Acoustically Transparent Earpiece: Equalization, Feedback cancellation, Active noise control and Own voice pickup

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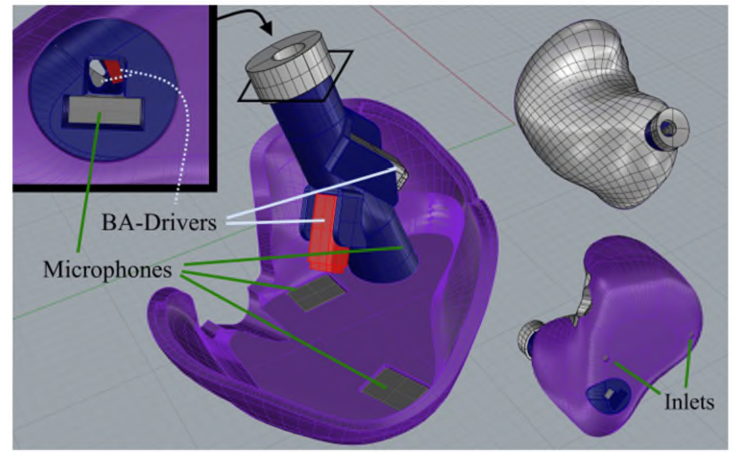
Acoustically Transparent Earpiece

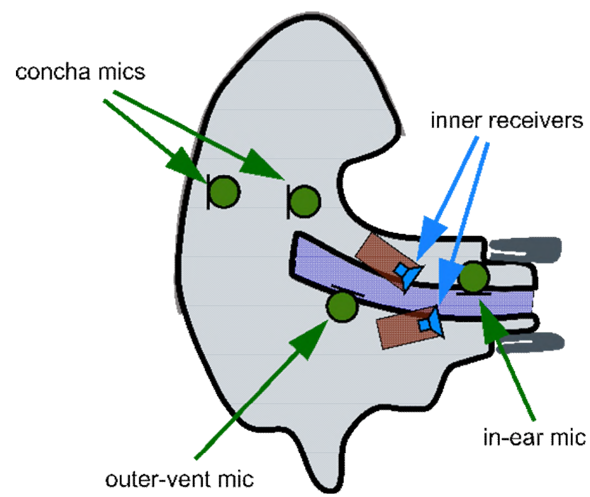
- **Long-term objective:**
  - Acoustically transparent speech communication using earpiece with multiple microphones and receivers/loudspeakers

- Develop, implement, and evaluate **individualized algorithms** for
  1. sound pressure equalization (transparency)
  2. acoustic feedback cancellation
  3. active noise/occlusion control
  4. own voice extraction

Acoustically Transparent Earpiece (Hearpiece)

- One-size-fits-all design: fits about 90% of human ears
- Vent: **2 microphones, 2 receivers**
- Concha: **2 microphones**
- Two versions: vented + closed
- ***Available at Hörzentrum / InEar GmbH:***
  https://www.hz-ol.de/en/hearpiece.html





[Denk et al., *AES Conference Headphone Technology*, 2019]

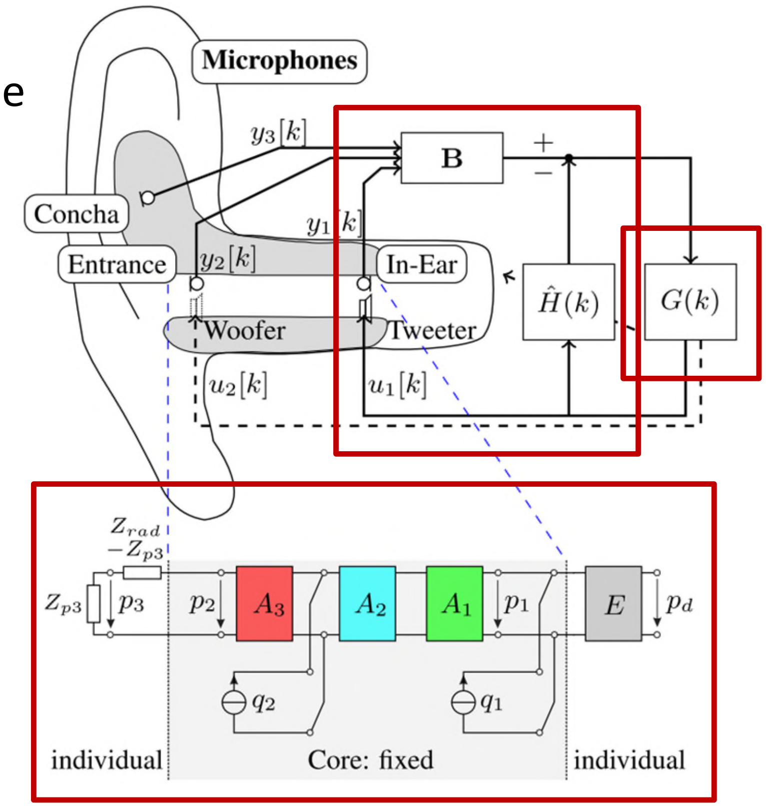
Acoustically Transparent Earpiece

1. Acoustically transparent sound presentation:

- Enable hearing comparable to open ear (equalization using single/multiple receivers)

2. Individualized Electro-Acoustic Model:

- Better understand acoustics
- Predict sound pressure and transfer functions (eardrum)



3. Acoustic Feedback cancellation

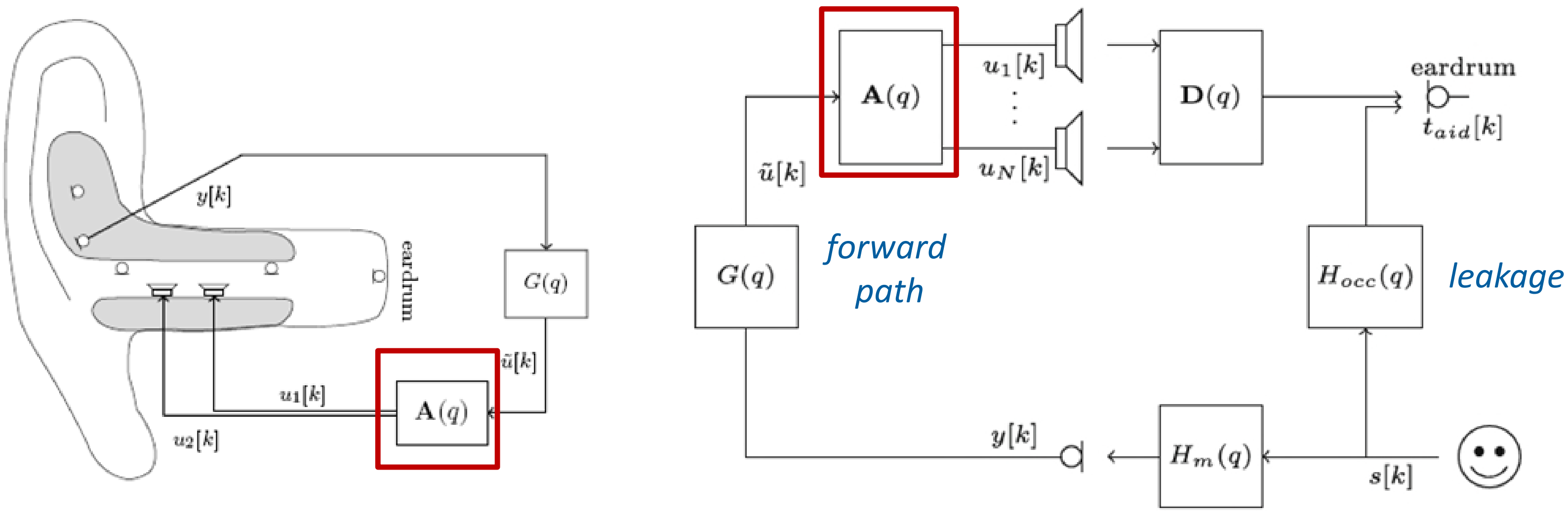
- Exploit multiple microphones to steer null towards position of receiver
- Exploit multiple receivers

4. Hearing support:

- Amplification and dynamic range compression
- Active noise and occlusion control

1. Acoustically transparent sound presentation

- **Single/Multi-Loudspeaker Equalization**
  - **Goal:** Achieve sound pressure at aided ear that is (physically or perceptually) equivalent to sound pressure at open ear
  - **Design and apply equalization filter(s) A*(q)*** to concha microphone signal, taking into account leakage and hearing device processing (forward path)



$$G(q)H_m(q)\mathbf{D}^T(q)\mathbf{A}(q) = G(q)H_{open}(q) - H_{occ}(q)$$

[Schepker et al., *EURASIP JASMP,* 2022]

1. Acoustically transparent sound presentation

- **Single/Multi-Loudspeaker Equalization**
  - **Goal:** Achieve sound pressure at aided ear that is (physically or perceptually) equivalent to sound pressure at open ear
  - **Design and apply equalization filter(s) A***(q)* to concha microphone signal, taking into account leakage and hearing device processing (forward path)
  - **Robust least-squares-based design procedure** (with group delay compensation and frequency-dependent regularization)
  - **Requires** (one or multiple) measurements of all transfer functions

multiple measurements — *regularization*

$$J_{mfr\Delta LS}(\mathbf{a}) = \sum_{i=1}^{I} \|\mathbf{D}_{\Delta,i}\mathbf{a} - \tilde{\mathbf{v}}_{\Delta,i}\|_2^2 + \lambda\|\mathbf{W}\mathbf{F}\mathbf{a}\|_2^2$$

