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Arenberg Doctoral School of Science, Engineering & Technology
Faculty of Engineering
Department of Electrical Engineering

A Flexible Speech Distortion Weighted Multi-Channel Wiener Filter for Noise Reduction in Hearing Aids

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Outline

- Introduction and problem statement
- Speech Distortion Weighted Multi-channel Wiener filter (SDW-MWF)
- Conditional speech presence probability (SPP)
- SDW-MWF incorporating the conditional SPP
- SDW-MWF incorporating a flexible weighting factor
- Conclusion

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Introduction

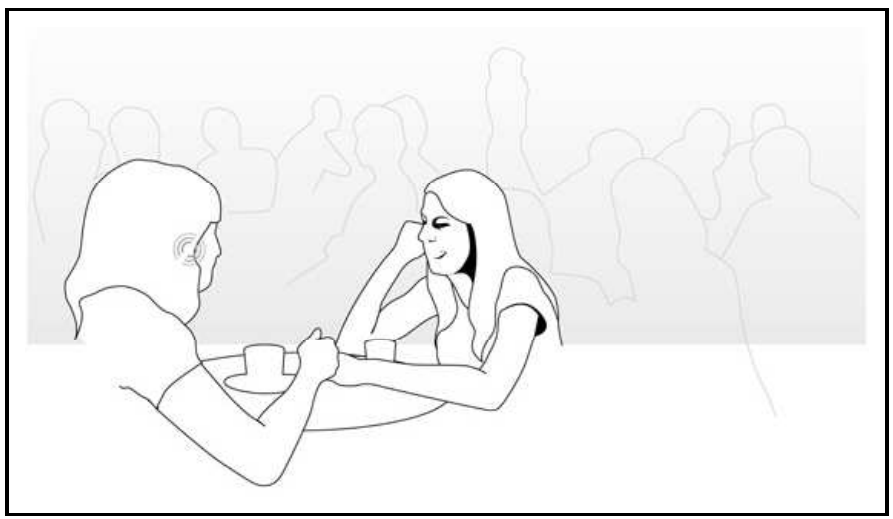
Hearing loss/Background Noise

Common causes of hearing loss:

- Age-related
- Daily exposure to excessive noise in the work environment
- Listening to loud music

Hearing impaired people:

- Reduced frequency resolution (separating sounds of different frequencies)
- Reduced temporal resolution (intense sounds mask weaker sounds)
- Reduced spatial cues (spatially separating desired signal from noise)



- Understanding speech in noise is a major problem
- Multiple speakers, fans, traffic etc.
- Reduces the intelligibility of speech.
- More sensitive to the noise level.
- Need higher SNR to communicate.

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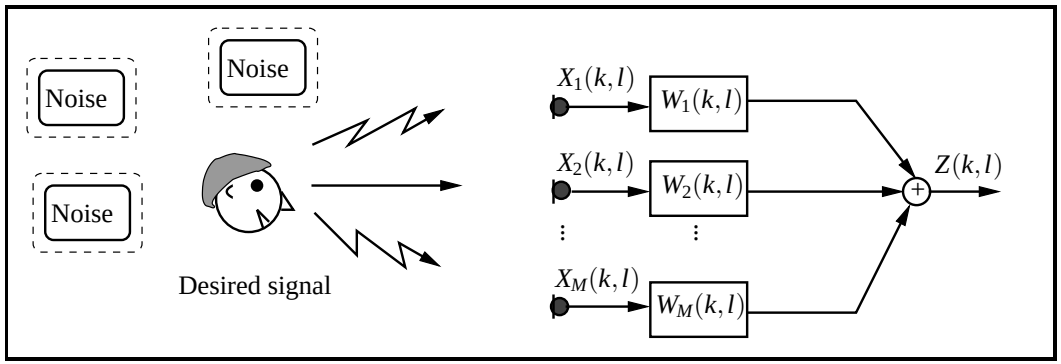
Introduction

Multi-microphone noise reduction

Common techniques:

- Directional microphones
- Delay-and-sum beamformers
- GSC, MVDR, LCMV beamformers.
- **Multi-channel Wiener filter**



Objective of NR:

- Maximally reduce the noise (SNR improvement)
- Minimize speech distortion (sound quality)
- Improve intelligibility of speech (perceptual quality)

