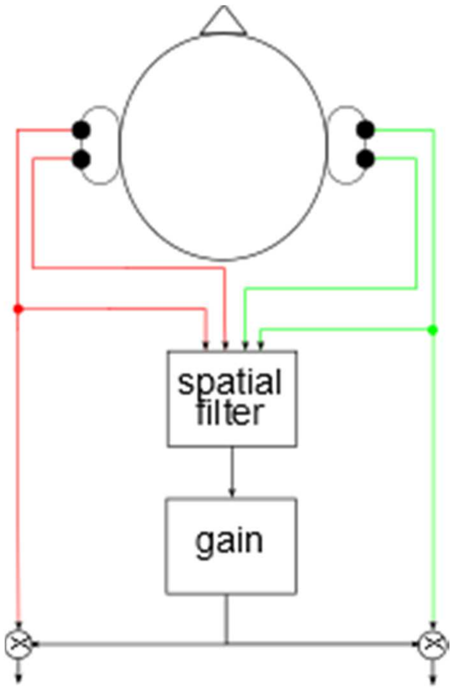
- All **binaural cues** can be written in terms of these matrices



Binaural noise reduction: Two main paradigms

Spectral post-filtering (based on multi-microphone noise reduction)

[Doerbecker 1996, Wittkop 2003, Lotter 2006, Rohdenburg 2007, Grimm 2009, Reindl 2012]

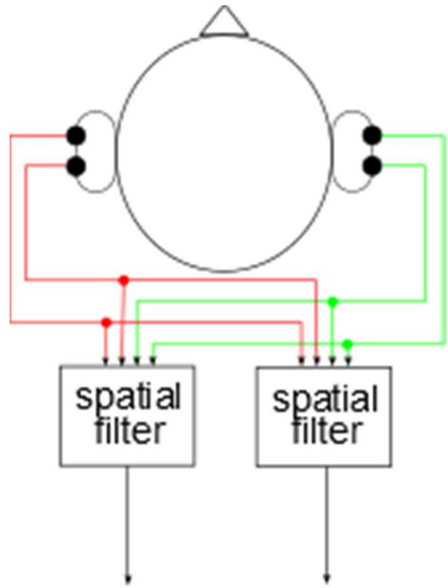


⊕ Binaural cue preservation

⊖ Possible single-channel artifacts

Binaural multi-microphone noise reduction techniques

[Welker 1997, Doclo 2010, Cornelis 2012, Hadad 2014-2016, Marquardt 2014-2016]



⊕ Larger noise reduction performance

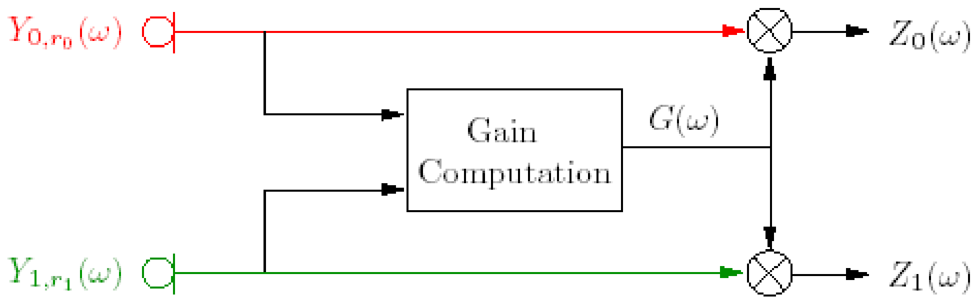
⊕ Merge spatial and spectral post-filtering

⊖ Binaural cue preservation not guaranteed

1) Spectral post-filtering

Time-frequency post-filtering/masking:

- Computation and application of **real-valued** spectral gain/mask
- Gain G(ω) based on **coherence, binaural cues (ITD/ILD)** and temporal/spectral cues (pitch, onset, modulation frequencies)



[Doerbecker 1996, Wittkop 2003, Grimm 2009, Martin 2015]

1) Spectral post-filtering

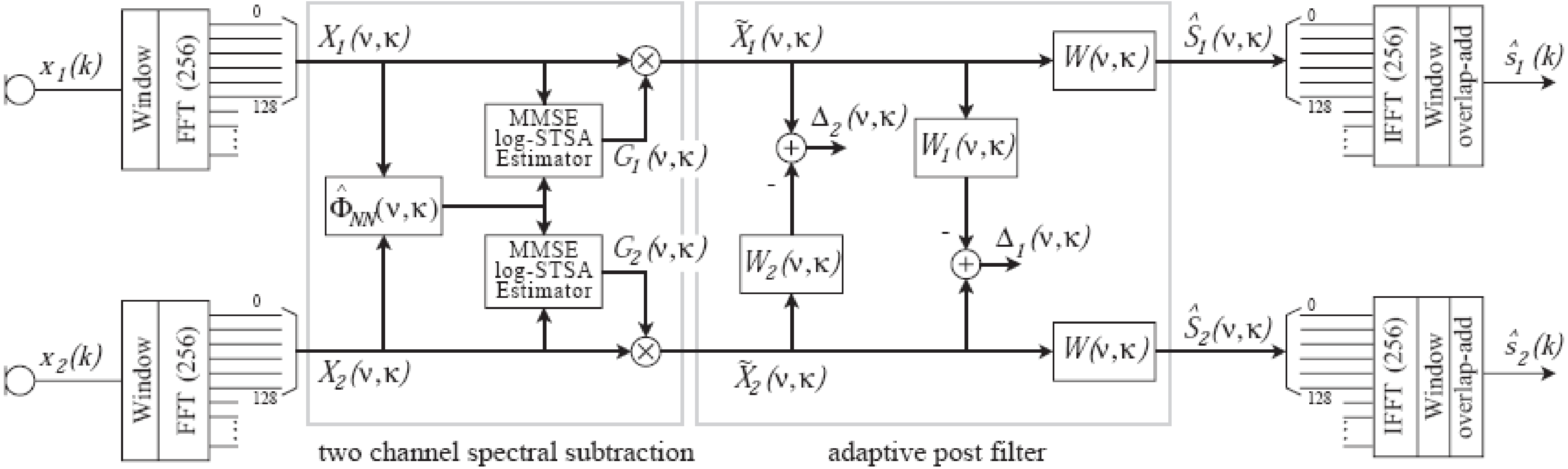


Figure 1: Proposed noise reduction system with two channel Spectral Subtraction and adaptive Wiener post-filtering
ν: frequency index, κ: index of decimated time

[Doerbecker 1996]

1) Spectral post-filtering

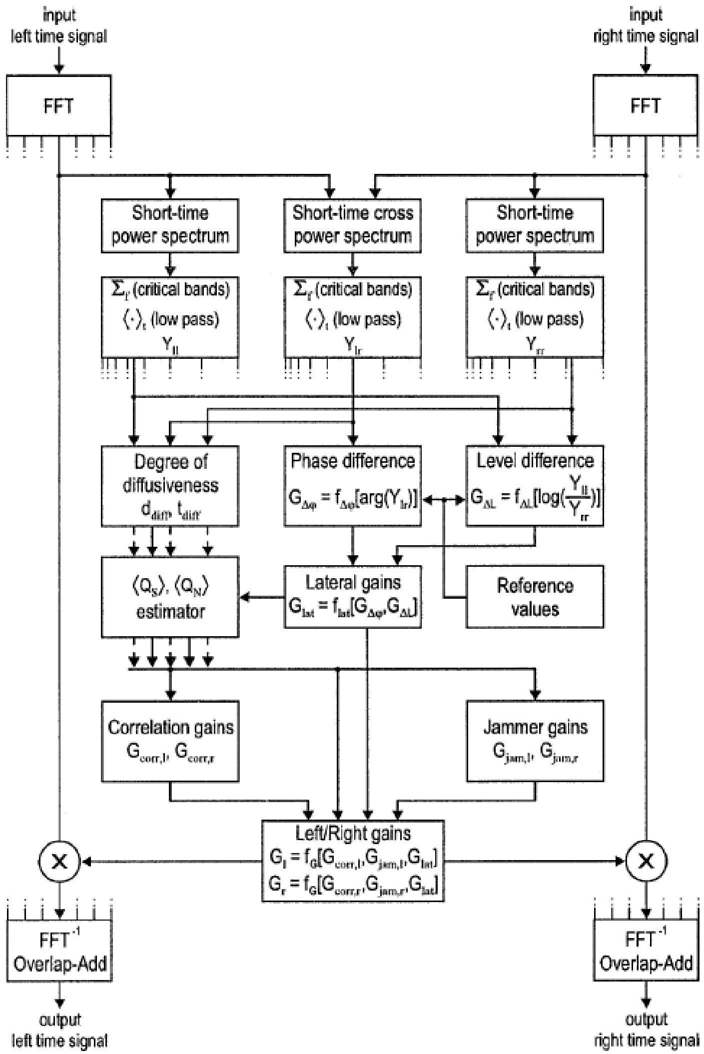


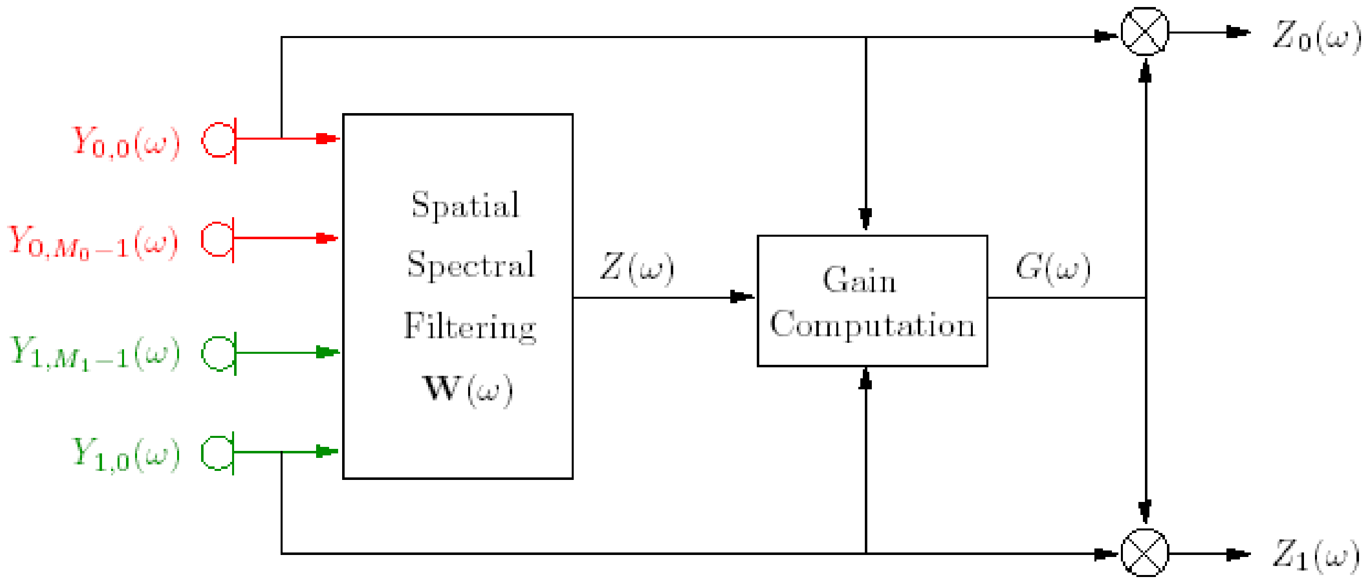
Fig. 8. Block diagram of the strategy-selective algorithm for dereverberation and suppression of lateral noise sources.

[Wittkop 2003]

1) Spectral post-filtering

Can be merged with multi-microphone noise reduction:

- E.g. based on fixed/adaptive beamforming or blind source separation
- **However**: still in principle single-channel noise reduction (noisy phase, possible artefacts)



[Lotter 2006, Wehr 2008, Rohdenburg 2009, Saruwatari 2010, Reindl 2012, Baumgaertel 2015]

1) Spectral post-filtering

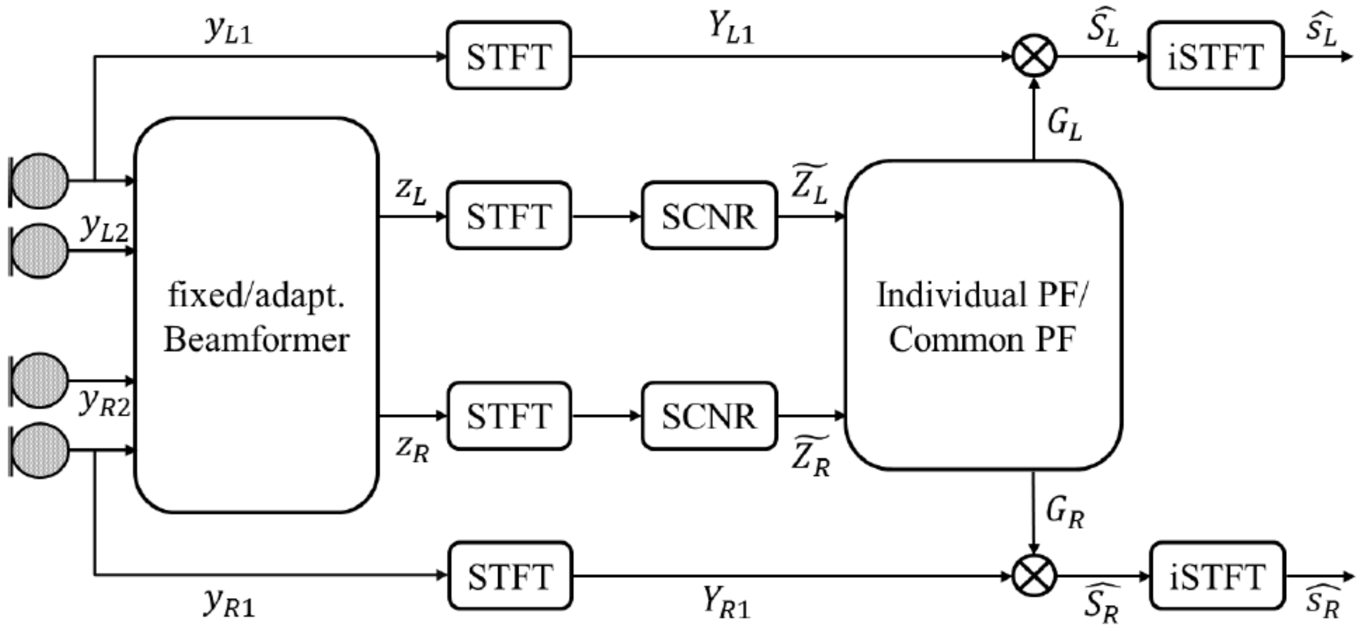


Figure 4. Block diagram illustrating the combination of a binaural MVDR beamformer with single-channel postfiltering. The indices n, k, and l were dropped for the sake of brevity.