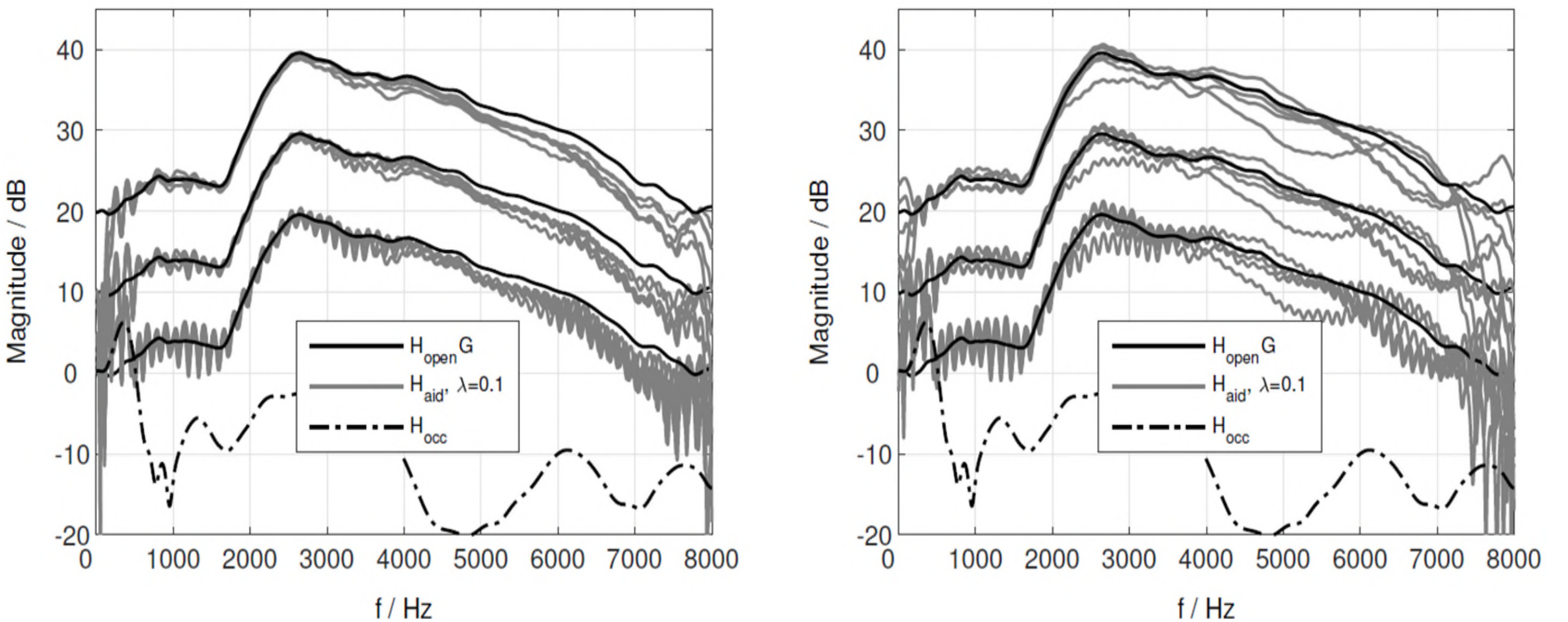
$$\mathbf{a}_{mfr\Delta LS} = \left(\bar{\mathbf{D}}_\Delta^T\bar{\mathbf{D}}_\Delta + \lambda\mathbf{F}^H\mathbf{W}^H\mathbf{W}\mathbf{F}\right)^{-1}\bar{\mathbf{D}}_\Delta^T\bar{\mathbf{v}}_\Delta$$

$$\tilde{\mathbf{v}}_\Delta = \left(\mathbf{H}_{m,\Delta}^T\mathbf{G}_\Delta^T\mathbf{G}_\Delta\mathbf{H}_{m,\Delta}\right)^{-1}\mathbf{H}_{m,\Delta}^T\mathbf{G}_\Delta^T\left(\mathbf{G}_\Delta\tilde{\mathbf{h}}_{open,\Delta} - \tilde{\mathbf{h}}_{occ,\Delta}\right)$$

[Schepker et al., *EURASIP JASMP,* 2022]

1. Acoustically transparent sound presentation

- **Single/Multi-Loudspeaker Equalization**



(a) $N = 1.$ (b) $N = 2.$

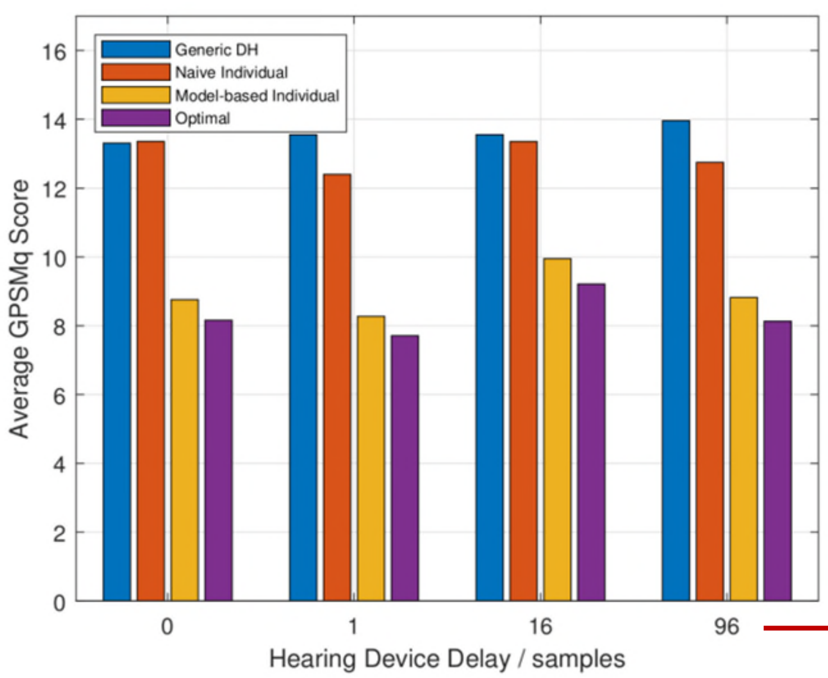
Robust equalization possible both using 1 and 2 loudspeakers

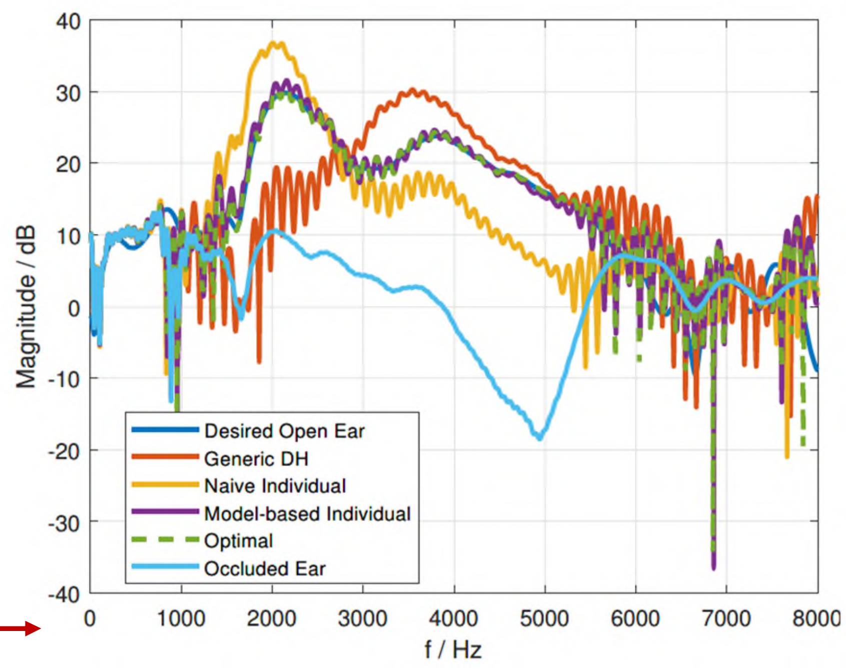
f_s = 16 kHz, τ = 6 ms,
L_A = 99, d_H = 32, λ = 0.1,
I = 4, G_0 = [0, 10, 20] dB

[Schepker et al., *EURASIP JASMP*, 2022]

1. Acoustically transparent sound presentation

- **Single/Multi-Loudspeaker Equalization**
  - **Individualized equalization filters** (based on individualized electro-acoustic model) outperform equalization filters based on dummy-head measurements or based on in-ear microphone signal

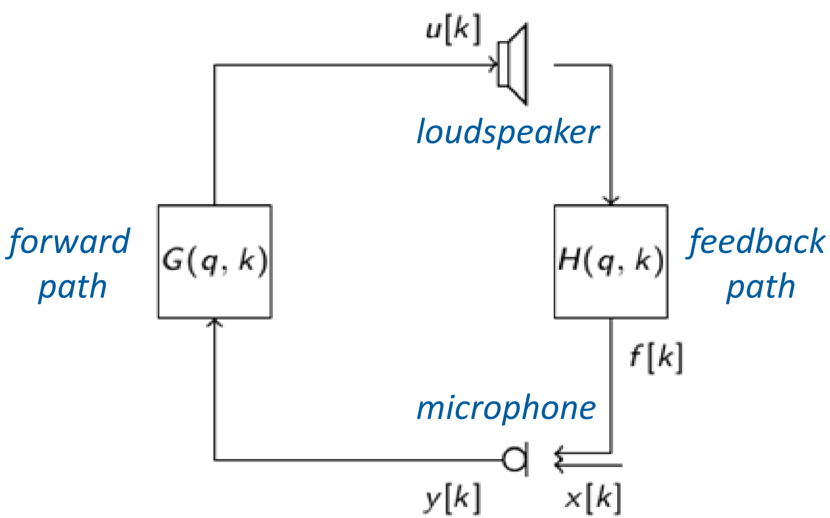


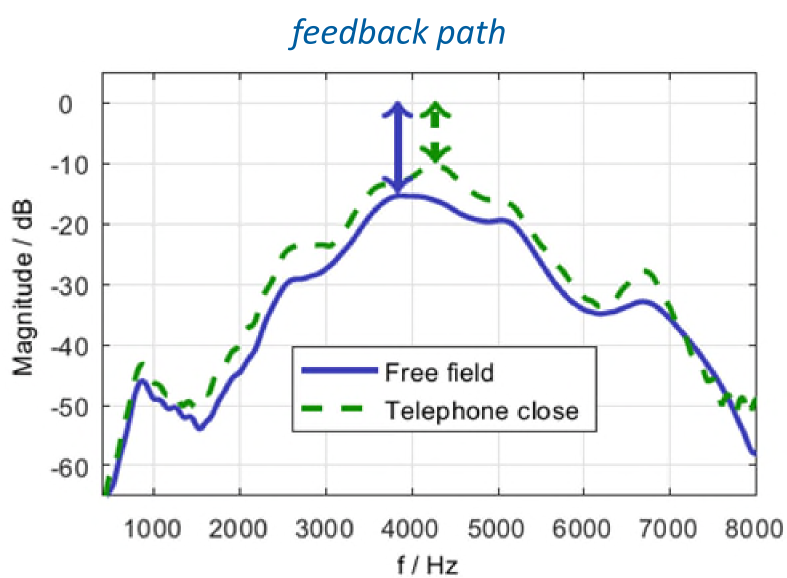


[Schepker et al., *JASA-EL*, submitted]