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Multi-channel Wiener filter

Speech distortion weighted multi-channel Wiener filter (SDW-MWF$_\mu$)

Frequency-domain microphone signals:

$$\mathbf{X}(k,l) = \mathbf{X}^s(k,l) + \mathbf{X}^n(k,l)$$

- k is the frequency bin index and l is the frame index

MWF MMSE criterion:

$$\mathbf{W}_{\mathrm{MMSE}}(k,l) = \arg\min_{\mathbf{W}} \ \varepsilon\{|X_1^s(k,l) - \mathbf{W}^H\mathbf{X}(k,l)|^2\}$$

SDW-MWF$_\mu$ MMSE criterion:

$$\mathbf{W}_\mu(k,l) = \arg\min_{\mathbf{W}} \ \varepsilon\{|X_1^s(k,l) - \mathbf{W}^H\mathbf{X}^s(k,l)|^2\} + \mu\varepsilon\{|\mathbf{W}^H\mathbf{X}^n(k,l)|^2\}$$

Optimal SDW-MWF$_\mu$ solution:

$$\boxed{\mathbf{W}_\mu(k,l) = \left(\mathbf{R}^s(k,l) + \mu\mathbf{R}^n(k,l)\right)^{-1}\mathbf{R}^s(k,l)\mathbf{e}_1}$$

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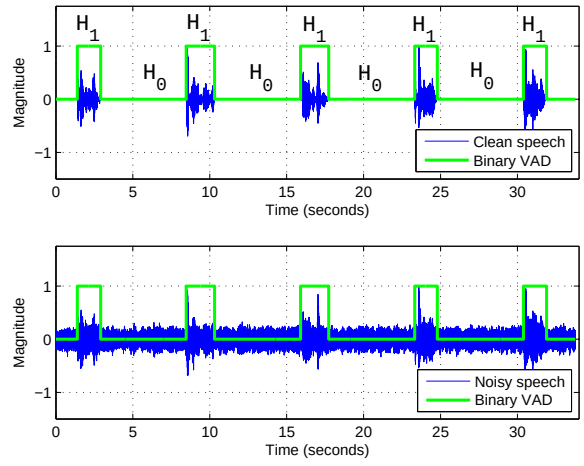
Multi-channel Wiener filter

Estimation and update of correlation matrices

- Second-order statistics of the noise are assumed to be stationary

$$\mathbf{R}^s(k,l) = \mathbf{R}^x(k,l) - \mathbf{R}^n(k,l)$$



- Estimation of $\mathbf{R}^x(k,l)$ and $\mathbf{R}^n(k,l)$: an averaging time window of 2-3 seconds is typically used.

$$\mathbf{R}_n(k,l+1) = \alpha_n \mathbf{R}_n(k,l) + (1-\alpha_n)\mathbf{X}(k,l)\mathbf{X}^H(k,l)$$
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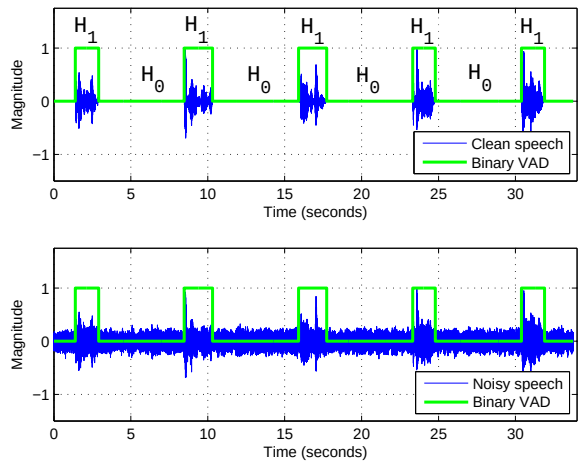

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Multi-channel Wiener filter

Motivation

Properties of the SDW-MWF$_\mu$:

- SDW-MWF depends on long-term average of spectral and spatial characteristics.
- Eliminates short-time effects, such as musical noise
- Weighting factor μ is a fixed value for all frequencies and for all frames

$$\mathbf{W}_\mu(k,l) = \left(\mathbf{R}^s(k,l) + \mu\mathbf{R}^n(k,l)\right)^{-1}\mathbf{R}^s(k,l)\mathbf{e}_1$$