[Baumgaertel 2015]

2) Binaural MVDR and MWF

Minimum-Variance-Distortionless-Response (MVDR) beamformer

Goal: minimize output noise power without distorting speech component in reference microphone signals

$$\min_{\mathbf{W}_0} \mathbf{W}_0^H \mathbf{R}_\mathrm{v} \mathbf{W}_0 \quad \text{subject to} \quad \mathbf{W}_0^H \mathbf{A} = A_0$$

$$\min_{\mathbf{W}_1} \underbrace{\mathbf{W}_1^H \mathbf{R}_\mathrm{v} \mathbf{W}_1}_{\text{noise reduction}} \quad \text{subject to} \quad \underbrace{\mathbf{W}_1^H \mathbf{A} = A_1}_{\text{distortionless constraint}}$$

$$\mathbf{W}_{\mathrm{MVDR},0} = \frac{\mathbf{R}_\mathrm{v}^{-1}\mathbf{A}}{\mathbf{A}^H \mathbf{R}_\mathrm{v}^{-1}\mathbf{A}} A_0^*$$

$$\mathbf{W}_{\mathrm{MVDR},1} = \frac{\mathbf{R}_\mathrm{v}^{-1}\mathbf{A}}{\mathbf{A}^H \mathbf{R}_\mathrm{v}^{-1}\mathbf{A}} A_1^*$$

Multi-channel Wiener Filter (MWF)

Goal: estimate speech component in reference microphone signals + trade off noise reduction and speech distortion

$$J_{\mathrm{MWF}}(\mathbf{W}) = \mathcal{E}\left\{ \underbrace{\left\| \begin{bmatrix} X_0 - \mathbf{W}_0^H \mathbf{X} \\ X_1 - \mathbf{W}_1^H \mathbf{X} \end{bmatrix} \right\|^2}_{\text{speech distortion}} + \mu \underbrace{\left\| \begin{bmatrix} \mathbf{W}_0^H \mathbf{V} \\ \mathbf{W}_1^H \mathbf{V} \end{bmatrix} \right\|^2}_{\text{noise reduction}} \right\}$$

$$\mathbf{W}_{\mathrm{MWF},0} = (\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{r}_{\mathrm{x},0}$$

$$\mathbf{W}_{\mathrm{MWF},1} = (\mathbf{R}_x + \mu \mathbf{R}_v)^{-1} \mathbf{r}_{\mathrm{x},1}$$

$$\mathbf{W}_{\mathrm{MWF},0} = \frac{\rho}{\mu+\rho} \frac{\mathbf{R}_\mathrm{v}^{-1}\mathbf{A}}{\mathbf{A}^H \mathbf{R}_\mathrm{v}^{-1}\mathbf{A}} A_0^* = \frac{\rho}{\mu+\rho} \mathbf{W}_{\mathrm{MVDR},0}$$

$$\mathbf{W}_{\mathrm{MWF},1} = \frac{\rho}{\mu+\rho} \frac{\mathbf{R}_\mathrm{v}^{-1}\mathbf{A}}{\mathbf{A}^H \mathbf{R}_\mathrm{v}^{-1}\mathbf{A}} A_1^* = \frac{\rho}{\mu+\rho} \mathbf{W}_{\mathrm{MVDR},1}$$

2) Binaural MVDR and MWF

Minimum-Variance-Distortionless-Response (MVDR) beamformer

Goal: minimize output noise power without distorting speech component in reference microphone signals

$$\min_{\mathbf{W}_0} \mathbf{W}_0^H \mathbf{R}_v \mathbf{W}_0 \quad \text{subject to} \quad \mathbf{W}_0^H \mathbf{A} = A_0$$

$$\min_{\mathbf{W}_1} \underbrace{\mathbf{W}_1^H \mathbf{R}_v \mathbf{W}_1}_{\text{noise reduction}} \quad \text{subject to} \quad \underbrace{\mathbf{W}_1^H \mathbf{A} = A_1}_{\text{distortionless constraint}}$$

Requires estimate/model of noise coherence matrix (e.g. diffuse) and estimate/model of relative transfer function (RTF) of target speech source

Multi-channel Wiener Filter (MWF)

Goal: estimate speech component in reference microphone signals + trade off noise reduction and speech distortion

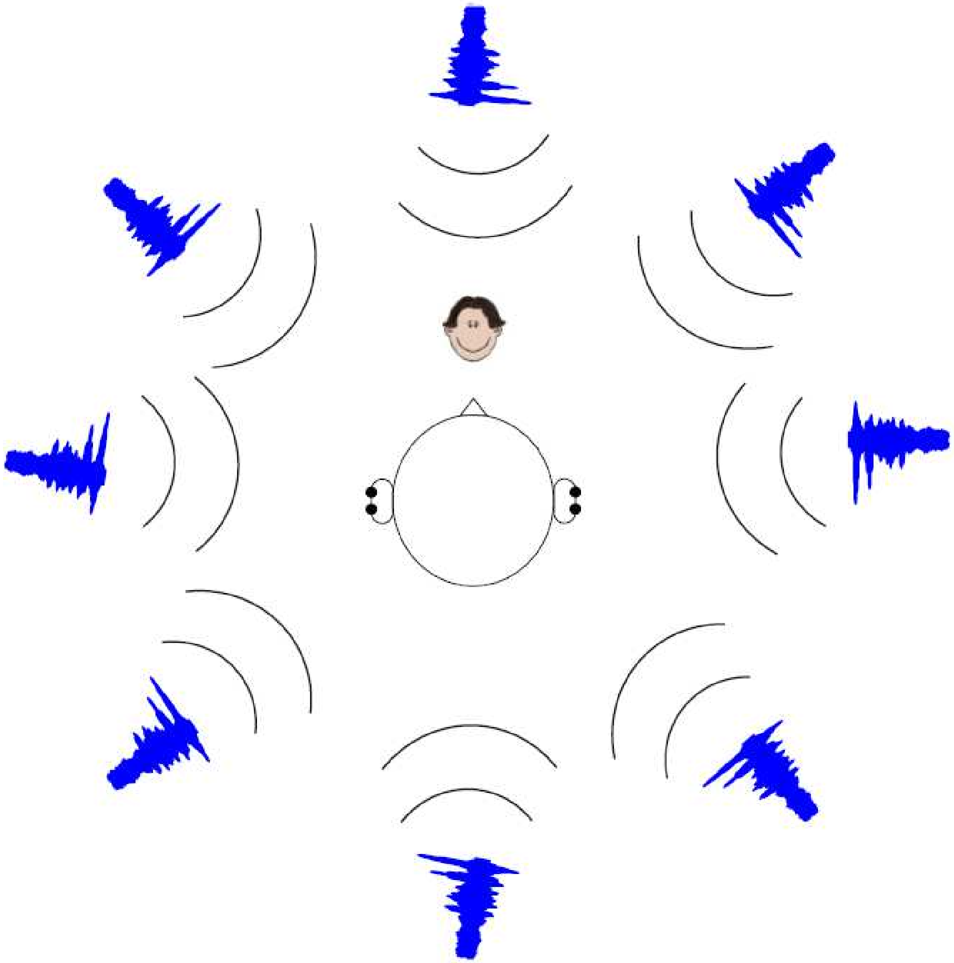
$$J_{\text{MWF}}(\mathbf{W}) = \mathcal{E}\left\{ \underbrace{\left\| \begin{bmatrix} X_0 - \mathbf{W}_0^H \mathbf{X} \\ X_1 - \mathbf{W}_1^H \mathbf{X} \end{bmatrix} \right\|^2}_{\text{speech distortion}} + \mu \underbrace{\left\| \begin{bmatrix} \mathbf{W}_0^H \mathbf{V} \\ \mathbf{W}_1^H \mathbf{V} \end{bmatrix} \right\|^2}_{\text{noise reduction}} \right\}$$

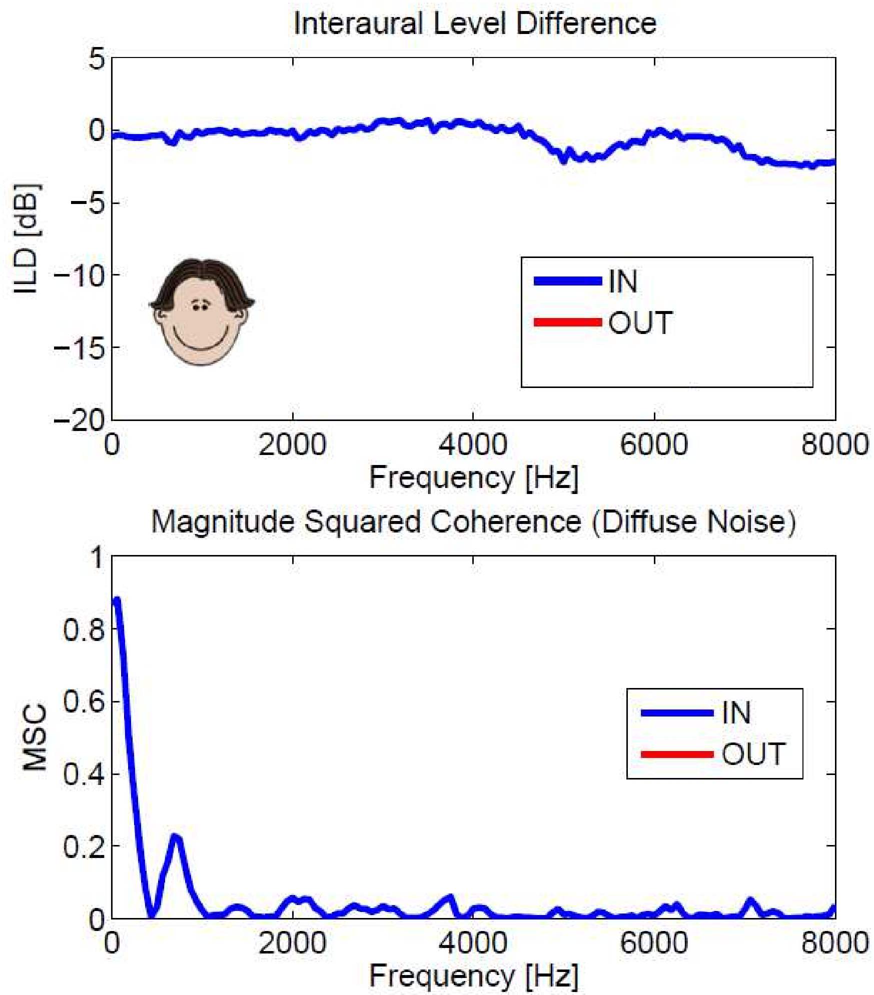
Requires estimate of speech and noise covariance matrices, e.g. based on VAD

Can be decomposed as binaural MVDR beamformer and spectral postfilter

Good noise reduction performance, what about binaural cues ?

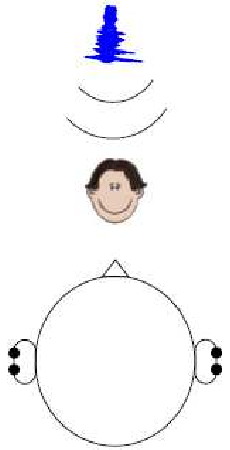
2) Binaural MVDR and MWF Binaural cues (diffuse noise)

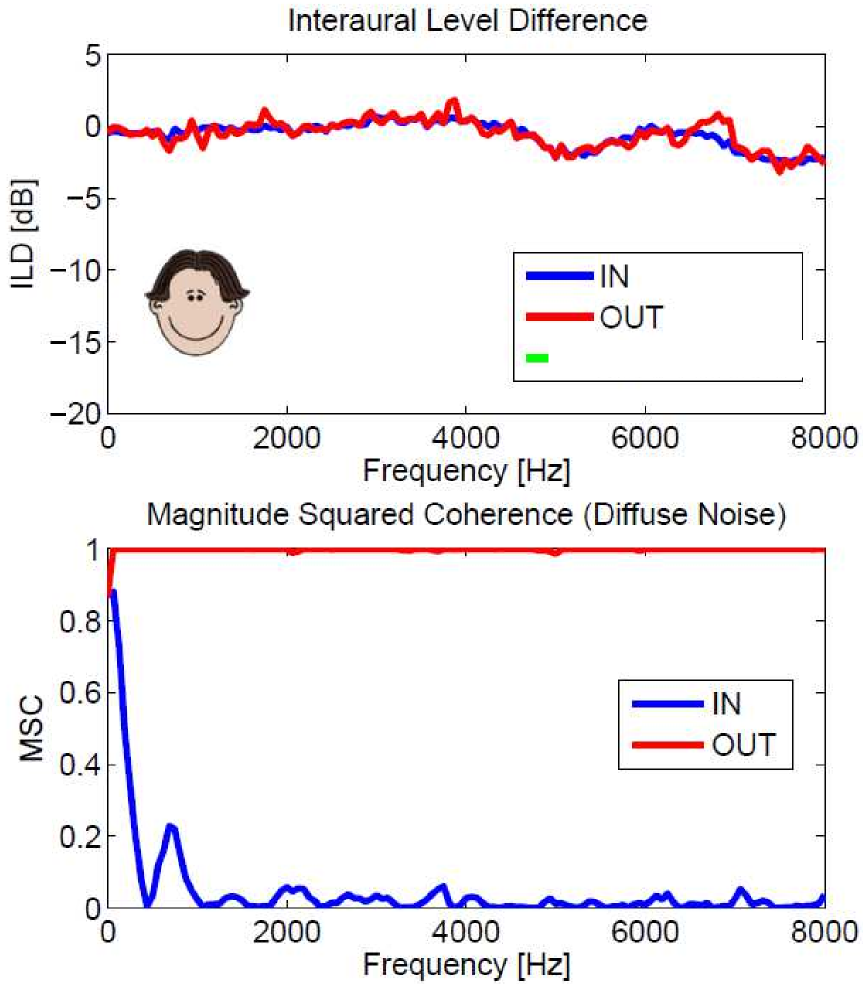




MSC = Magnitude Squared Coherence=$|IC|^2$

2) Binaural MVDR and MWF Binaural cues (diffuse noise)