2. Acoustic feedback cancellation

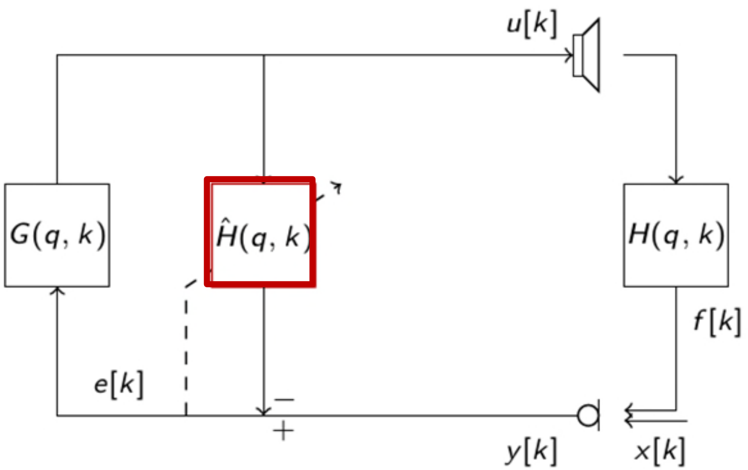
- Feedback arises due to **acoustic coupling** between loudspeaker(s) and microphone(s)

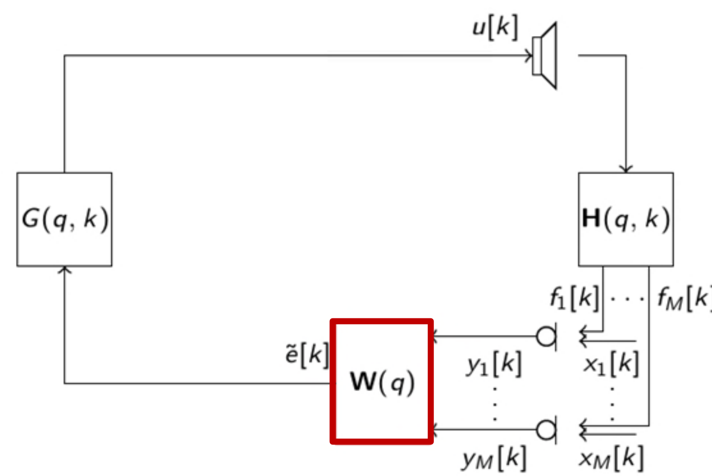




2. Acoustic feedback cancellation

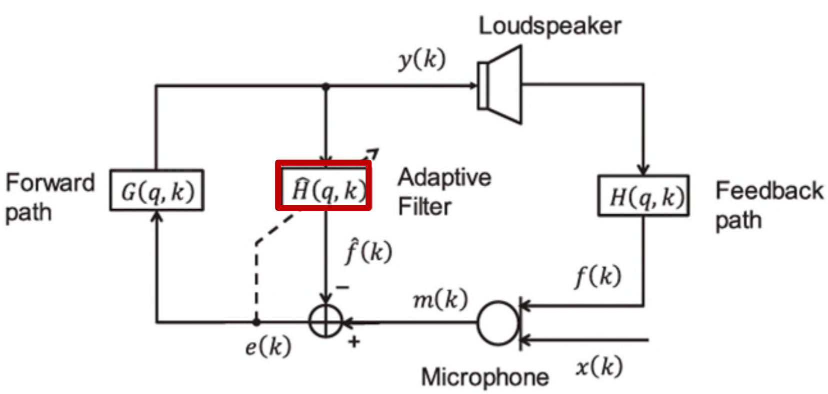
- Feedback arises due to **acoustic coupling** between loudspeaker(s) and microphone(s)
- **Feedback suppression approaches:**
  1. Feedforward suppression → distortion
  2. Adaptive feedback cancellation → decorrelation between loudspeaker and incoming signal
  3. Spatial filtering → requires multiple microphones

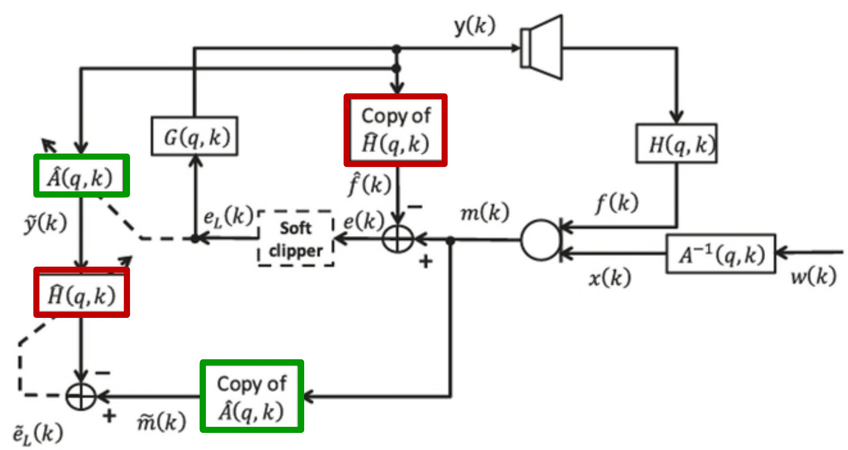




2. Acoustic feedback cancellation

- **Adaptive feedback cancellation**
  1. Normalized least mean squares (NLMS): bias due to correlation, fast re-convergence from howling
  2. Prediction error method (PEM-NLMS): pre-whitening based on auto-regressive model → reduced bias, but slow re-convergence from howling





2. Acoustic feedback cancellation

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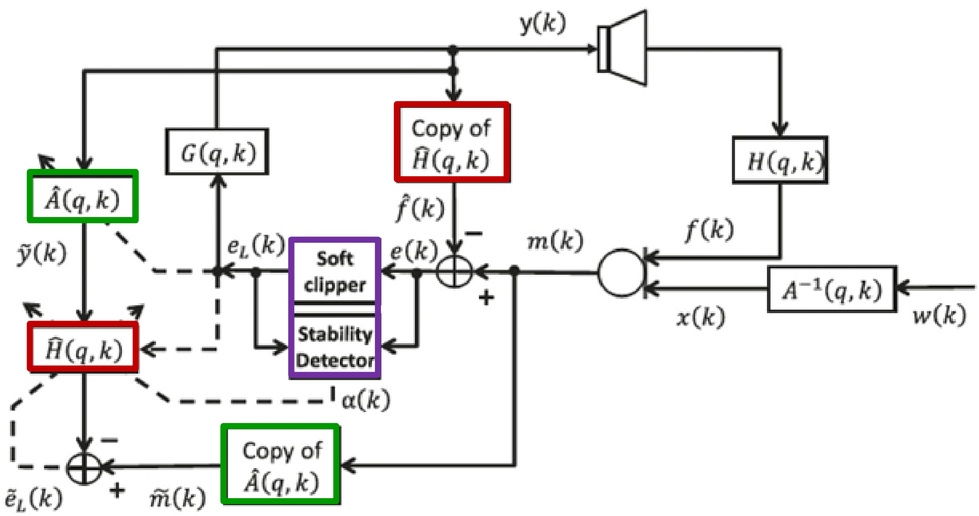
  3. **Hybrid algorithm (H-NLMS):** switched combination of NLMS and PEM-NLMS update, controlled by soft-clipping-based stability detector



$$\hat{\mathbf{h}}(k+1) = \hat{\mathbf{h}}(k) + \underbrace{[1-\alpha(k)]\overbrace{\mu_1(k)\tilde{\mathbf{y}}(k)\tilde{e}_L(k)}^{\textit{PEM-NLMS}}}_{} + \alpha(k)\underbrace{\mu_2(k)\mathbf{y}(k)e_L(k)}_{\textit{NLMS}},$$

Binary control signal:

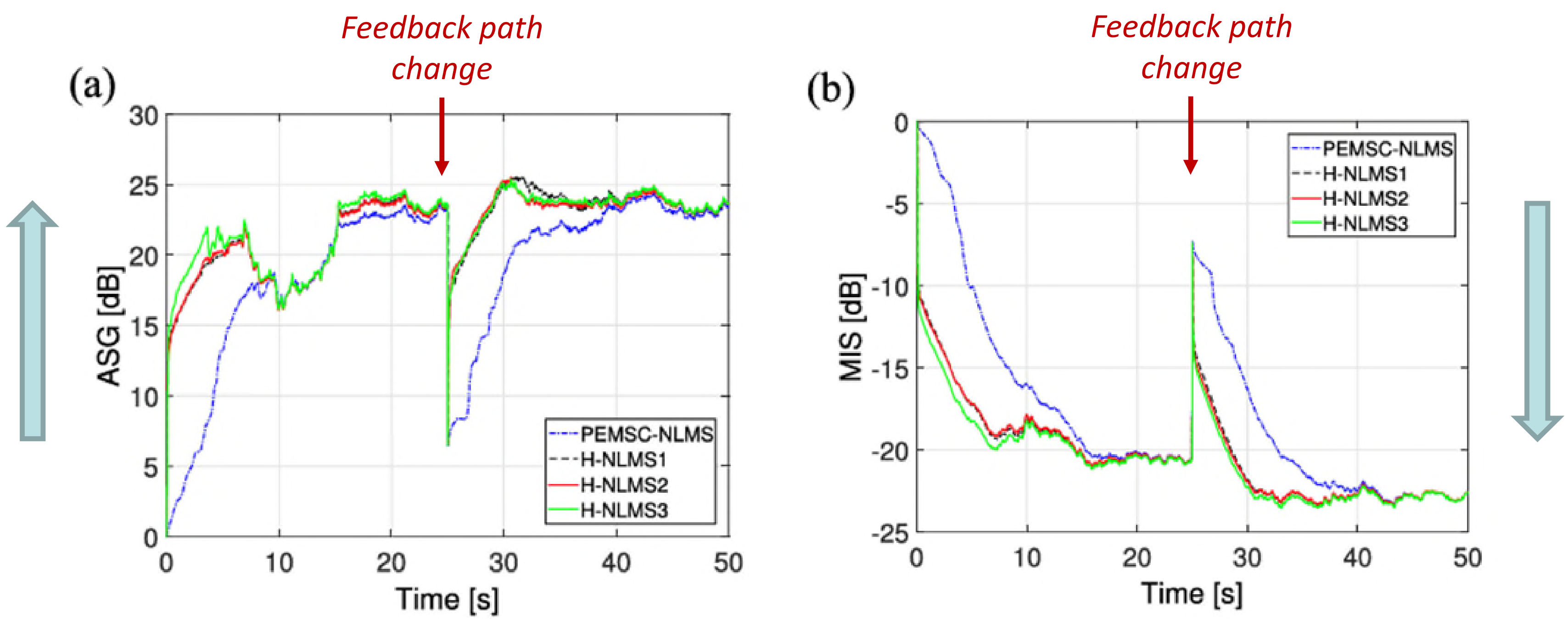
$$\alpha(k) = I\{|e(k) - e_L(k)| < \gamma\}$$

$$e_L(k) = \beta \tanh\left(\frac{e(k)}{\beta}\right)$$

[Nordholm et al., *JASA,* 2018]

2. Acoustic feedback cancellation

- **Simulation results:** added stable gain (ASG), misalignment (MIS)