Properties not included in the SDW-MWF$_\mu$:

- Speech and noise can be non-stationary spectrally and temporally.
- Speech contains many pauses while noise can be continuously present.
- Different weight to speech dominant segments and to noise dominant segments

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Multi-channel Wiener filter

Speech presence probability

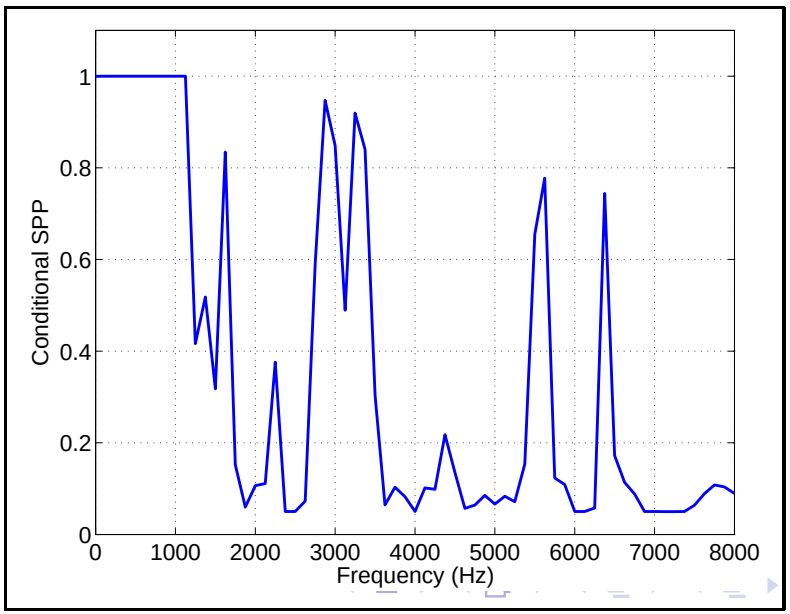
Two-state speech model:

$$H_0(k,l) : \mathbf{X}(k,l) = \mathbf{X}^n(k,l)$$
$$H_1(k,l) : \mathbf{X}(k,l) = \mathbf{X}^s(k,l) + \mathbf{X}^n(k,l).$$

Conditional speech presence probability $p(k,l) \triangleq P(H_1(k,l)|X_i(k,l))$:

$$p(k,l) = \left\{1 + \frac{q(k,l)}{1-q(k,l)}(1+\xi(k,l))\exp(-\upsilon(k,l))\right\}^{-1}$$

- $q(k,l) \triangleq P(H_0(k,l))$ is the a priori speech absence probability (SAP)
- $\xi(k,l)$ is the a priori SNR
- $\gamma(k,l)$ is the a posteriori SNR
- $p(k,l)$ is estimated for each frequency bin and each frame



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Multi-channel Wiener filter

SDW-MWF incorporating the conditional SPP (SDW-MWF$_{\text{SPP}}$)

SDW-MWF$_{\text{SPP}}$ MMSE criterion:

$$\mathbf{W}_{\text{SPP}}(k,l) = \arg\min_{\mathbf{W}} \; p(k,l)\varepsilon\{|X_1^s - \mathbf{W}^H\mathbf{X}|^2|H_1\} + (1-p(k,l))\varepsilon\{|\mathbf{W}^H\mathbf{X}|^2|H_0\}$$

Optimal SDW-MWF$_{\text{SPP}}$ solution:

$$\boxed{\mathbf{W}_{\text{SPP}}(k,l) = \left(\mathbf{R}^s + \left(\frac{1}{p(k,l)}\right)\mathbf{R}^n\right)^{-1}\mathbf{R}^s\mathbf{e}_1.}$$

- If $p = 0$, the SDW-MWF$_{\text{SPP}}$ attenuates the noise by applying $\mathbf{W}_{\text{SPP}} \leftarrow 0$.
- If $p = 1$, the SDW-MWF$_{\text{SPP}}$ solution corresponds to the MWF solution (μ=1).
- If $0 < p < 1$ there is a trade-off between noise reduction and speech distortion.