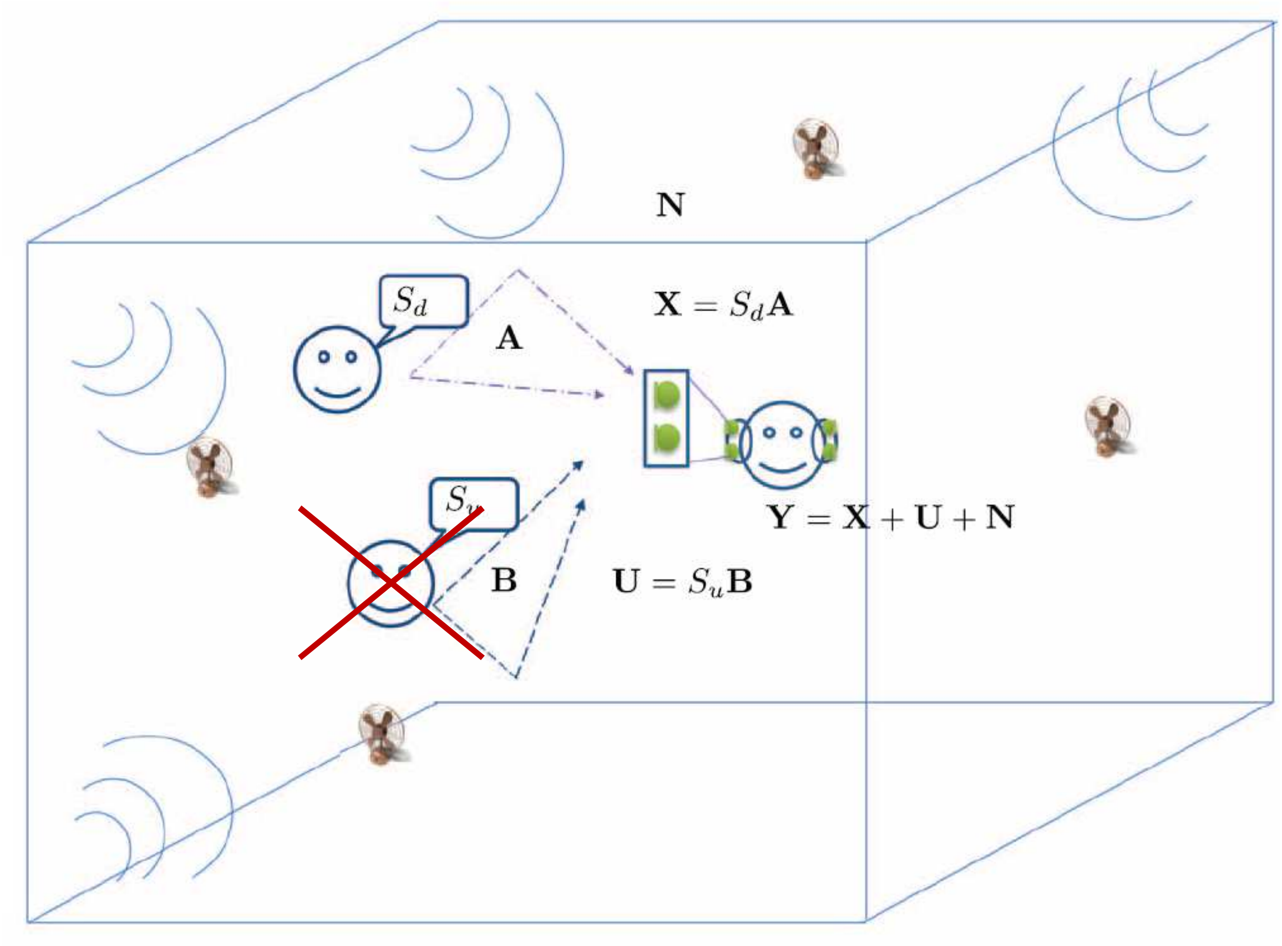


Binaural cues for residual noise/interference in binaural MVDR/MWF not preserved

Binaural cue preservation for diffuse noise

Acoustic scenario

- Speech source + background noise



Binaural MWF: Extensions for diffuse noise

Binaural MWF

- ⊕ SNR improvement
- ⊕ Binaural cues of speech source
- ⊖ Binaural cues of noise

Interaural coherence preservation (MWF-IC)

Partial noise estimation (MWF-N)

$$J_{MWF-IC}(\mathbf{W}) = J_{MWF}(\mathbf{W}) + \lambda \left| \frac{\mathbf{W}_0^H \mathbf{R}_v \mathbf{W}_1}{\sqrt{\mathbf{W}_0^H \mathbf{R}_v \mathbf{W}_0 \mathbf{W}_1^H \mathbf{R}_v \mathbf{W}_1}} - IC_v^{des} \right|^2$$

$$J_{\mathrm{MWF-N}}(\mathbf{W}) = \mathcal{E}\left\{ \left\| \begin{bmatrix} X_0 - \mathbf{W}_0^H \mathbf{X} \\ X_1 - \mathbf{W}_1^H \mathbf{X} \end{bmatrix} \right\|^2 + \mu \left\| \begin{bmatrix} \eta V_0 - \mathbf{W}_0^H \mathbf{V} \\ \eta V_1 - \mathbf{W}_1^H \mathbf{V} \end{bmatrix} \right\|^2 \right\}$$

⊖ No closed-form solution, iterative optimization procedures required

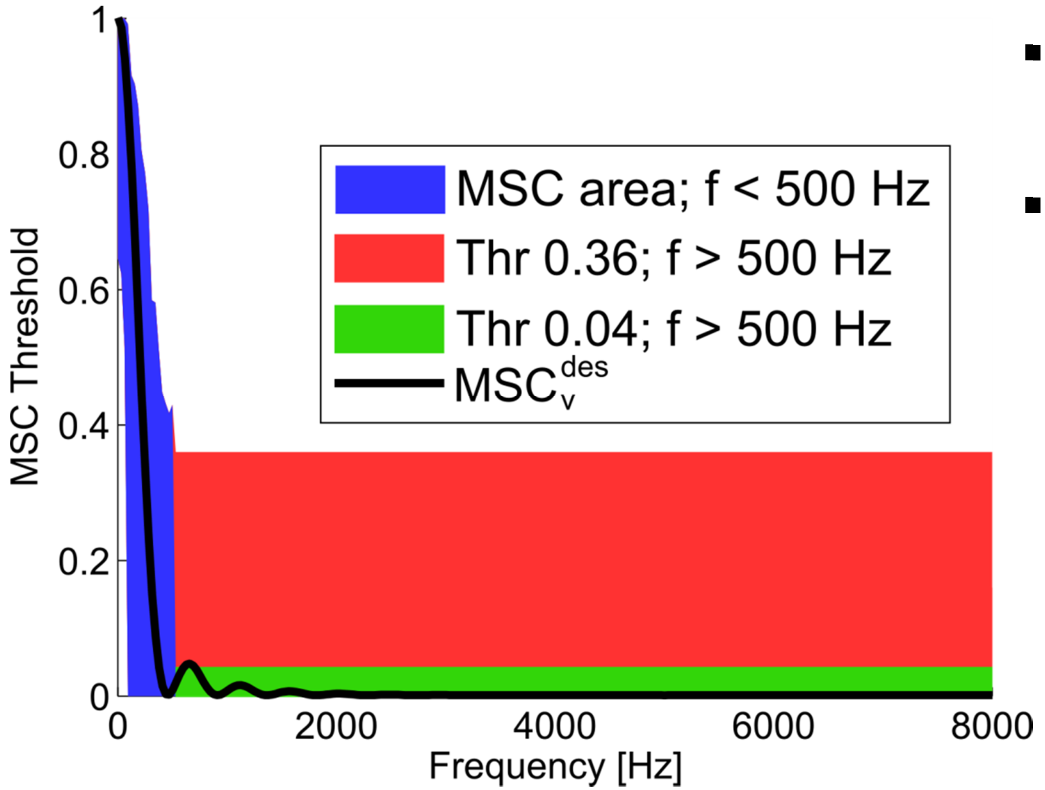
⊕ Closed-form solution (mixing with reference microphone signals)

⊜ **Trade-off** between SNR improvement and binaural cue preservation, depending on **parameters** (η and λ)

[Marquardt 2013/2014/2015, Braun 2014] [Doclo 2010, Cornelis 2010/2012]

Binaural MWF: Extensions for diffuse noise

- **Determine (frequency-dependent) trade-off parameters based on psycho-acoustic criteria**
  - Amount of IC preservation based on subjective listening experiments evaluating the IC discrimination abilities of the human auditory system



- IC discrimination ability depends on magnitude of reference IC
- **Boundaries on Magnitude Squared Coherence** (MSC=|IC|^2) :
  - For f < 500 Hz ("large" IC): frequency-dependent MSC boundaries (**blue**)
  - For f > 500 Hz ("small" IC): fixed MSC boundary, e.g. 0.36 (**red**) or 0.04 (**green**)

[Marquardt 2014/2015]

Binaural MWF: Extensions for diffuse noise

- **MWF-IC: Interaural coherence preservation**
  - IC preservation cost function: minimize difference between IC of output noise component and desired IC

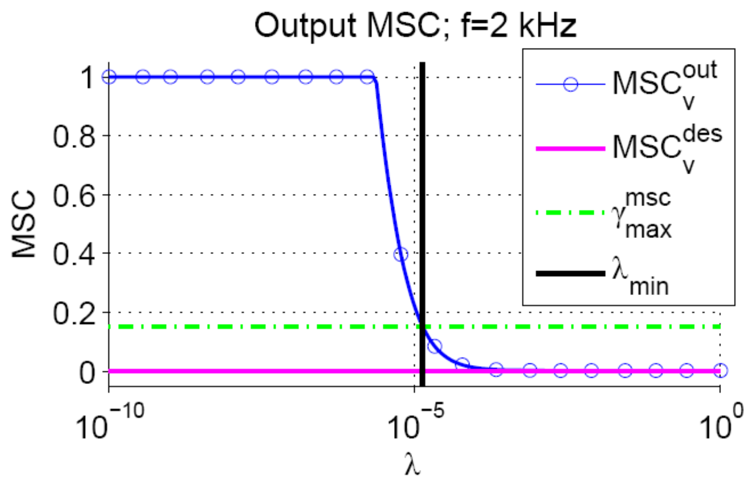
$$
\boxed{
\begin{aligned}
J_{\mathrm{IC}}(\mathbf{W}) &= \left| IC_{\mathrm{v}}^{\mathrm{out}} - IC_{\mathrm{v}}^{\mathrm{des}} \right|^2 , \\
&= \left| \frac{\mathbf{W}_0^H \mathbf{R}_{\mathrm{v}} \mathbf{W}_1}{\sqrt{\left(\mathbf{W}_0^H \mathbf{R}_{\mathrm{v}} \mathbf{W}_0\right)\left(\mathbf{W}_1^H \mathbf{R}_{\mathrm{v}} \mathbf{W}_1\right)}} - IC_{\mathrm{v}}^{\mathrm{des}} \right|^2
\end{aligned}
}
$$

  - **Desired IC** can be computed using estimated input noise correlation matrix, or based on head model / measured HRTFs
  - **No closed-form filter expression** → iterative optimization procedures required

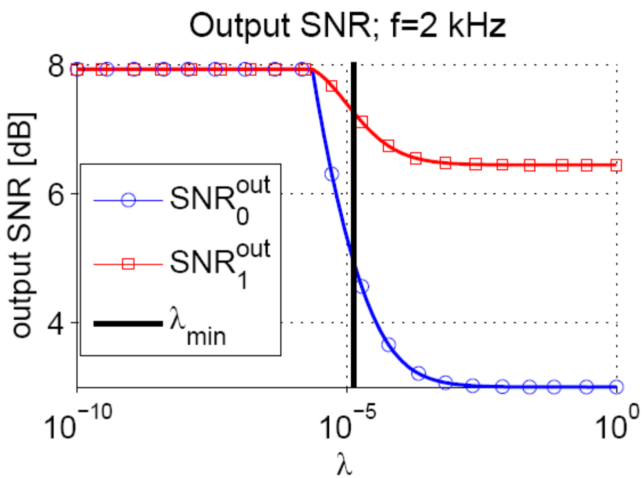
[Marquardt 2013-2015]

Binaural MWF: Extensions for diffuse noise

- **MWF-IC: Interaural coherence preservation**
  - **Trade-off parameter λ** trades off MSC error and output SNR



(a) Output MSC



(b) Output SNR

  - Exhaustive / iterative search to determine optimal trade-off parameter λ, satisfying psycho-acoustically motivated MSC boundaries

$$\Lambda = \{\lambda \,|\, \gamma_{\min}^{\mathrm{msc}} \leq MSC_{\mathrm{v}}^{\mathrm{out}}(\mathbf{W}_{\mathrm{MWF-IC}}(\lambda)) \leq \gamma_{\max}^{\mathrm{msc}}\}$$