H-NLMS algorithm converges much faster than PEM-NLMS while maintaining similar misalignment

f_s = 16 kHz, L_h = 64, L_a = 20 (Levinson-Durbin), forward path: τ = 6 ms, G_0 = 45 dB, β = 2, γ = 0.15, μ_1 = 0.001, μ_2 = [0.1, 0.2, 0.5]

[Nordholm et al., *JASA*, 2018]

2. Acoustic feedback cancellation

- **Spatial filtering:** reduce acoustic feedback in the vent microphone by steering a (robust) spatial null towards the hearing aid receiver
- Perfect feedback cancellation:

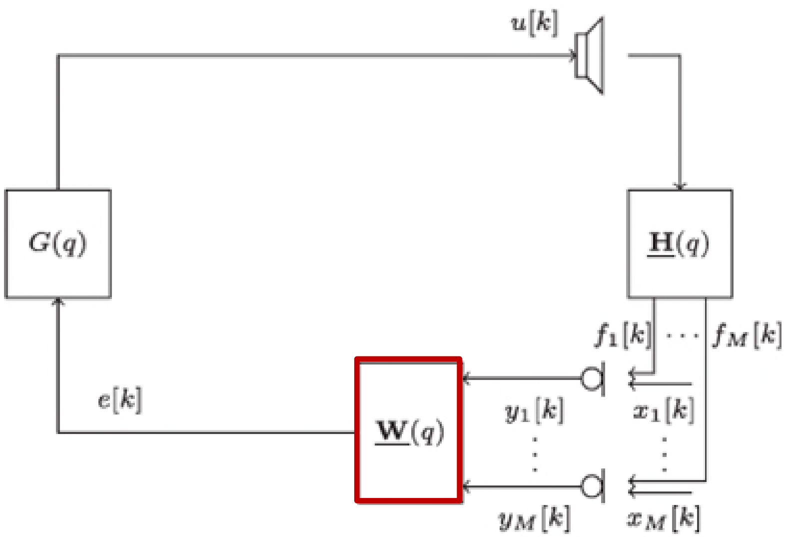
$$\underline{\mathbf{W}}^T(q)\underline{\mathbf{H}}(q) = 0$$

feedback paths

- Incoming signal preservation:

$$\underline{\mathbf{W}}^T(q)\underline{\tilde{\mathbf{D}}}(q) = q^{-L_d}$$

relative transfer functions for incoming source



[Schepker et al., *IEEE/ACM TASLP,* 2020]

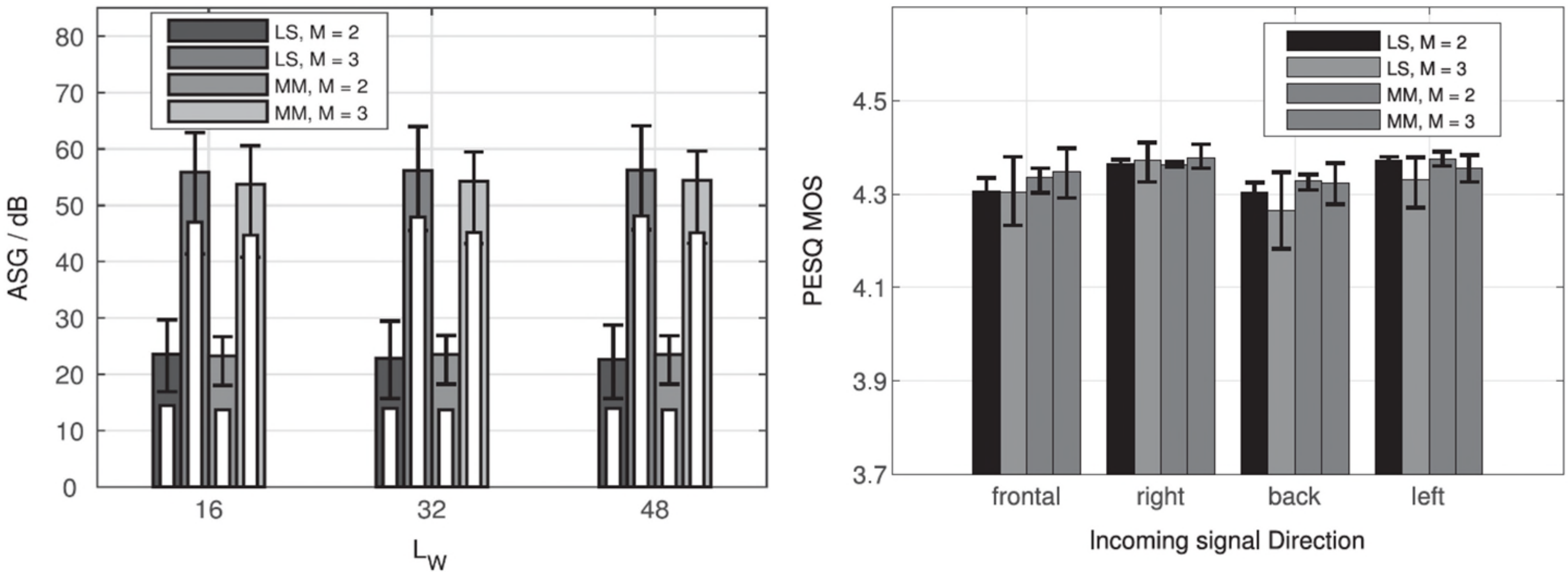
2. Acoustic feedback cancellation

- **Robust design procedures for fixed beamformer** based on (multiple) measurements of acoustic feedback paths

	Minimize residual feedback power	Maximize maximum stable gain
Hard constraint	$\min_{\mathbf{w}} \sum_{i=1}^{I} \|(\mathbf{H}^{(i)})\mathbf{w}\|_2^2$ subject to $\tilde{\mathbf{D}}^{(j)}\mathbf{w} = \tilde{\mathbf{e}}_{L_d} \quad \forall j = 1, \ldots, J$ *Constrained least-squares problem*	$\min_{\mathbf{w}} \max_{\omega_n, i} \|(\underline{\mathbf{H}}^{(i)})^H(\omega_n)\underline{\mathbf{W}}(\omega_n)\|^2$ subject to $\tilde{\mathbf{D}}^{(j)}\mathbf{w} = \tilde{\mathbf{e}}_{L_d} \quad j = 1, \ldots, J$ *Linear programming problem*
Soft constraint	$\min_{\mathbf{w}} \|\bar{\mathbf{H}}\mathbf{w}\|_2^2 + \lambda\|\bar{\mathbf{D}}\mathbf{w} - \bar{\mathbf{e}}_{L_d}\|_2^2$ *Unconstrained least-squares problem*	$\min_{\mathbf{w}} \max_{\omega_n, i} \|(\underline{\mathbf{H}}^{(i)})^H(\omega_n)\underline{\mathbf{W}}(\omega_n)\|^2 + \lambda\|\bar{\mathbf{D}}\mathbf{w} - \bar{\mathbf{e}}_{L_d}\|_2^2$ *Quadratically constrained quadratic programming (QCQP) problem*

[Schepker et al., *IEEE/ACM TASLP*, 2020]

2. Acoustic feedback cancellation



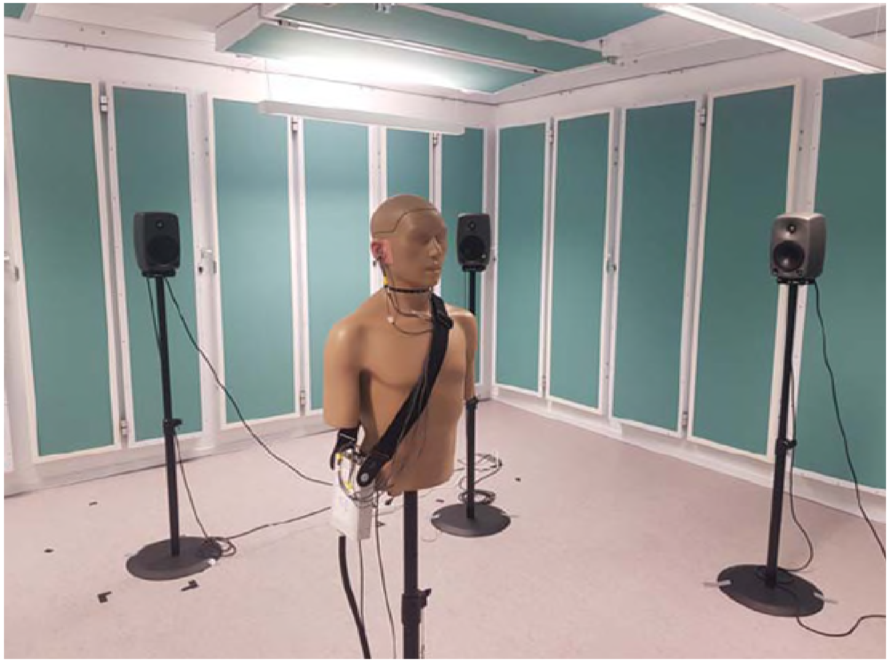
Robust reduction of acoustic feedback of up to 50dB while hardly distorting incoming signal

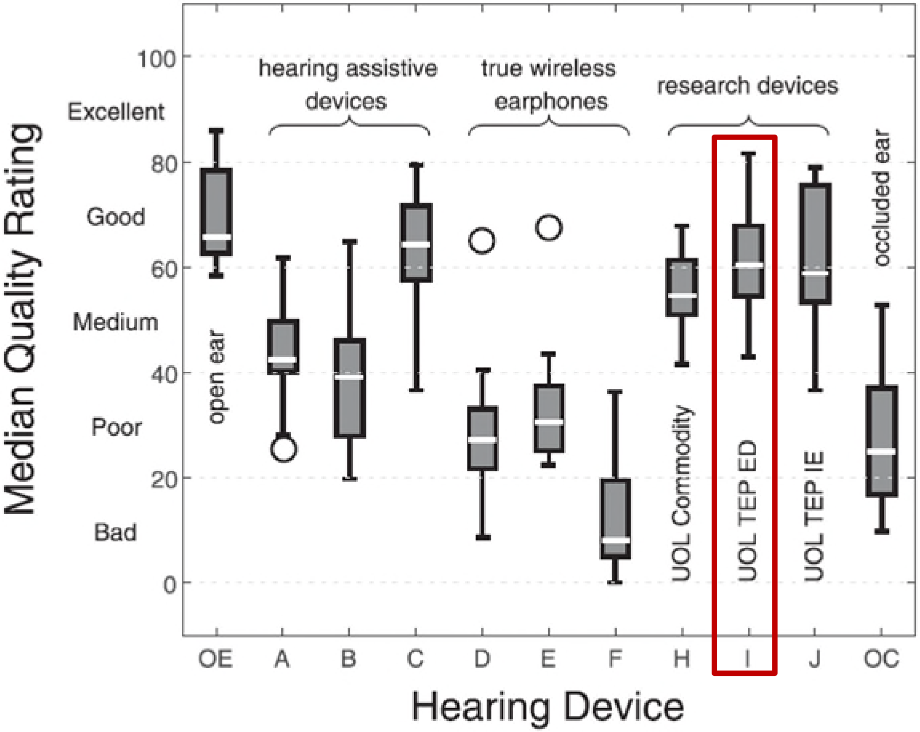
f_s = 16 kHz, T_{60} = 300 ms,
I = 20, 4 source directions,
forward path: τ = 6 ms,
G_0 = 45 dB, ε_{MSG} = 10 dB