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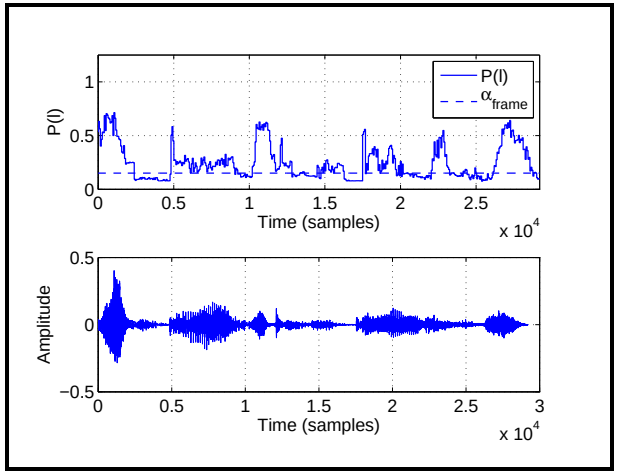
Multi-channel Wiener filter

H_0 and H_1 state detection based on SPP

Binary decision:

$$P(l) = \begin{cases} H_1 : 1 & \text{if} \quad \frac{1}{K}\sum_{k=1}^{K} p(k,l) \geq \alpha_{\text{frame}} \\ H_0 : 0 & \text{otherwise} \end{cases}$$



Rationale:

- Reducing the noise in the H_0 state can be related to increasing listening comfort, since speech is not present in the H_0 state, which means that a greater attenuation can be applied.
- Reducing the noise in the H_1 state is a more challenging task since this relates to speech intelligibility and hence the speech distortion weighted concept truly only makes sense in the H_1 state.

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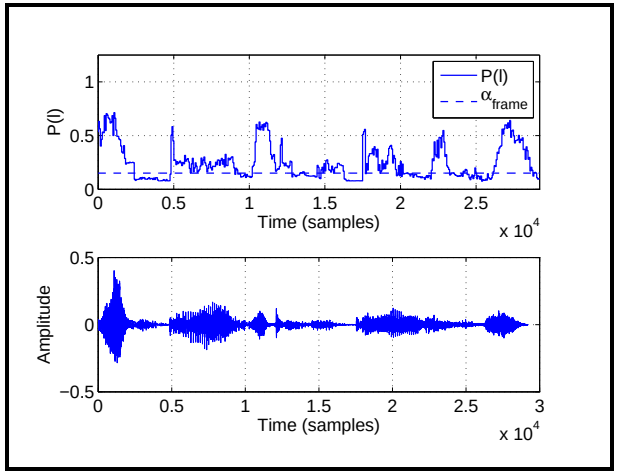

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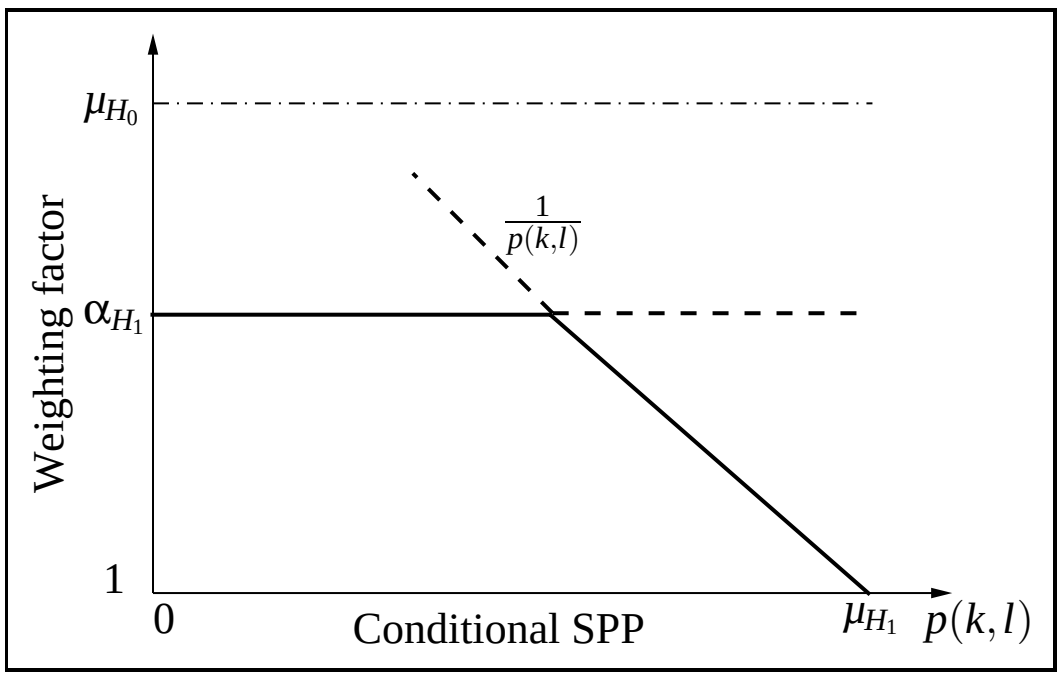
Multi-channel Wiener filter