Binaural MWF: Extensions for diffuse noise

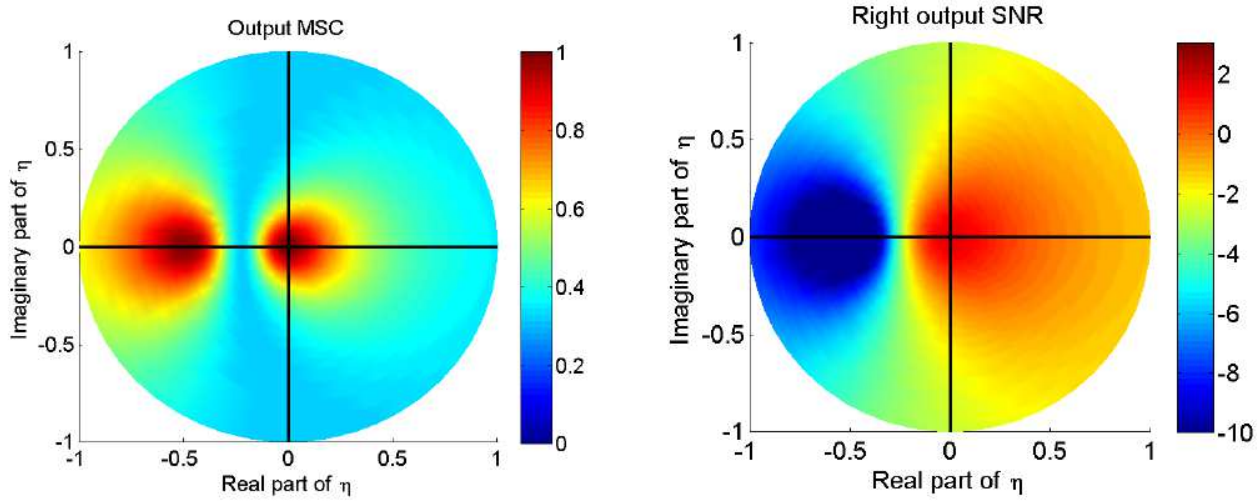
- **MWF-N: Partial noise estimation**
  - **Closed form filter expression** → mixing of binaural MWF output signals and reference microphone signals

$$\boxed{\begin{aligned}\mathbf{W}_{\mathrm{MWF-N},0} &= (1-\eta^*)\,\mathbf{W}_{\mathrm{MWF},0} + \eta^*\mathbf{e}_0 \\ \mathbf{W}_{\mathrm{MWF-N},1} &= (1-\eta^*)\,\mathbf{W}_{\mathrm{MWF},1} + \eta^*\mathbf{e}_1\end{aligned}}$$

  - η **= 0 :** binaural MWF (optimal noise reduction, but no cue preservation)
  - η **= 1 :** reference microphone signals (perfect cue preservation, but no noise reduction)

Binaural MWF: Extensions for diffuse noise

- **MWF-N: Partial noise estimation**
  - **Trade-off parameter η** trades off MSC error and output SNR
    - **MWF-N** : exhaustive search for optimal trade-off parameter



(a) $MSC_{\mathrm{v}}^{\mathrm{out}}$ for the MWF-N (b) SNR_{1}^{out} for the MWF-N

$$\Upsilon = \{\eta \,|\, \gamma_{\min}^{\mathrm{msc}} \leq MSC_{\mathrm{v}}^{\mathrm{out}}(\eta) \leq \gamma_{\max}^{\mathrm{msc}}\} \qquad \eta_{\mathrm{opt}} = \underset{\eta \in \Upsilon}{\arg\max} \frac{SNR_{\mathrm{MWF-N},0}^{\mathrm{out}}(\eta) + SNR_{\mathrm{MWF-N},1}^{\mathrm{out}}(\eta)}{2}$$

Binaural MWF: Extensions for diffuse noise

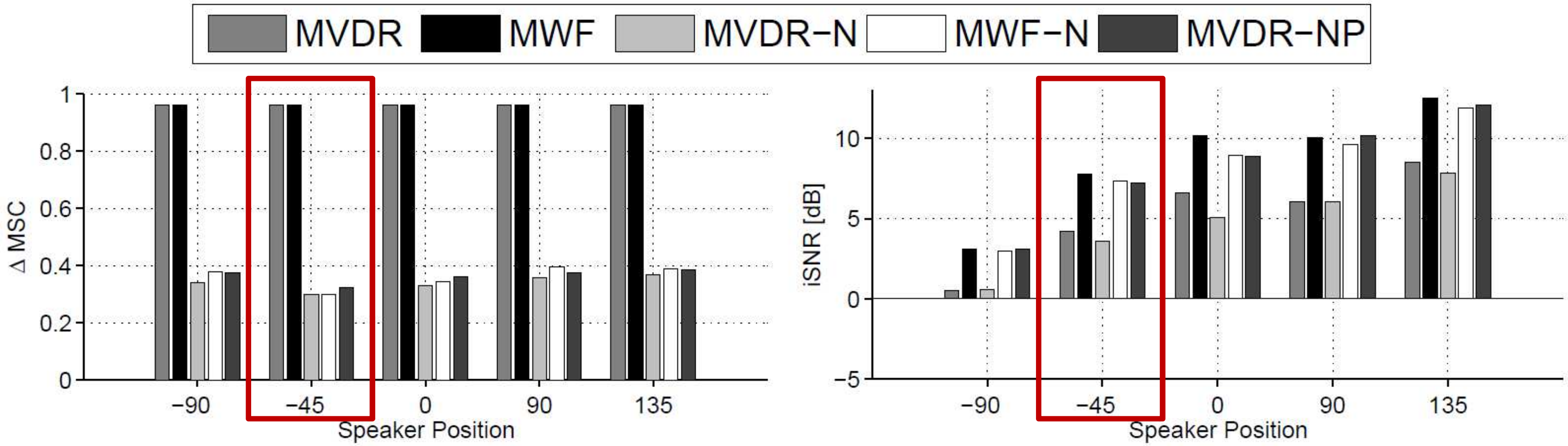
- **MWF-N: Partial noise estimation**
  - **Trade-off parameter η** trades off MSC error and output SNR
    - **MWF-N** : exhaustive search for optimal trade-off parameter
    - **MVDR-N** (i.e. special case of MWF-N with μ=0) :
      - Closed-form expression for optimal trade-off parameter
      - No spectral filtering as in MWF-N
    - **MVDR-N + spectral postfilter**
      - Not equivalent to MWF-N, but combining spatial and spectral filtering with closed-form expression for both filter and trade-off parameter
  - Note: main difference with previous work is **frequency-dependency and signal-dependency of trade-off parameter**
  - Note: also other criteria for determining trade-off parameter possible, e.g. based on **output SNR**

Table 1 Comparison of mixing factors for binaural beamforming algorithms

	MVDR	MVDR-N	SBB
α	1	$1-\eta$	$1 \quad \hat{\phi}_s(n)/\hat{\phi}_v(n) > 1$ $0 \quad$ otherwise
β	0	η	$0 \quad \hat{\phi}_s(n)/\hat{\phi}_v(n) > 1$ $\gamma \quad$ otherwise

Binaural MWF: Extensions for diffuse noise

❑ Instrumental evaluation / sound samples



(a) $\Delta\mathrm{MSC}_{\mathrm{v}}$ (b) $\mathrm{iSNR}_{\mathrm{be}}^{\mathrm{out}}$

Input	MVDR	MWF	MVDR-N	MWF-N	MVDR-NP

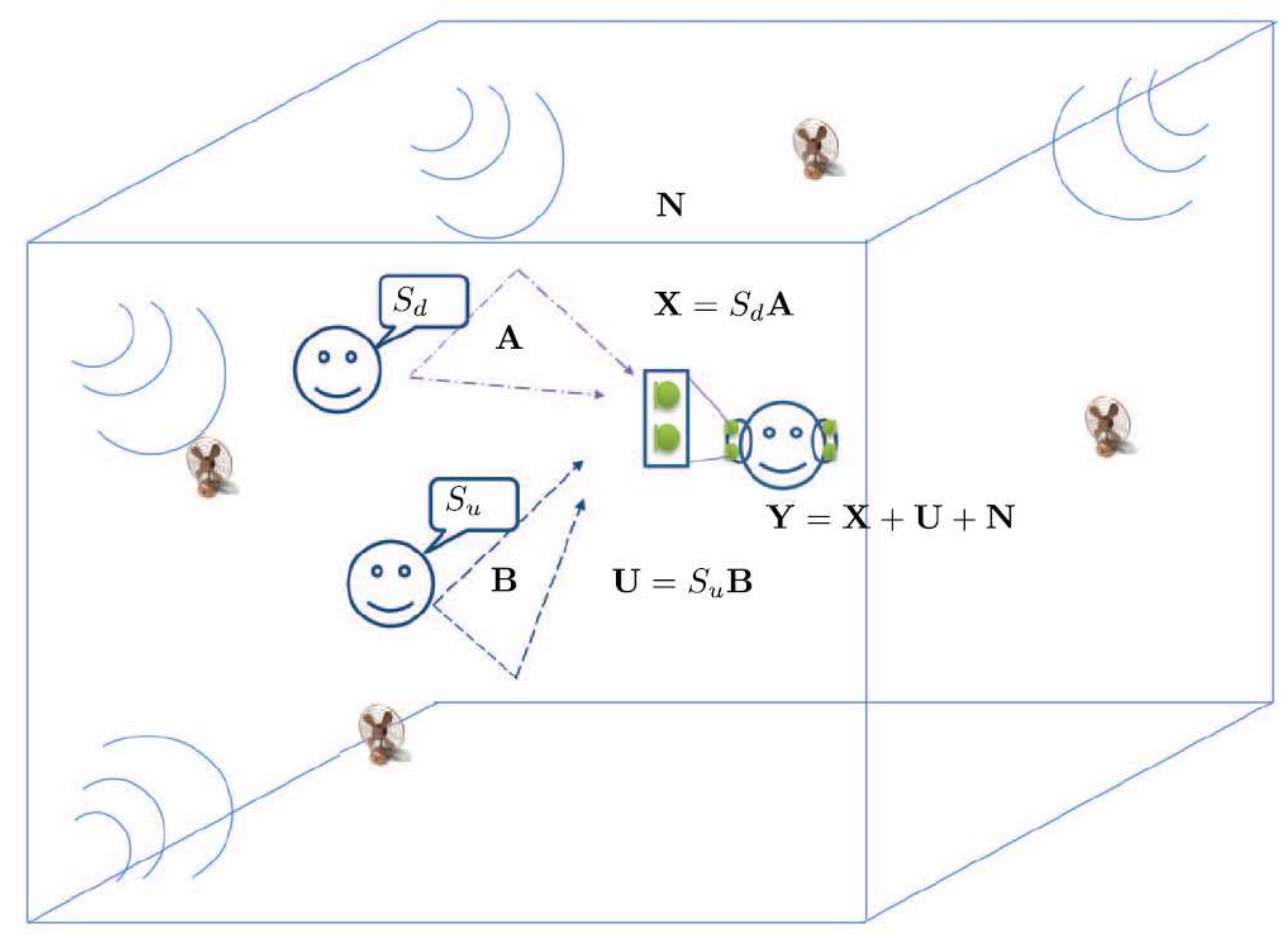
Cafeteria with recorded ambient noise, speaker at -35°, 0 dB input iSNR (left hearing aid)
MVDR: anechoic ATF, DOA known, spatial coherence matrix calculated from anechoic ATFs / MWF = MVDR + postfilter (SPP-based)

[Marquardt 2016 - unpublished]

Binaural cue preservation for interfering source

Acoustic scenario

- Speech source + interfering speaker + background noise



Binaural MVDR: Extensions for interfering source

Binaural MVDR

- ⊕ SNR improvement
- ⊕ Binaural cues of speech source
- ⊖ Binaural cues of interferer

Relative transfer function (BMVDR-RTF)

$$\min_{\mathbf{W}_0,\mathbf{W}_1} \left\{\mathbf{W}_0^H \mathbf{R}_v \mathbf{W}_0 + \mathbf{W}_1^H \mathbf{R}_v \mathbf{W}_1\right\}$$

$$\text{s.t. } \mathbf{W}_0^H \mathbf{A} = A_0, \mathbf{W}_1^H \mathbf{A} = A_1, \frac{\mathbf{W}_0^H \mathbf{B}}{\mathbf{W}_1^H \mathbf{B}} = \frac{B_0}{B_1}.$$

Interference rejection (BMVDR-IR)

$$\min_{\mathbf{W}_0} \left\{\mathbf{W}_0^H \mathbf{R}_v \mathbf{W}_0\right\} \text{ s.t. } \mathbf{W}_0^H \mathbf{A} = A_0, \mathbf{W}_0^H \mathbf{B} = \eta B_0$$

$$\min_{\mathbf{W}_1} \left\{\mathbf{W}_1^H \mathbf{R}_v \mathbf{W}_1\right\} \text{ s.t. } \mathbf{W}_1^H \mathbf{A} = A_1, \mathbf{W}_1^H \mathbf{B} = \eta B_1$$

- ⊕ Binaural cues of speech source **and** interfering source preserved
- ⊕ Also binaural MWF-based versions (incl. spectral filtering) can be derived
- ⊖ Background noise: MSC not exactly preserved, possible noise amplification