[Schepker et al., *IEEE/ACM TASLP*, 2020]

Acoustically transparent sound presentation

- **Acoustic transparency feature compared to six commercial hearables**

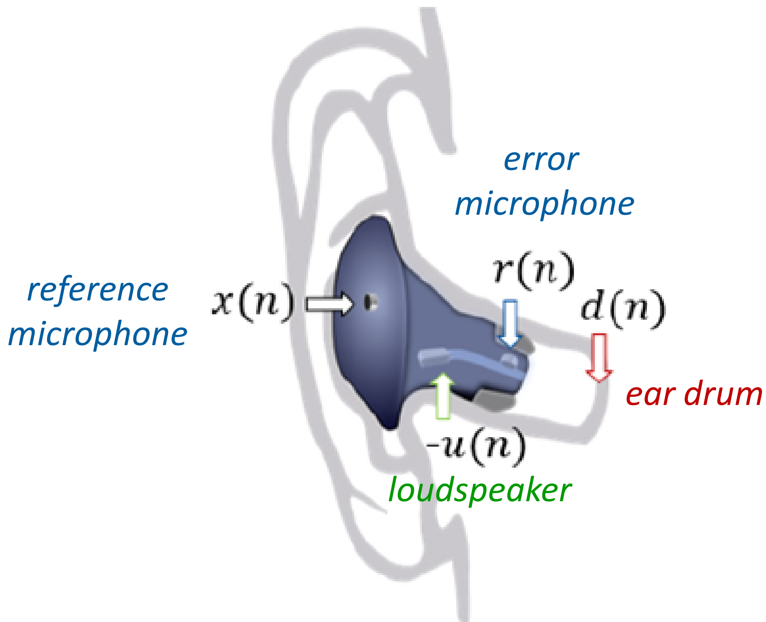




[Schepker et al., *JAES,* 2020]

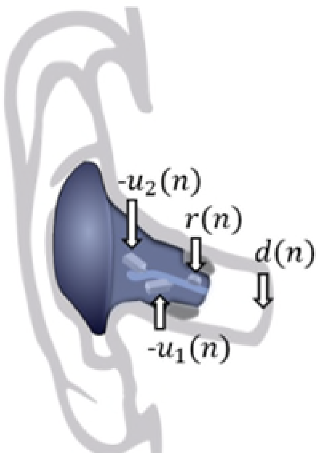
3. Active noise control

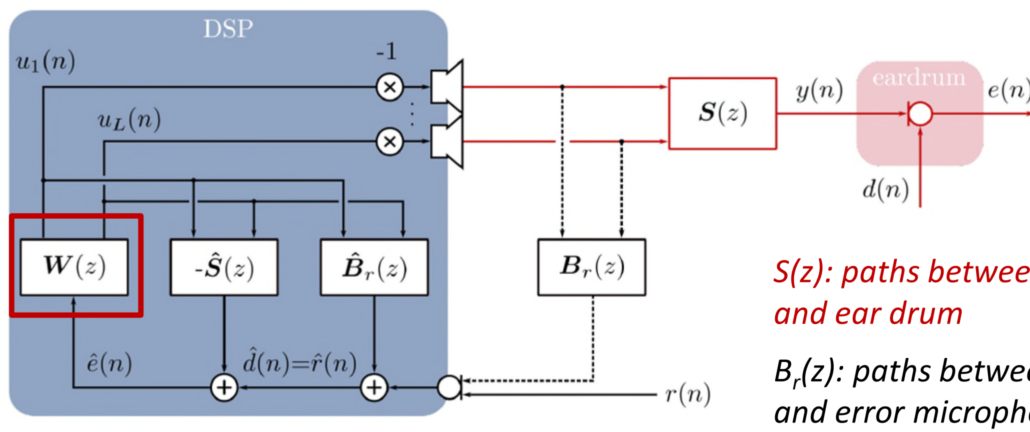
- **Aim:** play back anti-noise by one or more loudspeakers aiming at generating “zone of quiet” at certain position (e.g. ear drum)
- **Approaches:**
  - **Feedforward ANC:** filter reference microphone signal
  - **Feedback ANC:** filter error microphone signal



3. Active noise control

- Virtual sensing fixed feedback ANC exploiting **multiple loudspeakers**, aiming at minimizing sound pressure at **ear drum**





S(z): paths between loudspeakers and ear drum

$B_r(z)$: paths between loudspeakers and error microphone

- Minimize power spectral density of sound pressure at ear drum

$$\Phi_{ee}(f) = \left(1 - \frac{|\Phi_{dr}(f)|^2}{\Phi_{dd}(f)\Phi_{rr}(f)}\right)\Phi_{dd}(f) + \left|\frac{\Phi_{dr}(f)}{\Phi_{rr}(f)} - \frac{\boldsymbol{W}^{\mathrm{T}}(f)\boldsymbol{S}(f)}{1 + \boldsymbol{W}^{\mathrm{T}}(f)\left(\hat{\boldsymbol{S}}(f) + \boldsymbol{B}_r(f) - \hat{\boldsymbol{B}}_r(f)\right)}\right|^2 \Phi_{rr}(f)$$

Virtual microphone arrangement → $d(n) = r(n)$

$$\Phi_{ee}^{\mathrm{vma}}(f) = \left|\frac{1}{1 + \boldsymbol{W}^{\mathrm{T}}(f)\hat{\boldsymbol{S}}(f)}\right|^2 \Phi_{rr}(f)$$

[Rivera Benois et al., *ICASSP*, 2022]

3. Active noise control

- Turn non-convex optimization problem into **convex optimization problem**

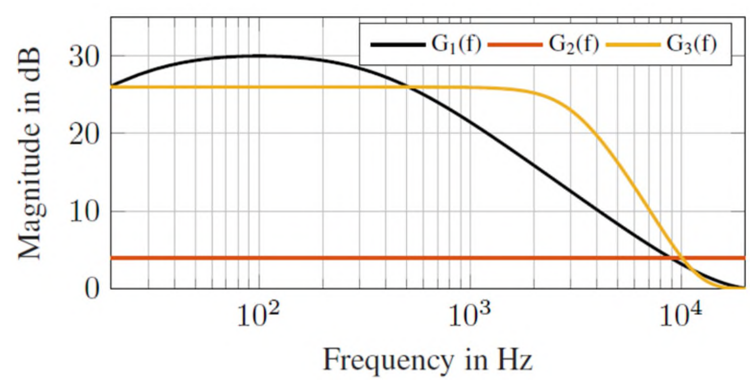
$$\min_{\boldsymbol{w}} \left| \frac{1}{1+\boldsymbol{W}^{\mathrm{T}}(f)\widehat{\boldsymbol{S}}(f)} \right|^2 \phi_{rr}(f) \quad \Longrightarrow \quad \max_{\mathbf{w}} \sum_{k=0}^{L_{\mathrm{DFT}}/2-1} \left|1+\boldsymbol{W}^{\mathrm{T}}(\Omega_k)\hat{\boldsymbol{S}}(\Omega_k)\right|^2 G_1^2(\Omega_k)$$

subject to constraints (stability, amplification, gain)

$$|\varrho - \boldsymbol{W}^{\mathrm{T}}(\Omega_k)\hat{\boldsymbol{S}}(\Omega_k)| \leq |\varrho + \boldsymbol{W}^{\mathrm{T}}(\Omega_k)\hat{\boldsymbol{S}}(\Omega_k)| + 2\rho, \forall \Omega_k$$

$$1 \leq G_2(\Omega_k)|1 + \boldsymbol{W}^{\mathrm{T}}(\Omega_k)\hat{\boldsymbol{S}}(\Omega_k)|, \forall \Omega_k$$

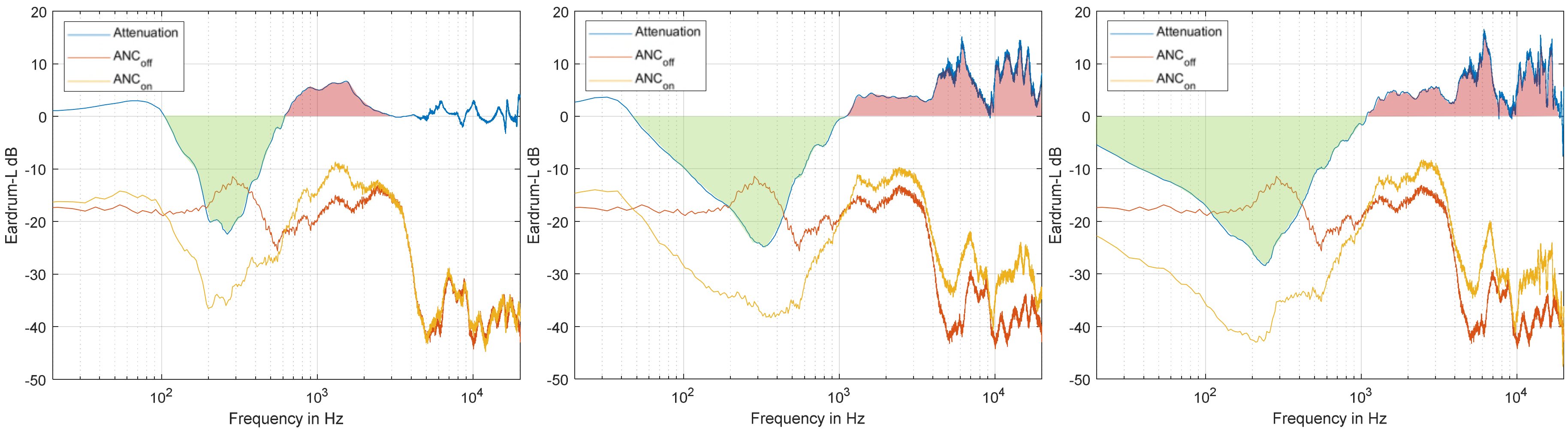
$$W_l(\Omega_k) \leq G_3(\Omega_k), \forall \Omega_k$$



[Rivera Benois et al., *ICASSP*, 2022]