H_0 and H_1 state detection based on SPP

Proposed weighting factor:

- A weighting factor μ_{H_1} is introduced, which is a function of $p(k,l)$, that defines the amount of noise reduction that can be applied in the H_1 state.
- A weighting factor μ_{H_0} is introduced, which is a constant weighting factor, that defines the amount of noise reduction that can be applied in the H_0 state.



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Multi-channel Wiener filter

SDW-MWF incorporating a flexible weighting factor (SDW-MWF$_{\text{flex}}$)

SDW-MWF$_{\text{flex}}$ MMSE criterion:

$$\mathbf{W}_{\text{Flex}}(k,l) = \arg\min_{\mathbf{W}} \begin{cases} P(l)\left[\mu_{H_1}\varepsilon\{|X_1^s - \mathbf{W}^H\mathbf{X}|^2|H_1\} + (1-\mu_{H_1})\varepsilon\{|\mathbf{W}^H\mathbf{X}|^2|H_0\}\right] \\ (1-P(l))\left[\frac{1}{\mu_{H_0}}\varepsilon\{|X_1^s - \mathbf{W}^H\mathbf{X}^s|^2\} + \varepsilon\{|\mathbf{W}^H\mathbf{X}^n|^2\}\right] \end{cases}$$

where $\mu_{H_1} = \max(p(k,l), \frac{1}{\alpha_{H_1}})$

Optimal SDW-MWF$_{\text{flex}}$ solution:

$$\mathbf{W}_{\text{Flex}}(k,l) = \left[\mathbf{R}^s + \gamma(k,l)\mathbf{R}^n\right]^{-1}\mathbf{R}^s\mathbf{e}_1$$

with the weighting factor defined as:

$$\gamma(k,l) = \left[P(l)\max(p(k,l), \tfrac{1}{\alpha_{H_1}}) + (1-P(l))\tfrac{1}{\mu_{H_0}}\right]^{-1}$$

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Experimental set-up MWF based NR

Simulation parameters:

- A 2-microphone behind-the-ear hearing aid mounted on a CORTEX MK2 manikin.
- The loudspeakers are positioned at 1 meter from the center of the head.
- The reverberation time $T_{60} = 0.21s$.
- Speech is located at $0°$, two multi-talker babble noise sources at $120°$ and $180°$.
- The speech signals consist of male sentences from the HINT-database
- and the noise signal consist of a multi-talker babble from Auditec
- The speech signals are sampled at 16kHz
- An FFT length of 128 with 50% overlap was used.

Intelligibility-weighted signal-to-noise ratio (SNR):

$$\Delta\mathrm{SNR}_{\mathrm{intellig}} = \sum_i I_i \left(\mathrm{SNR}_{i,out} - \mathrm{SNR}_{i,in}\right)$$

frequency-weighted log-spectral signal distortion (SD)

$$\mathrm{SD} = \frac{1}{K}\sum_{k=1}^{K}\sqrt{\int_{f_l}^{f_u} w_{ERB}(f)\left(10log_{10}\frac{P^s_{out,k}(f)}{P^s_{in,k}(f)}\right)^2 df}$$