Binaural MVDR: Extensions for interfering source

❑ Comparison between BMVDR-RTF and BMVDR-IR

$$\min_{\mathbf{W}_0,\mathbf{W}_1} \{\mathbf{W}_0^H \mathbf{R}_v \mathbf{W}_0 + \mathbf{W}_1^H \mathbf{R}_v \mathbf{W}_1\}$$

$$\text{s.t. } \mathbf{W}_0^H \mathbf{A} = A_0, \mathbf{W}_1^H \mathbf{A} = A_1, \frac{\mathbf{W}_0^H \mathbf{B}}{\mathbf{W}_1^H \mathbf{B}} = \frac{B_0}{B_1}.$$

$$\min_{\mathbf{W}_0} \{\mathbf{W}_0^H \mathbf{R}_v \mathbf{W}_0\} \text{ s.t. } \mathbf{W}_0^H \mathbf{A} = A_0, \mathbf{W}_0^H \mathbf{B} = \eta B_0$$

$$\min_{\mathbf{W}_1} \{\mathbf{W}_1^H \mathbf{R}_v \mathbf{W}_1\} \text{ s.t. } \mathbf{W}_1^H \mathbf{A} = A_1, \mathbf{W}_1^H \mathbf{B} = \eta B_1$$

$$\begin{aligned}
\mathbf{W}_0 &= \frac{1}{\sigma_a}\left[A_0^* + \frac{(A_0+\alpha A_1)^*}{(1+|\alpha|^2)}\frac{\Sigma}{(1-\Sigma)}\right]\mathbf{R}_v^{-1}\mathbf{A} \\
&\quad - \frac{(A_0+\alpha A_1)^*}{(1+|\alpha|^2)\,\sigma_{ab}}\frac{\Sigma}{(1-\Sigma)}\mathbf{R}_v^{-1}\mathbf{B}, \\
\mathbf{W}_1 &= \frac{1}{\sigma_a}\left[A_1^* + \alpha\frac{(A_0+\alpha A_1)^*}{(1+|\alpha|^2)}\frac{\Sigma}{(1-\Sigma)}\right]\mathbf{R}_v^{-1}\mathbf{A} \\
&\quad - \alpha\frac{(A_0+\alpha A_1)^*}{(1+|\alpha|^2)\,\sigma_{ab}}\frac{\Sigma}{(1-\Sigma)}\mathbf{R}_v^{-1}\mathbf{B},
\end{aligned}$$

$$\begin{aligned}
\mathbf{W}_0 &= \left(\frac{A_0^*}{\sigma_a} - \frac{\eta B_0^* \sigma_{ab}}{\sigma_a\sigma_b}\right)\frac{\mathbf{R}_v^{-1}\mathbf{A}}{1-\Sigma} + \left(\frac{\eta B_0^*}{\sigma_b} - \frac{A_0^*\sigma_{ab}^*}{\sigma_a\sigma_b}\right)\frac{\mathbf{R}_v^{-1}\mathbf{B}}{1-\Sigma}, \\
\mathbf{W}_1 &= \left(\frac{A_1^*}{\sigma_a} - \frac{\eta B_1^* \sigma_{ab}}{\sigma_a\sigma_b}\right)\frac{\mathbf{R}_v^{-1}\mathbf{A}}{1-\Sigma} + \left(\frac{\eta B_1^*}{\sigma_b} - \frac{A_1^*\sigma_{ab}^*}{\sigma_a\sigma_b}\right)\frac{\mathbf{R}_v^{-1}\mathbf{B}}{1-\Sigma}.
\end{aligned}$$

Binaural MVDR: Extensions for interfering source

Comparison between BMVDR-RTF and BMVDR-IR

$$\min_{\mathbf{W}_0,\mathbf{W}_1} \{\mathbf{W}_0^H \mathbf{R}_v \mathbf{W}_0 + \mathbf{W}_1^H \mathbf{R}_v \mathbf{W}_1\}$$
$$\text{s.t. } \mathbf{W}_0^H \mathbf{A} = A_0, \mathbf{W}_1^H \mathbf{A} = A_1, \frac{\mathbf{W}_0^H \mathbf{B}}{\mathbf{W}_1^H \mathbf{B}} = \frac{B_0}{B_1}.$$

$$\min_{\mathbf{W}_0} \{\mathbf{W}_0^H \mathbf{R}_v \mathbf{W}_0\} \text{ s.t. } \mathbf{W}_0^H \mathbf{A} = A_0, \mathbf{W}_0^H \mathbf{B} = \eta B_0$$
$$\min_{\mathbf{W}_1} \{\mathbf{W}_1^H \mathbf{R}_v \mathbf{W}_1\} \text{ s.t. } \mathbf{W}_1^H \mathbf{A} = A_1, \mathbf{W}_1^H \mathbf{B} = \eta B_1$$

- **BMVDR-RTF:** one constraint (relative transfer function)
  BMVDR-IR: two constraints (interference reduction parameter η)
- BMVDR-RTF is a special case of BMVDR-IR for specific (typically complex-valued) parameter η
- **Implementation** requires:
  - estimate of noise correlation matrix $\mathbf{R}_v$
  - estimates of relative transfer function vectors for speech source and interfering source(s) **A** and **B** – estimation procedures available

[Hadad 2014/2015/2016, Marquardt 2014]

Binaural MVDR: Extensions for interfering source

- **Comparison between BMVDR-RTF and BMVDR-IR**

- **Signal-to-interference-and-noise ratio (SINR)**

$$\mathrm{SINR}^{\mathrm{out}}_{\mathrm{BMVDR}} \geq \mathrm{SINR}^{\mathrm{out}}_{\mathrm{BMVDR-RTF}} \geq \mathrm{SINR}^{\mathrm{out}}_{\mathrm{BMVDR-IR}}$$

- **Signal-to-interference ratio (SIR)**

$$\begin{aligned}\mathrm{SIR}^{\mathrm{in}} &= \mathrm{SIR}^{\mathrm{out}}_{\mathrm{BMVDR-IR}_{\eta=1}} \\ &\leq \mathrm{SIR}^{\mathrm{out}}_{\mathrm{BMVDR-IR}} \leq \mathrm{SIR}^{\mathrm{out}}_{\mathrm{BMVDR-IR}_{\eta=0}},\end{aligned}$$

$$\mathrm{SIR}^{\mathrm{out}}_{\mathrm{BMVDR}} \leq \mathrm{SIR}^{\mathrm{out}}_{\mathrm{BMVDR-RTF}}$$

- **Signal-to-noise ratio (SNR)**

$$\mathrm{SNR}^{\mathrm{out}}_{\mathrm{BMVDR}} \geq \mathrm{SNR}^{\mathrm{out}}_{\mathrm{BMVDR-RTF}}$$

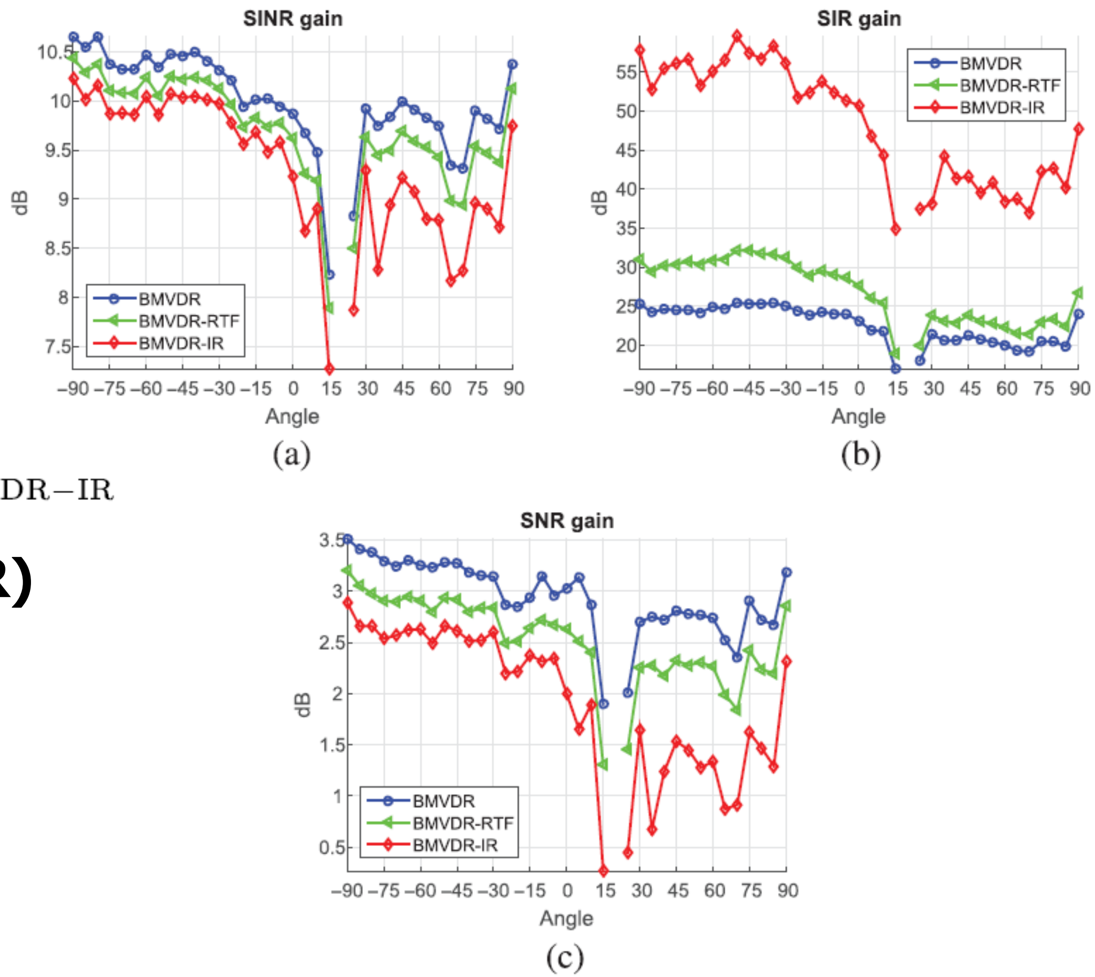


Fig. 4. Global binaural SINR, SIR and SNR gains for BMVDR, BMVDR-RTF and BMVDR-IR ($\eta = \eta_{opt}$) beamformers for different angles of the interfering source (Office environment, desired source at 20°, $M = 3$). (a) SINR gain (b) SIR gain (c) SNR gain.

Binaural MVDR: Extensions for interfering source

- Comparison between BMVDR-RTF and BMVDR-IR
  - **Beampattern**

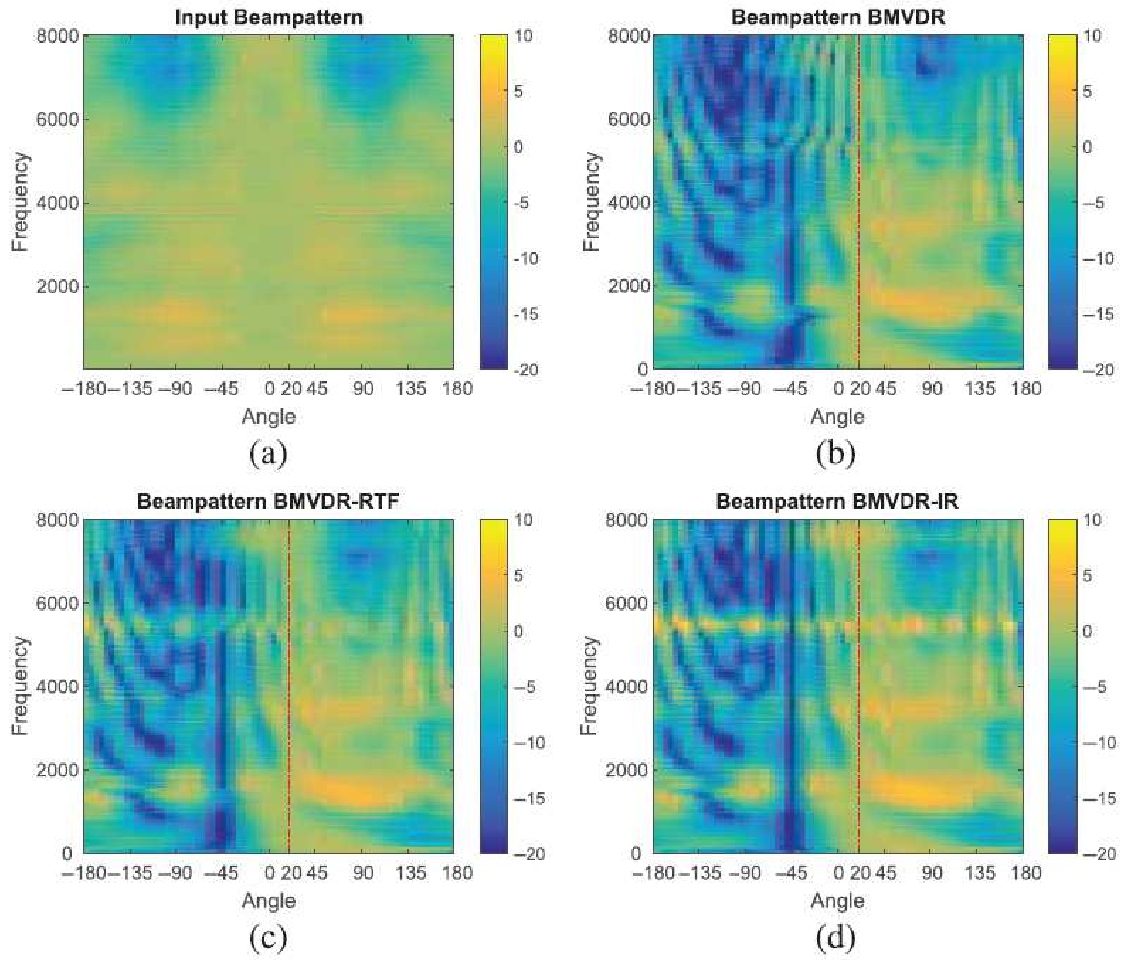


Fig. 3. Beampattern of the BMVDR, BMVDR-RTF and BMVDR-IR ($\eta = 0$) beamformers, together with the input beampattern (anechoic environment, desired source at 20°, interfering source at $-45°$, $M = 3$). (a) Input (b) BMVDR (c) BMVDR-RTF (d) BMVDR-IR.