3. Active noise control

	Classic	Virtual Microphone	Virtual Microphone
Loudspeakers	Single	Single	Multi
Available acoustic paths	$\hat{B}_r(z)$	$\hat{B}_r(z)$ $\hat{S}(z)$	$\hat{\boldsymbol{B}}_r(z)$ $\hat{\boldsymbol{S}}(z)$

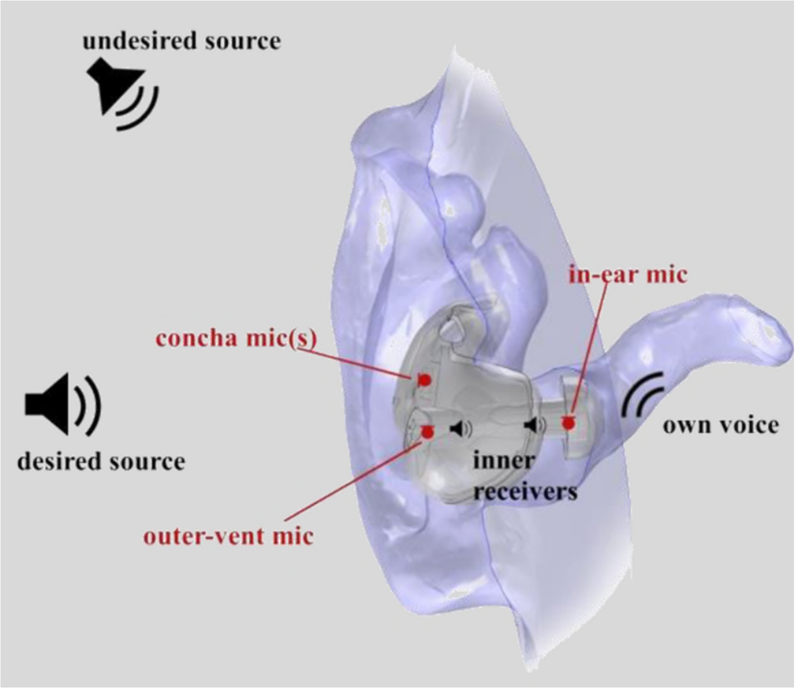


Multi-loudspeaker virtual sensing ANC approach improves attenuation magnitude and bandwidth

[Rivera Benois et al., *ICASSP*, 2022]

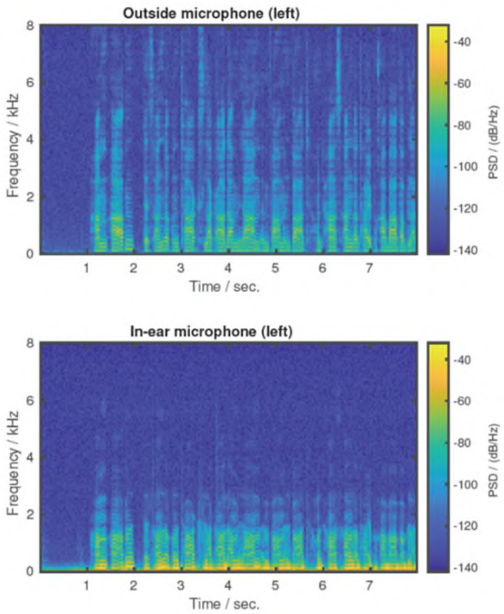
4. Own voice extraction

- **Aim:** enhance own voice of user wearing earpiece in noisy acoustic environment (e.g. industrial workplace)
- **Approach:** exploit in-ear microphone, possibly in combination with outer microphone(s)

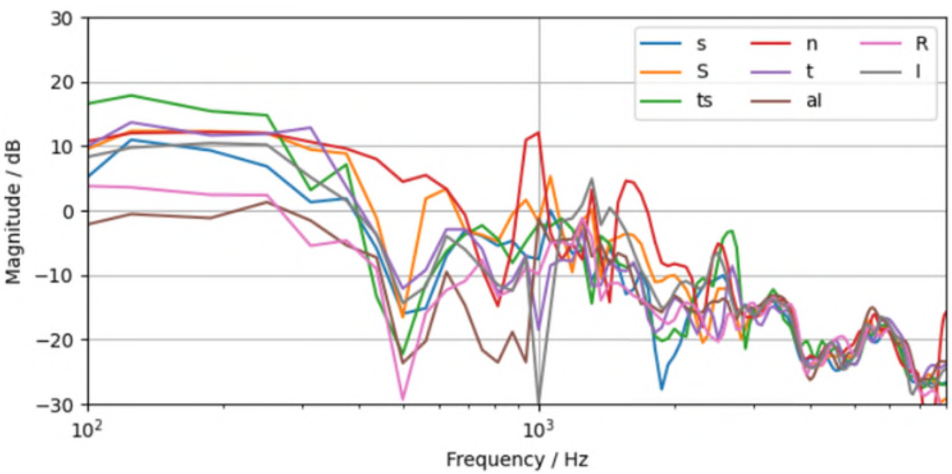


4. Own voice extraction

- **Different characteristics** for own voice and external noise at in-ear and outer microphones
  - **Outer microphone:** full bandwidth own voice, possibly low SNR (external noise)
  - **In-ear microphone:** bandlimited own voice (up to about 2 kHz), high SNR (external noise), body noise

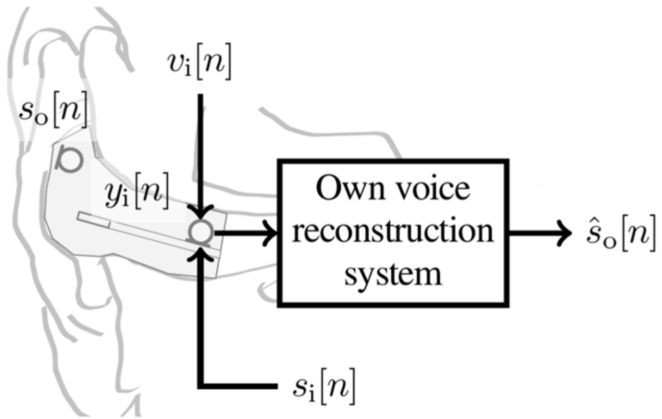


- **Relative transfer characteristics for own voice**
  - Time-varying (speech-dependent)
  - User- and device-dependent

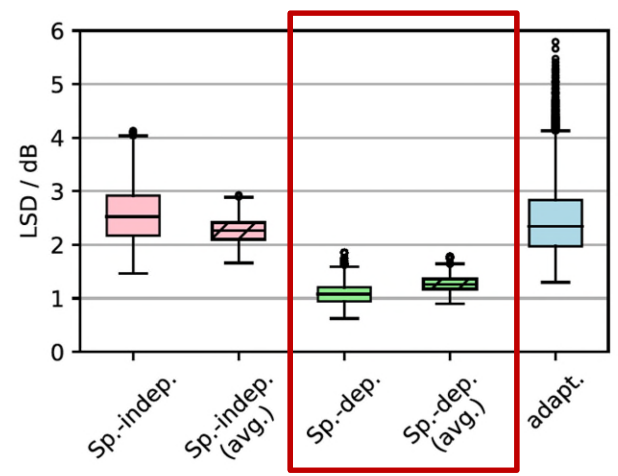


4. Own voice extraction

- **Objectives of algorithm:** estimate clean speech signal at outer microphone from
  - **in-ear microphone:** combined bandwidth extension, equalization and noise reduction (body + external noise)
  - **in-ear and outer microphone**



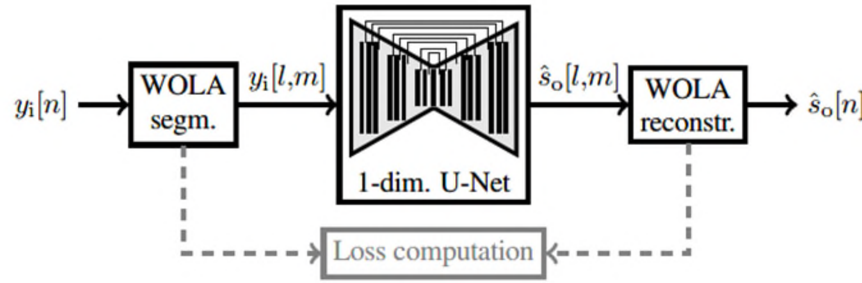
- **Limited training data available**:
  - use **models** to generate simulated data (data augmentation):
    - Fixed relative transfer function (sp.-indep.)
    - Phoneme-dependent relative transfer function (sp.dep.)
  - **domain transfer** (train with simulated data, fine-tune with real recordings)

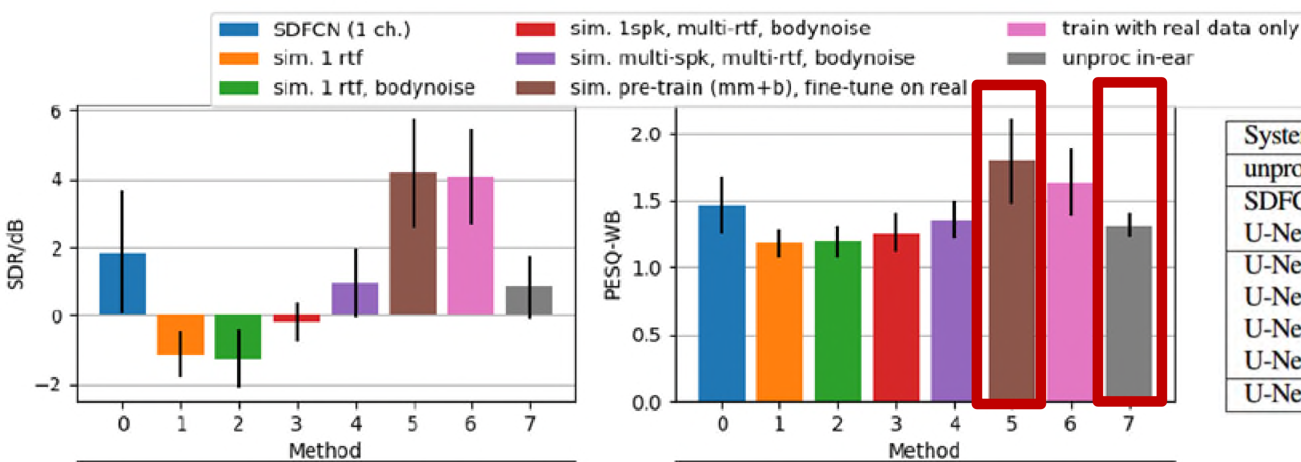


[Ohlenbusch et al., *Forum Acusticum,* 2023]

4. Own voice extraction

- **Results:**
  - Based on bandwidth extension system using U-Net architecture [Wang 2021]
  - Only exploiting in-ear microphone signal, only body noise (no external noise)
  - **Different training procedures** (real data, simulated data with one/multiple RTFs and one/multiple talkers, simulated data + fine-tuning with real data)