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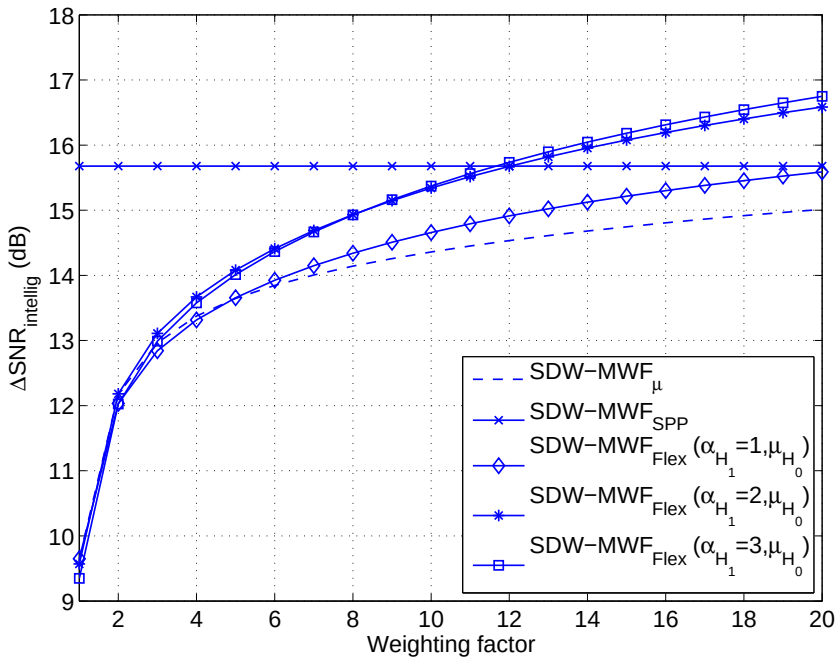
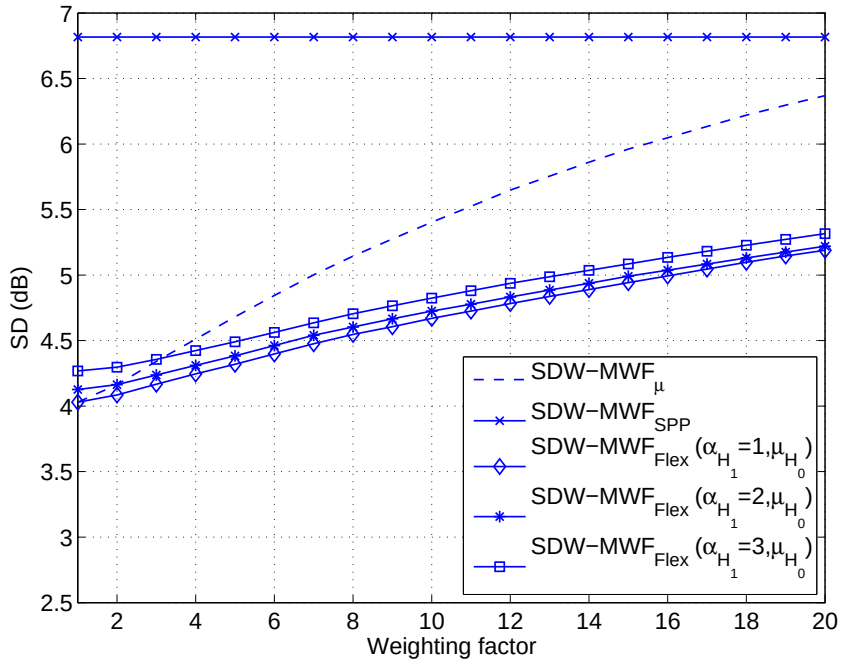
Experimental results MWF based NR

- SDW-MWF$_{\mu}$ - low SNR improvement - high distortion
- SDW-MWF$_{\mathrm{SPP}}$ - high SNR improvement - high distortion
- SDW-MWF$_{\mathrm{Flex}}$ - **high SNR improvement** - **low distortion**





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Conclusion

Summary:

- Different extensions of the SDW-MWF algorithms
- SDW-MWF$_{\mu}$ fixed weighting for each frame and for each frequency
- SDW-MWF$_{\mathrm{SPP}}$ weighting based on the conditional SPP
- SDW-MWF$_{\mathrm{Flex}}$ weighting based on combined soft and binary detection

Future/current work:

- Perceptual evaluation using hearing impaired listeners
- Using a perceptual motivated weighting factor in the SDW-MWF

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End of presentation

Thank you!.....Questions?