Binaural MVDR: Extensions for interfering source

- Comparison between BMVDR-RTF and BMVDR-IR
  - **MSC of background noise**

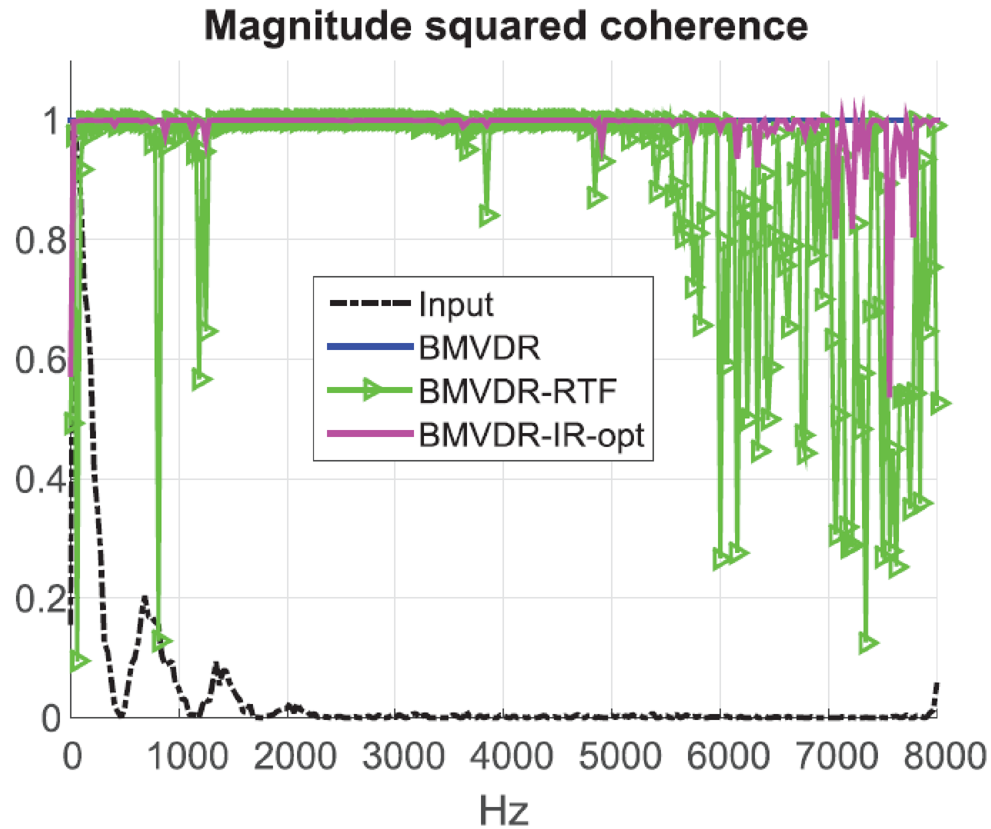
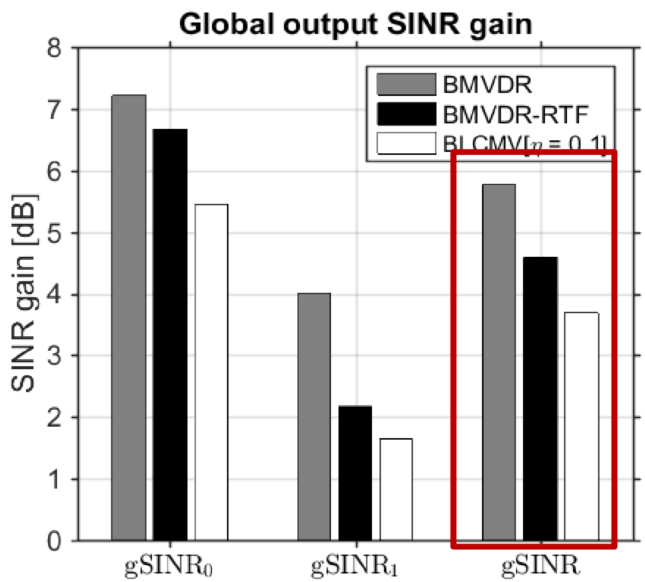


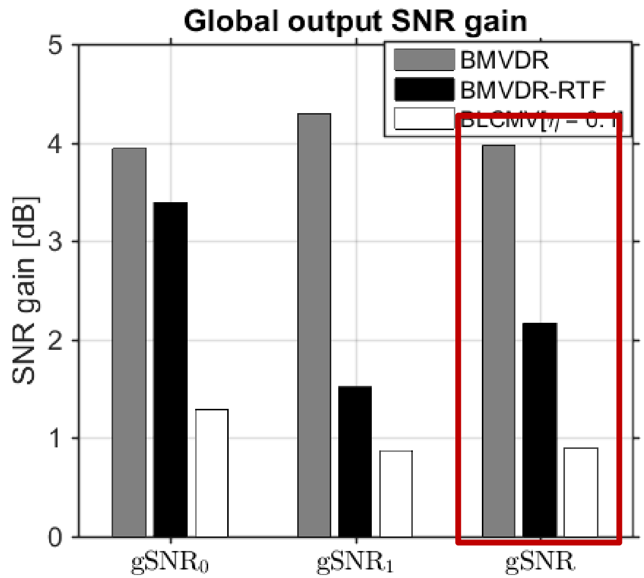
Fig. 6. The MSC for diffuse noise field at the input and at the output of the BMVDR, BMVDR-RTF and BMVDR-IR ($\eta = \eta_{opt}$) beamformers (Office, desired source at 20°, interfering source at $-45°$, $M = 3$).

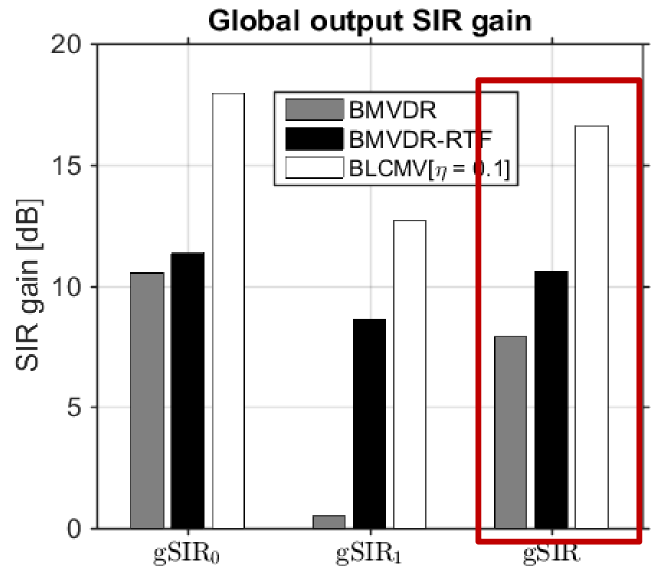
[Hadad 2015]

Binaural MVDR: Extensions for interfering source

❑ Instrumental evaluation / sound samples







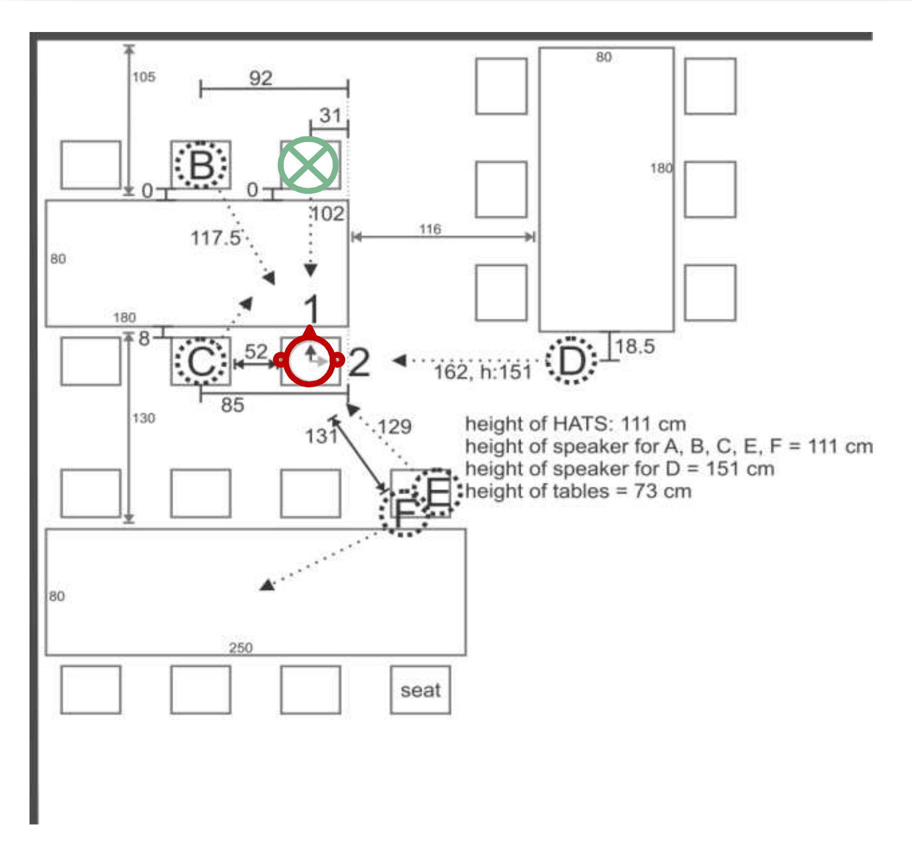
Input	BMVDR	BMVDR-RTF	BMVDR-IR (η = 0.1)

Cafeteria with recorded ambient noise, speaker at 0°, Interference at -45°, 0 dB input SIR and SNR (left hearing aid)
RTF calculated from correlation matrix (Rx and Ru), 3 microphones (2 left, 1 right)

[Marquardt 2014]

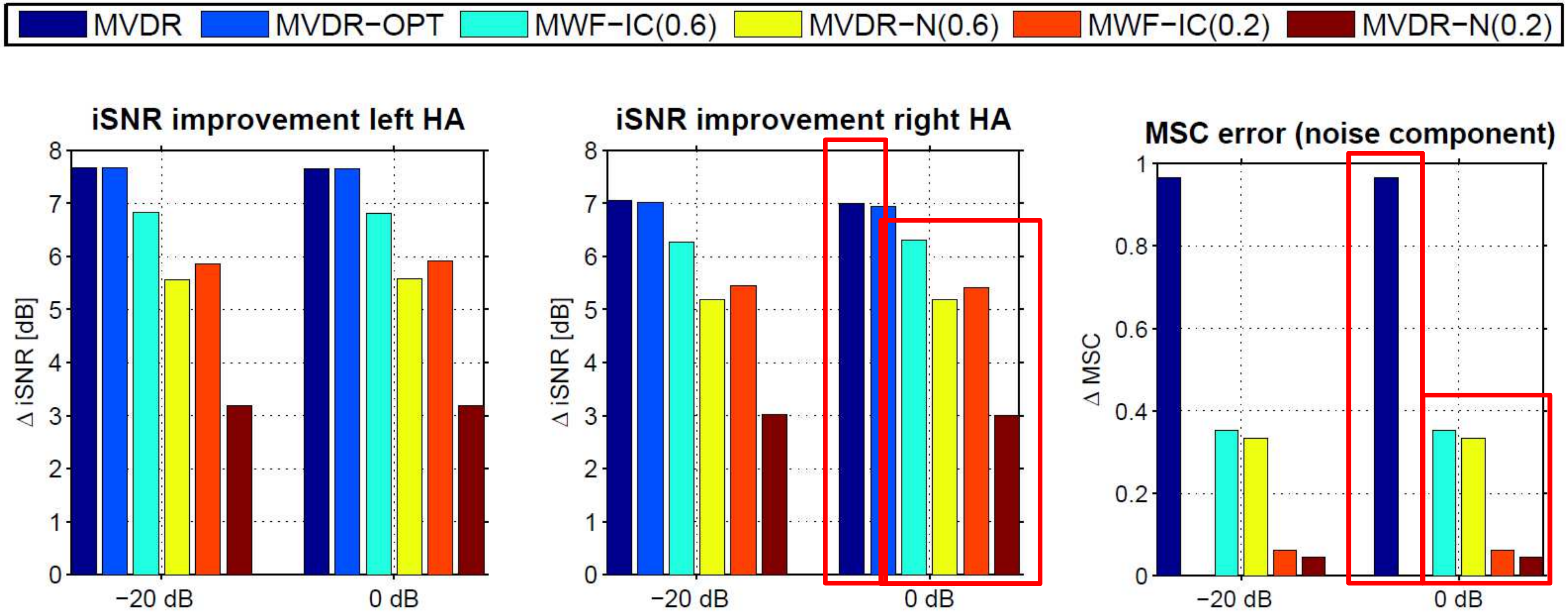
Evaluation Study 1 (NH)

Evaluation: Test setup



- Binaural hearing aid recordings (4 mics) in **cafeteria** (T_{60} ≈ 1250 ms) [Kayser 2009]
- **Noise:** realistic cafeteria ambient noise
- **Algorithms**: binaural MVDR + cue preservation extensions (MWF-IC, MVDR-N)
- **Instrumental measures**: MSC error and intelligibility-weighted SNR gain
- **Subjective listening experiments**:
  - 15 normal-hearing subjects
  - **SRT** using Oldenburg Sentence Test (OLSA)
  - **Spatial quality (diffuseness)** using MUSHRA

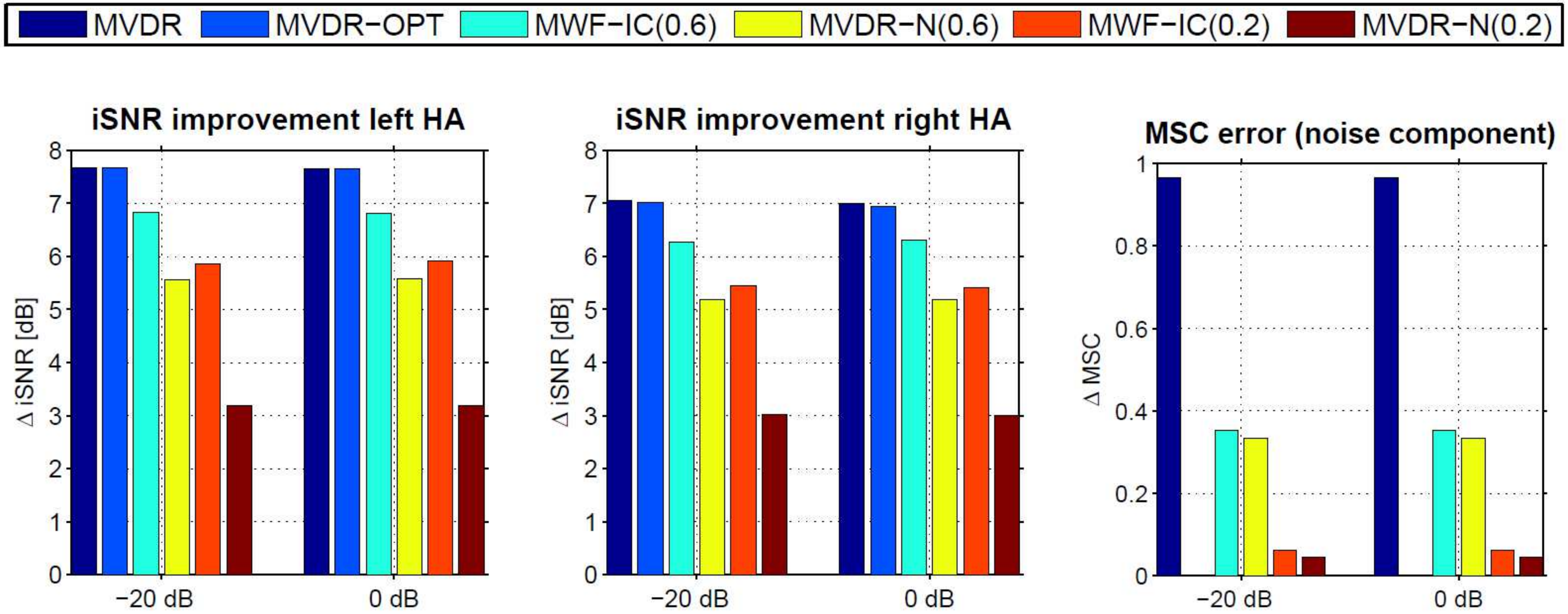
Evaluation: Instrumental measures



- Compared to MVDR, MSC error can be significantly reduced using MWF-IC and MVDR-N, but SNR improvement decreases (MWF-IC > MVDR-N)

Does binaural unmasking compensate for SNR decrease ?