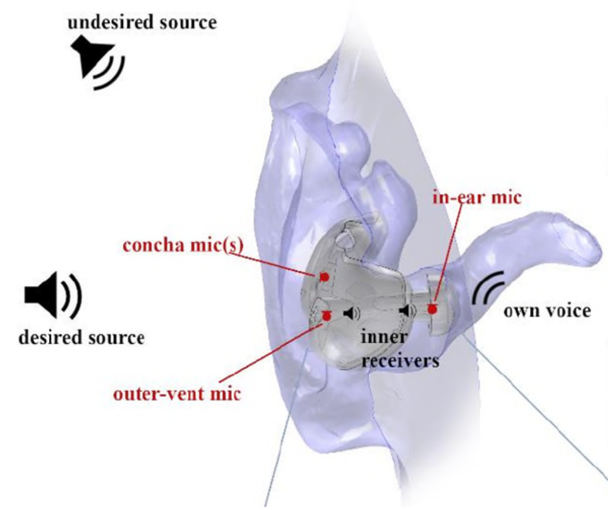


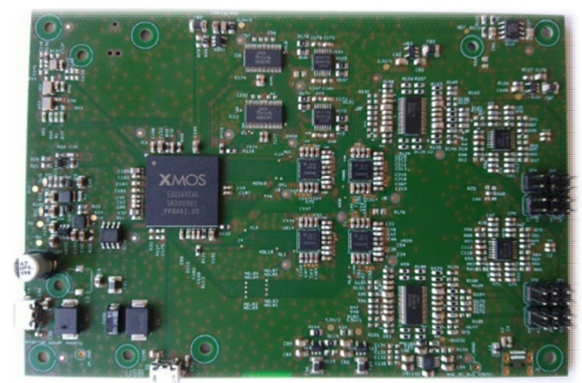
System	Data	RTFs used	LSD / dB	PESQ
unproc.	-	-	2.51	1.31
SDFCN	[R]	-	1.53	1.47
U-Net	[R]	-	1.48	1.64
U-Net	[S]	1T, s-RTF	1.35	1.18
U-Net	[S+]	1T, s-RTF	1.54	1.19
U-Net	[S+]	1T, m-RTF	1.51	1.26
U-Net	[S+]	14T, m-RTF	1.24	1.36
U-Net	[S+R]	14T, m-RTF	**1.05**	**1.80**

[Ohlenbusch et al., *IWAENC,* 2022]

Current / Future work

- **Direction-selective** acoustic transparency and active noise control, steered by CASA
- **Deep learning-based active noise control**
- **Speech communication exploiting in-ear microphone** (phoneme-dependent own voice models, DNN-based algorithms)
- Individualized and phoneme-dependent occlusion models and **active occlusion reduction**
- Implementation on **low-latency processor** (cooperation with Fraunhofer HSA)
- **Integration** with speech enhancement algorithms and self-adjusted hearing support





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DFG Deutsche Forschungsgemeinschaft

HAPPAA

Hearing 4all

DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service

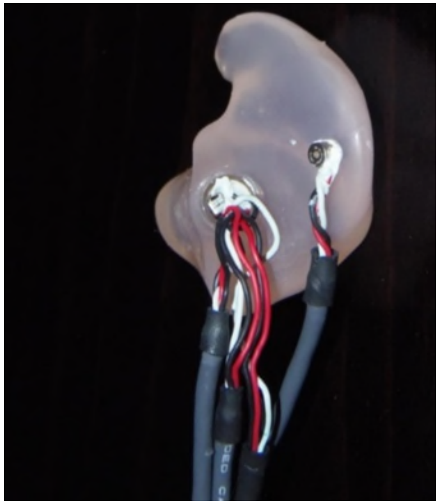
Questions ?

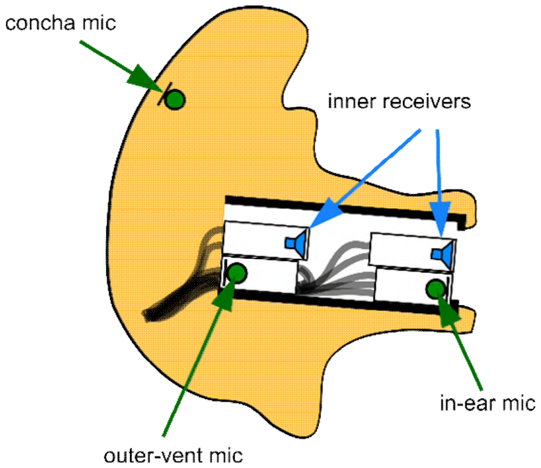
http://www.sigproc.uni-oldenburg.de

YouTube Signal Processing Uni Oldenburg

Acoustically Transparent Earpiece (v1)

- **Custom in-the-ear earpiece** with multiple integrated microphones and receivers and relatively open acoustics
  - Vent/core: **2 microphones and 2 receivers** (woofer/tweeter)
  - Concha: **1 microphone**
- Insertion into individual silicone ear mould or generic earplugs

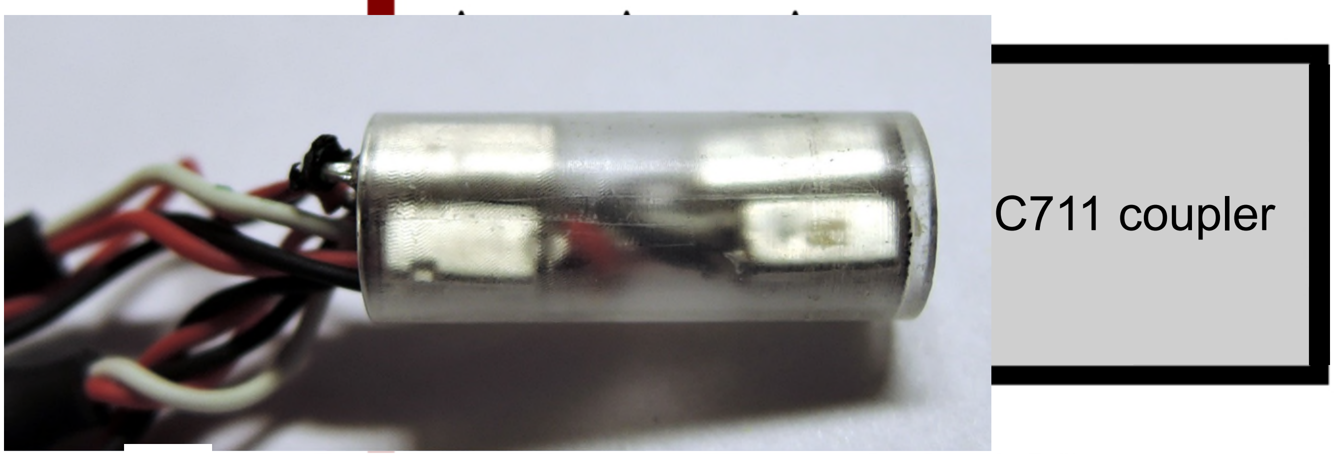


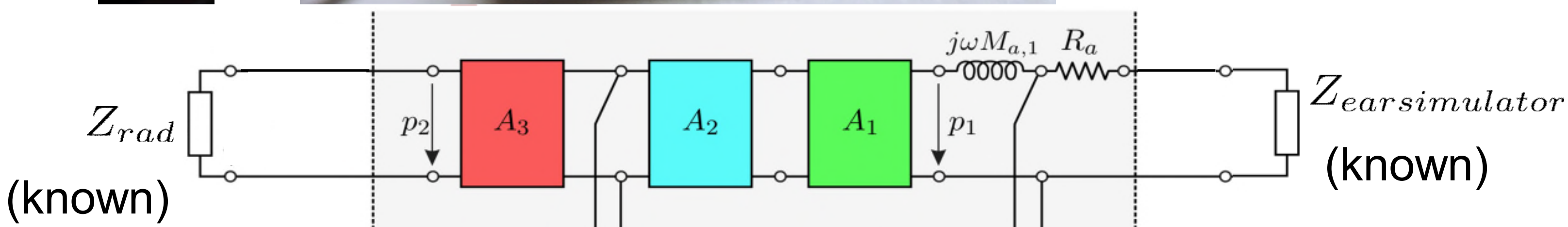


[Denk et al., *International Journal of Audiology*, 2018]

Electro-acoustic model

- Earpiece Model (Fixed)



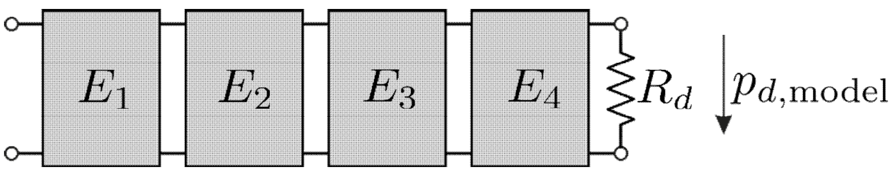


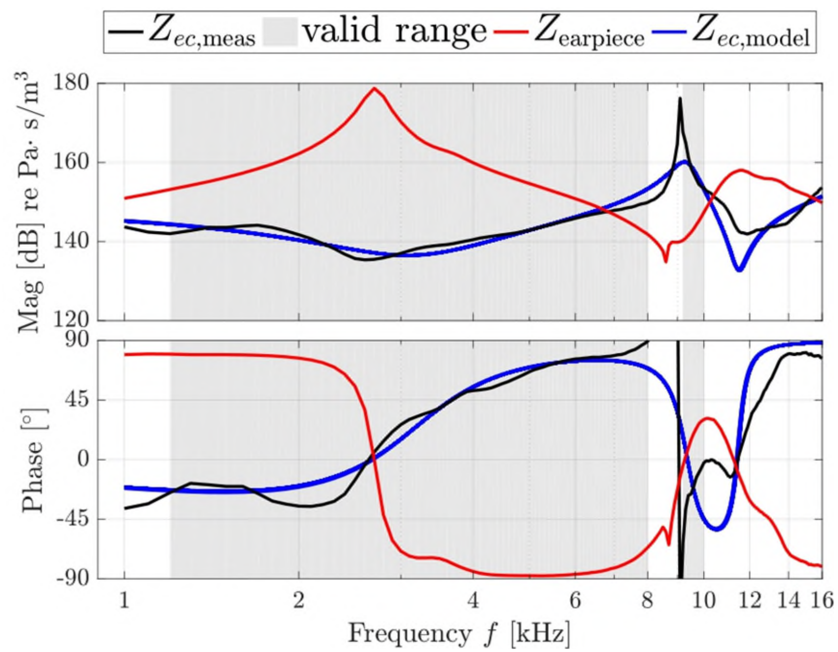
[Vogl and Blau 2019, JASA]