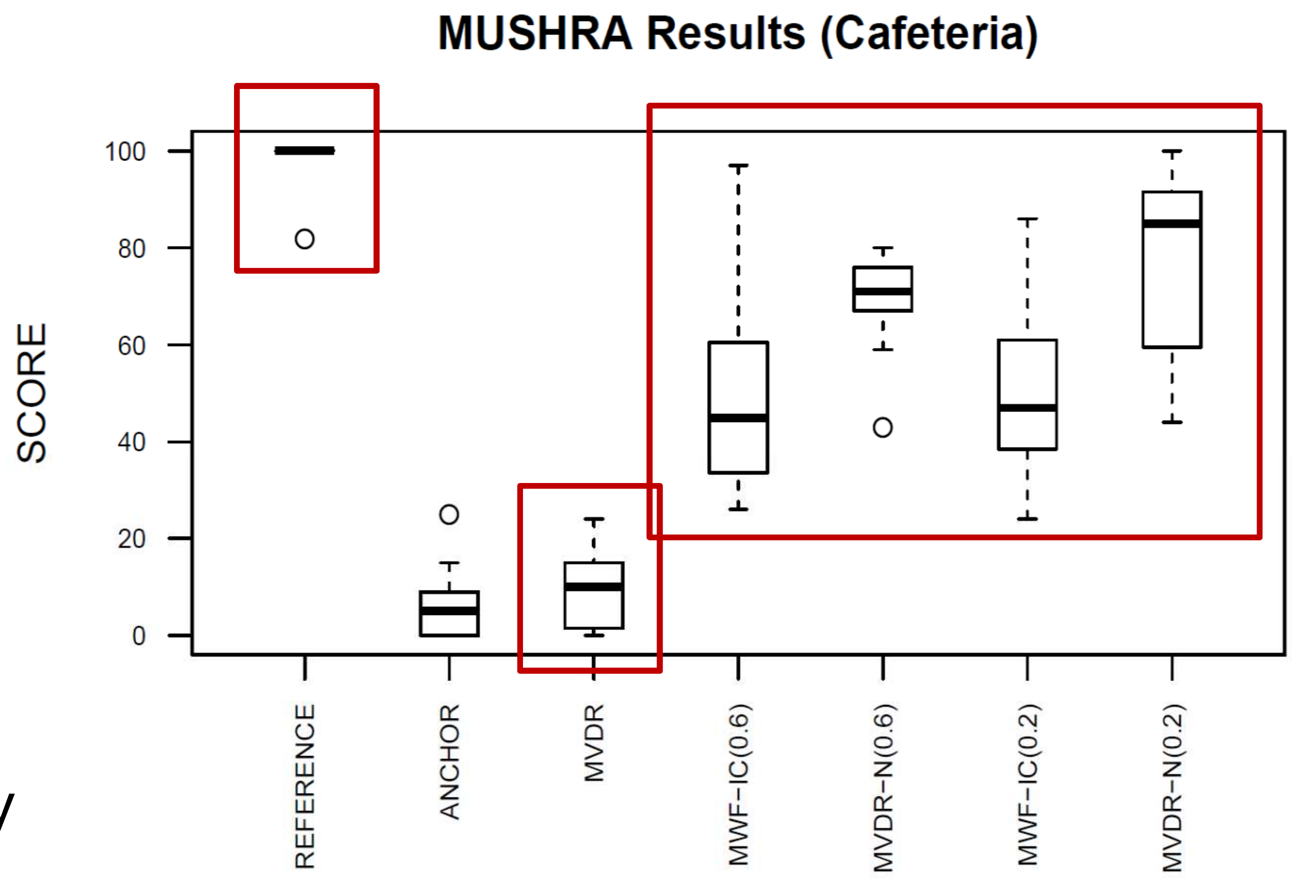
Evaluation: Audio Examples



Input	MVDR	MVDR-OPT	MWF-IC (0.6)	MVDR-N (0.6)	MWF-IC (0.2)	MVDR-N (0.2)

Evaluation: Spatial quality (MUSHRA)

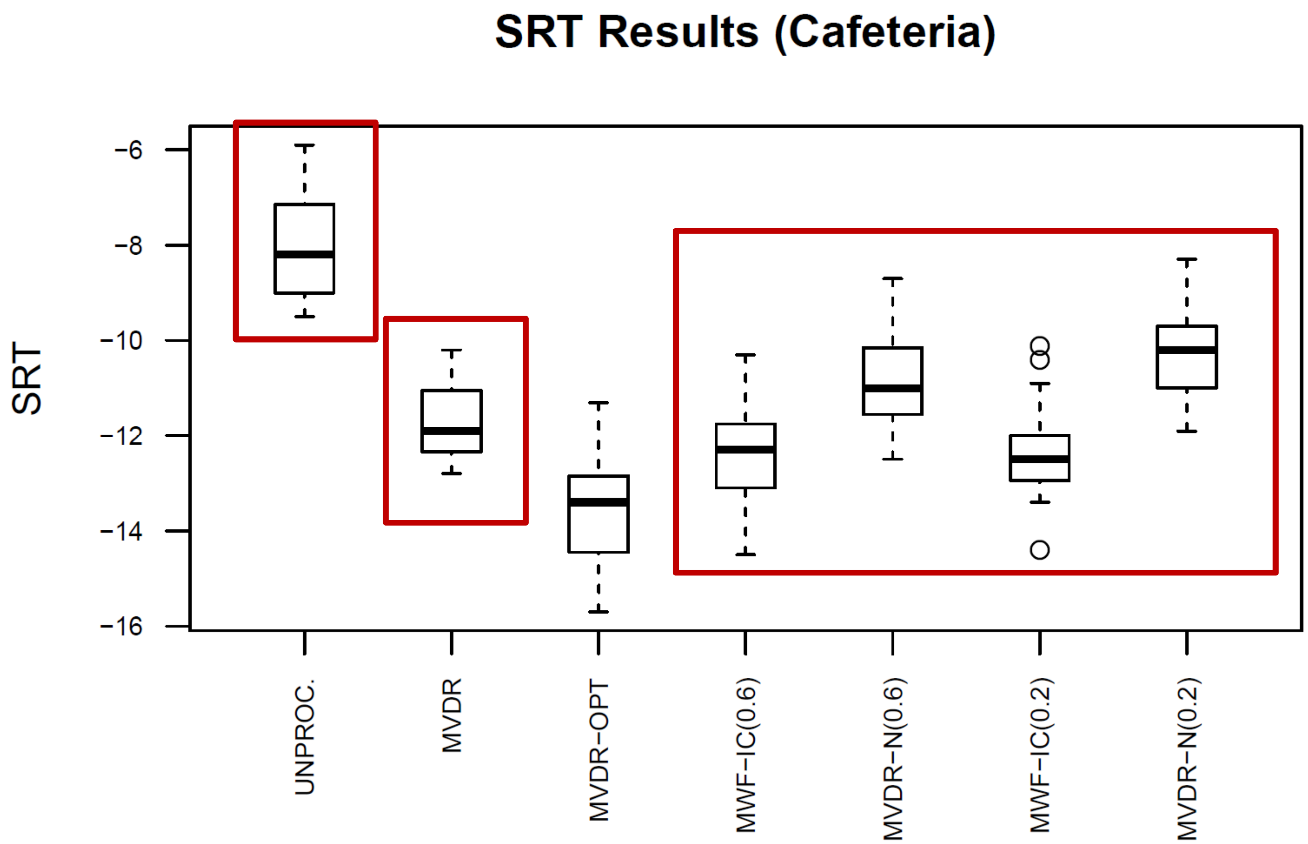
- Evaluate spatial difference between reference and output signal
- **MWF-IC and MVDR-N outperform MVDR**
    - MVDR-N shows better results than MWF-IC
    - Decreasing the MSC threshold slightly improves spatial quality



Binaural cue preservation for diffuse noise improves spatial quality

Evaluation: Speech intelligibility (SRT)

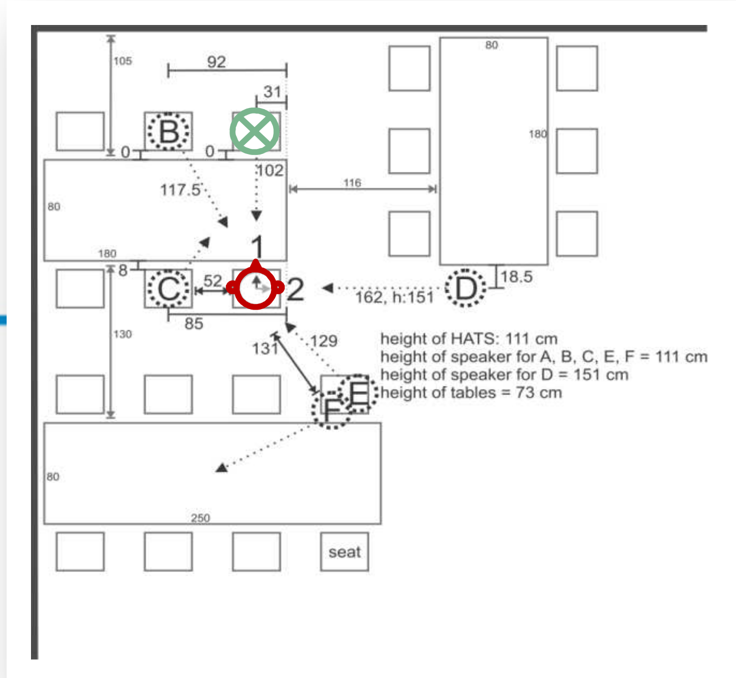
- All algorithms show a highly significant SRT improvement
- The SRT results mainly reflect the SNR differences between algorithms: MWF-IC outperforms MVDR-N
- **No significant SRT difference between MVDR and MWF-IC**



Binaural cue preservation for diffuse noise does not/hardly affect speech intelligibility

Evaluation Study 2 (CI)

Test Environment



- Cafeteria environment
  - T_{60} = 1250ms
- Speech material: Oldenburg sentence test (OLSA)
- Noise scenarios:
  - OlNoise (**OLN**):
    - Speech shaped noise, stationary, omnidirectional
  - 20 Talker-Babble (**20T**):
    - 20 Male talkers, EUROM1 speech corpus, omnidirectional
  - Cafeteria Ambient Noise (**CAN**):
    - KEMAR recording at UniOl cafeteria, omnidirectional
  - Single interfering talker (**SCT**):
    - 1 Male talker, EUROM1 speech corpus, directional (90°)

Algorithms

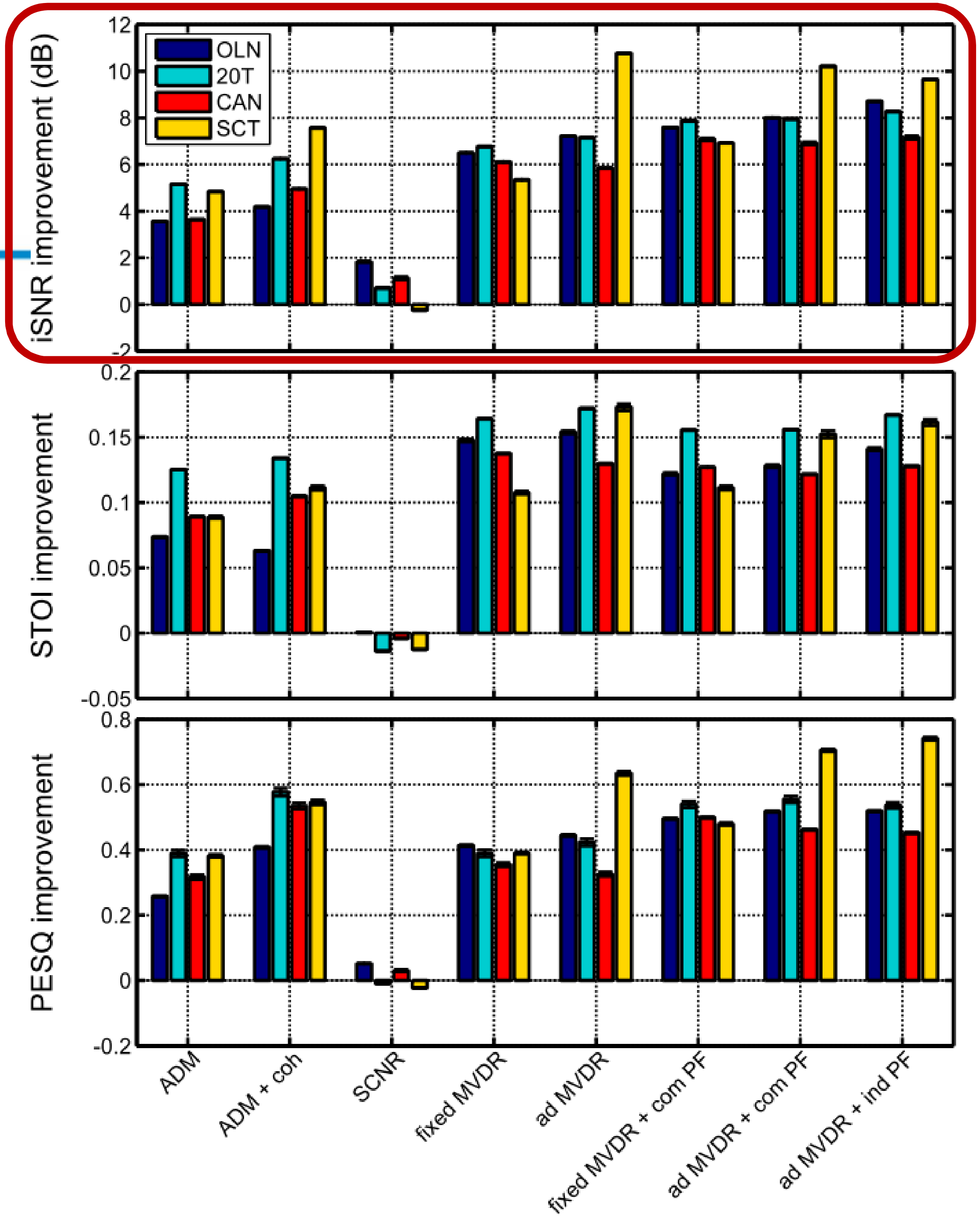
#	Abbreviation	Algorithm	monaural / binaural
1	NoPre	no preprocessing	
2	ADM	adaptive differential microphones	monaural
3	ADM + coh	adaptive differential microphone + coherence-based postfilter* (paradigm 1)	binaural
4	SCNR	single channel noise reduction **	monaural
5	fixed MVDR	fixed binaural MVDR beamformer (paradigm 2)	binaural
6	ad MVDR	adaptive binaural MVDR beamformer (paradigm 2)	binaural
7	fixed MVDR + com PF	common postfilter based on fixed binaural MVDR beamformer (paradigm 1)	binaural
8	ad MVDR + com PF	common postfilter based on adaptive binaural MVDR beamformer (paradigm 1)	binaural
9	ad MVDR + ind PF	Individual postfilter based on adaptive binaural MVDR beamformer (paradigm 1)	binaural

* Grimm et al. (2009)

** Gerkmann and Hendriks (2012), Breithaupt et al. (2008)

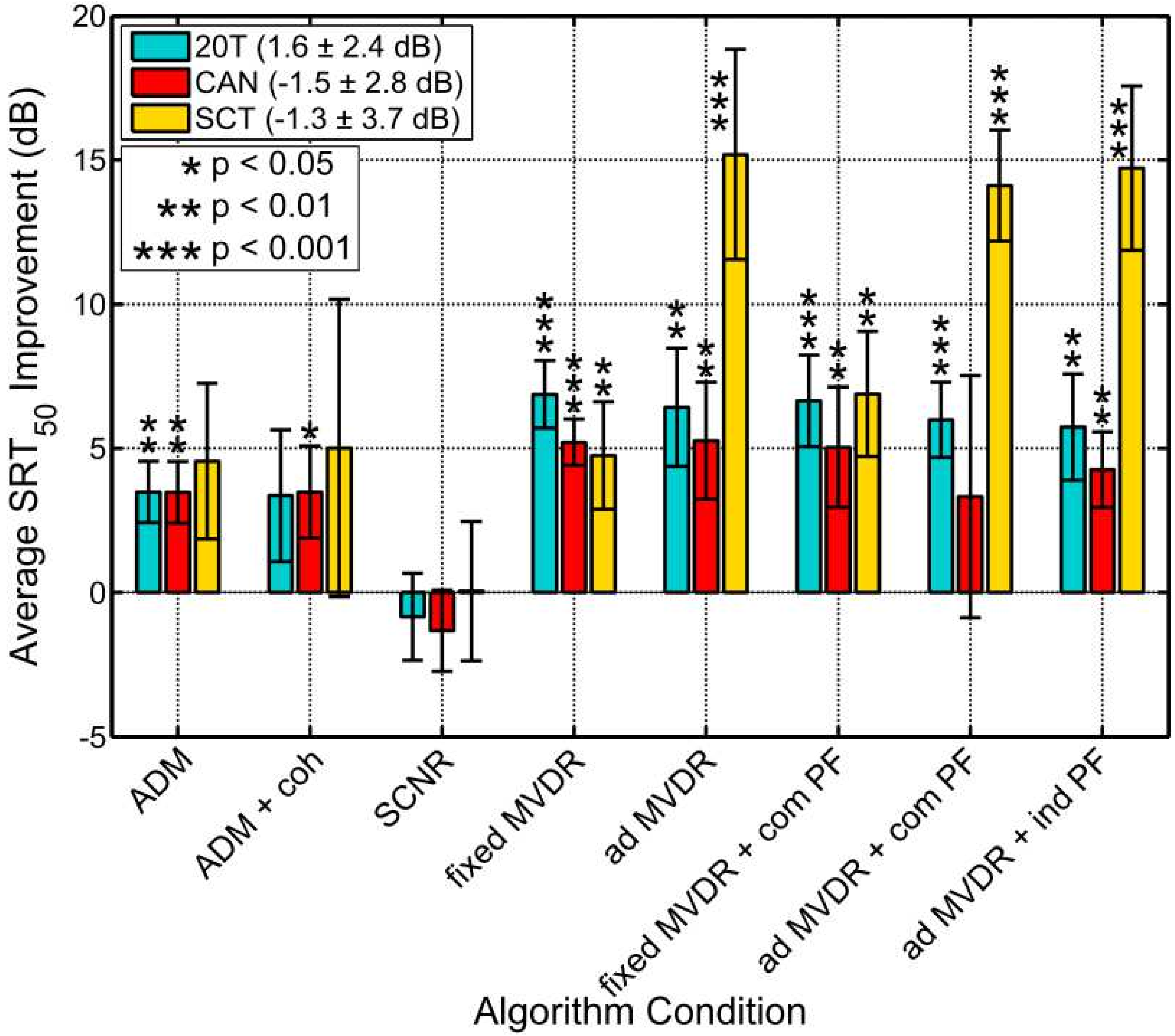
Instrumental Evaluation

- **Instrumental measures:**
  - Intelligibility weighted signal to noise ratio (iSNR)
  - STOI (speech intelligibility)
  - PESQ (speech quality)
- Input SNR: 0 dB
- **Results:**
  - SCNR: minor improvement
  - (Binaural) adaptive MVDR better than (bilateral) ADM
  - Adaptive MVDR similar to fixed MVDR, much better for single-competing-talker (SCT)
  - Post-filtering seems to improve quality (PESQ) but not intelligibility (STOI)
  - Individual post-filter slightly better as common post-filter



Perceptual Evaluation - Results

- **8 CI subjects**
- Substantial and significant SRT improvements
- Large inter-individual variability
- **Similar results as instrumental evaluation**
- Binaural MVDR performs especially well
- *Note: large SRT improvement in SCT due to simple scenario and "perfect" assumptions*



Conclusion

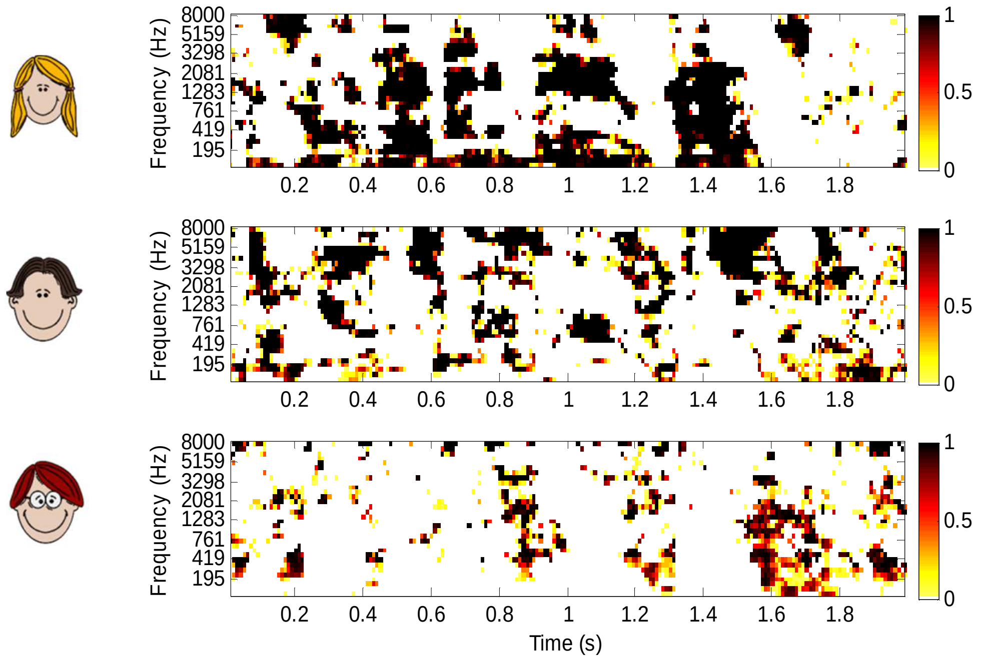
- **Binaural noise reduction algorithms**: 2 main paradigms
  - Spectral post-filtering
  - "True" binaural multi-microphone noise reduction
- **Extensions of binaural MVDR/MWF** for diffuse noise and interfering speaker
- Evaluation of **binaural MVDR extensions for diffuse noise (NH)**
  - Binaural cue preservation improves **spatial quality**
  - Binaural cue preservation does not/hardly affect **speech intelligibility**
  - MVDR-N : best spatial quality, MWF-IC : best SRT
- Evaluation of **several binaural algorithms for different noise conditions (CI)**
  - Binaural algorithms better as bilateral/monaural algorithms
  - No SRT improvement by (common/individual) postfiltering
  - Best performance for binaural adaptive MVDR beamformer

Current/Future work

- Binaural noise reduction algorithms for **interfering sources** (BMVDR-IR, BMVDR-RTF):
  - Subjective evaluation (incl. binaural cue preservation) for HA/CI users
  - Robustness against RTF estimation errors

- **Mixed noise fields and time-varying scenarios**: incorporate computational acoustic scene analysis (CASA) into developed algorithms

- Extend algorithms to include **external microphones (acoustic sensor networks)**



Acknowledgments

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  - Cluster of Excellence Hearing4All (DFG)
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  - German-Israeli Foundation Project "Signal Dereverberation Algorithms for Next-Generation Binaural Hearing Aids" (Partners: International Audiolabs Erlangen; Bar-Ilan University, Israel)

DFG Deutsche Forschungsgemeinschaft

VolkswagenStiftung

GIF German-Israeli Foundation for Scientific Research and Development

Recent publications

- D. Marquardt, V. Hohmann, S. Doclo, *Interaural Coherence Preservation in Multi-channel Wiener Filtering Based Noise Reduction for Binaural Hearing Aids*, *IEEE/ACM Trans. Audio, Speech and Language Processing*, vol. 23, no. 12, pp. 2162-2176, Dec. 2015.
- J. Thiemann, M. Müller, D. Marquardt, S. Doclo, S. van de Par, *Speech Enhancement for Multimicrophone Binaural Hearing Aids Aiming to Preserve the Spatial Auditory Scene*, *EURASIP Journal on Advances in Signal Processing*, 2016:12, pp. 1-11.
- E. Hadad, S. Doclo, S. Gannot, *The Binaural LCMV Beamformer and its Performance Analysis*, *IEEE/ACM Trans. Audio, Speech and Language Processing*, vol. 24, no. 3, pp. 543-558, Mar. 2016.
- E. Hadad, D. Marquardt, S. Doclo, S. Gannot, *Theoretical Analysis of Binaural Transfer Function MVDR Beamformers with Interference Cue Preservation Constraints*, *IEEE/ACM Trans. Audio, Speech and Language Processing*, vol. 23, no. 12, pp. 2449-2464, Dec. 2015.
- D. Marquardt, E. Hadad, S. Gannot, S. Doclo, *Theoretical Analysis of Linearly Constrained Multi-channel Wiener Filtering Algorithms for Combined Noise Reduction and Binaural Cue Preservation in Binaural Hearing Aids*, *IEEE/ACM Trans. Audio, Speech and Language Processing*, vol. 23, no. 12, pp. 2384-2397, Dec. 2015.
- R. Baumgärtel, M. Krawczyk-Becker, D. Marquardt, C. Völker, H. Hu, T. Herzke, G. Coleman, K. Adiloglu, S. Ernst, T. Gerkmann, S. Doclo, B. Kollmeier, V. Hohmann, M. Dietz, *Comparing binaural pre-processing strategies I: Instrumental evaluation*, *Trends in Hearing*, vol. 19, pp. 1-16, 2015.
- R. Baumgärtel, H. Hu, M. Krawczyk-Becker, D. Marquardt, T. Herzke, G. Coleman, K. Adiloglu, K. Bomke, K. Plotz, T. Gerkmann, S. Doclo, B. Kollmeier, V. Hohmann, M. Dietz, *Comparing binaural pre-processing strategies II: Speech intelligibility of bilateral cochlear implant users*, *Trends in Hearing*, vol. 19, pp. 1-18, 2015.

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Questions ?