Parameter optimization: minimize difference between all 4 measured and modeled transfer functions

Electro-acoustic model

- Ear Canal Model (Individualized)





Parameter optimization (4 radii, 1 length, 1 resistive load) by minimizing the difference between measured and modeled ear canal (Nelder-Mead simplex optimization procedure):

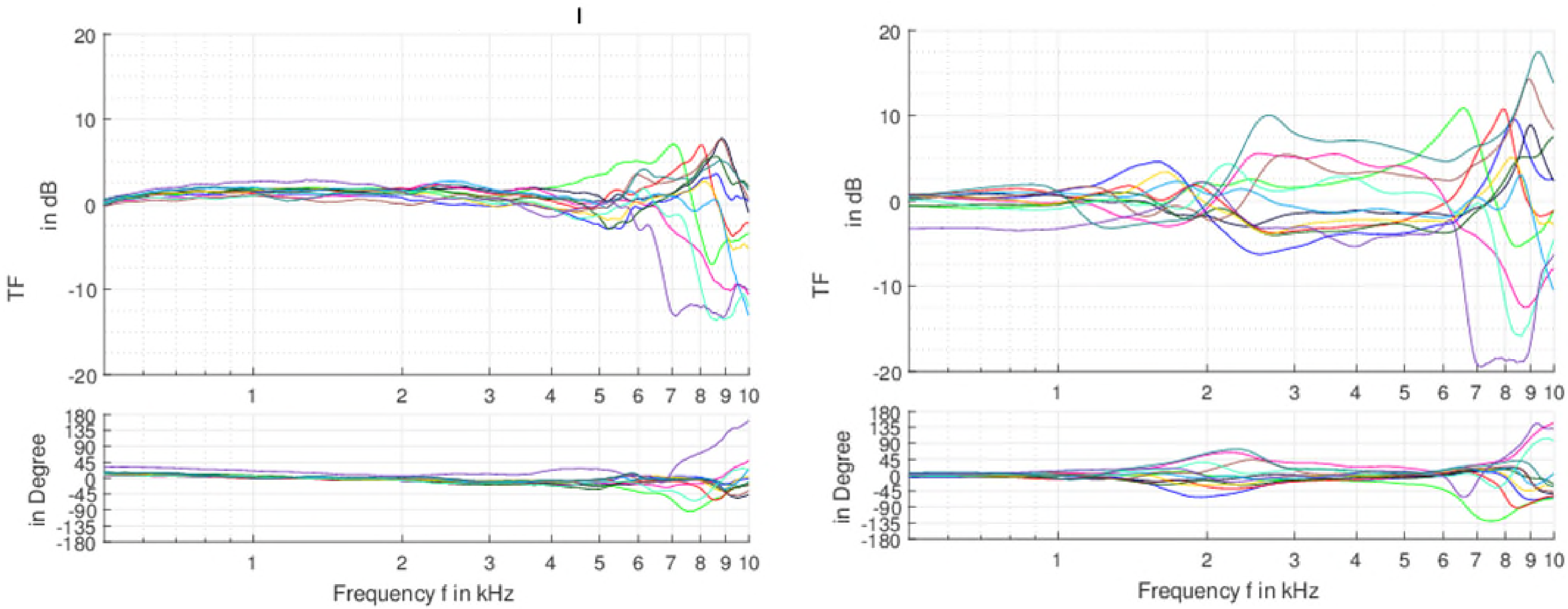
$$J(p) = \sum_{f_{\text{valid}}} \left(db(Z_{ec,\text{meas}}) - db(Z_{ec,\text{model}}(p))\right)^2 + 10 \cdot \left(arg(Z_{ec,\text{meas}}) - arg(Z_{ec,\text{model}}(p))\right)^2$$

Electro-acoustic model

- Evaluation (sound pressure at ear drum) for 12 subjects

$$\frac{p_{d,\text{Model (i.e. individualized)}}}{p_{d,\text{Probe Tube Meas}}}$$

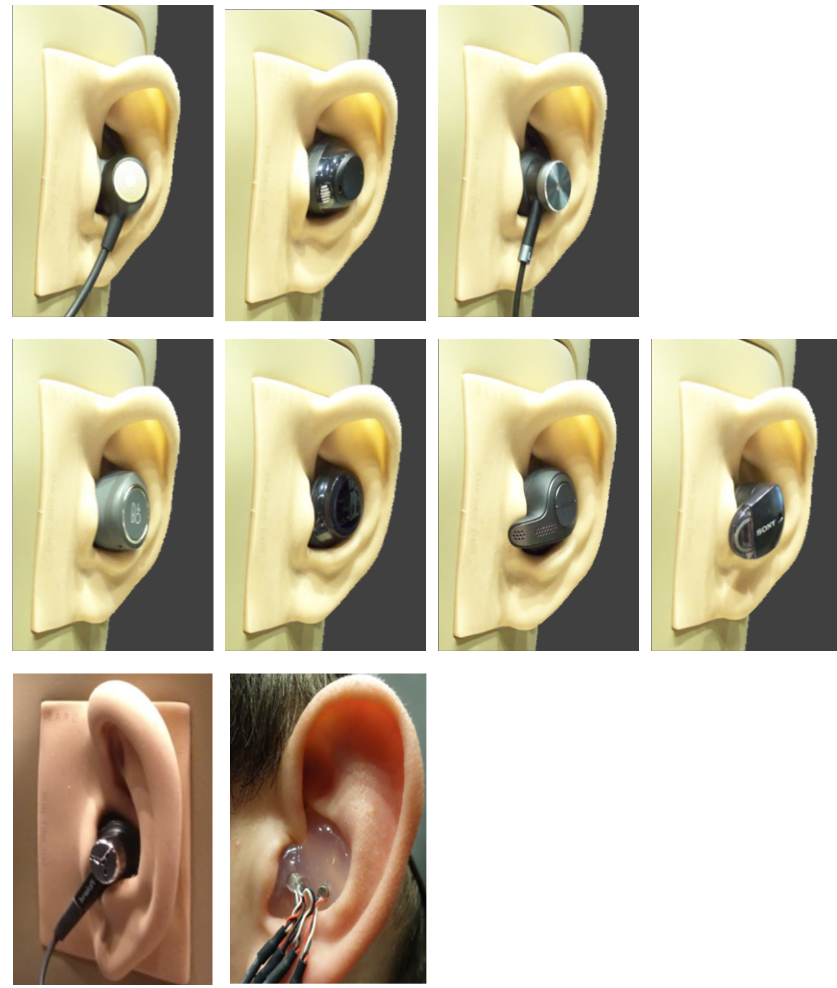
$$\frac{p_{d,\text{from average correction of p1 (i.e. non-individualized)}}}{p_{d,\text{Probe Tube Meas}}}$$



accurate prediction of sound pressure at ear drum possible using individualized electro-acoustic model up to about 6 kHz

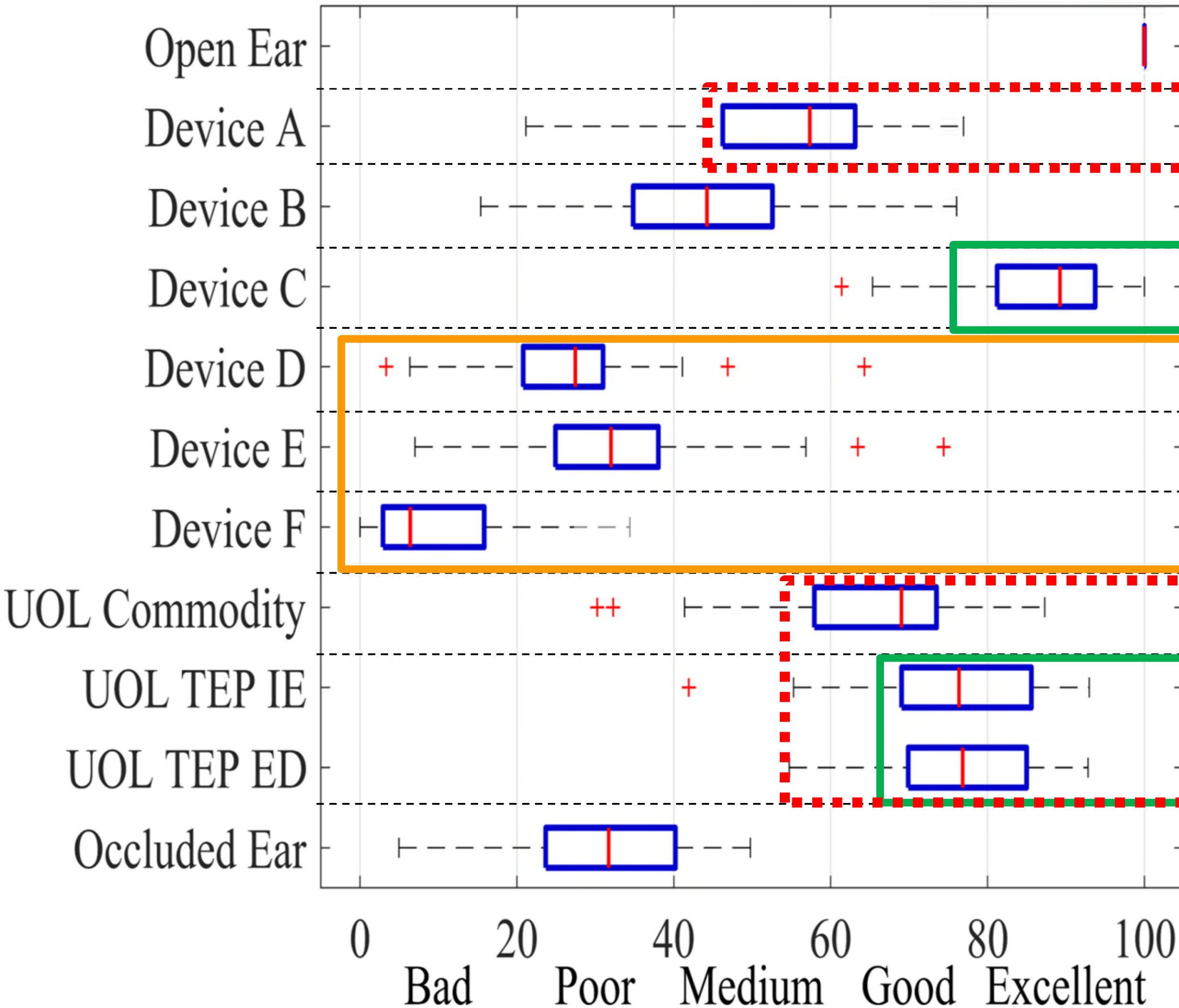
Evaluation of hear-through feature

- **7 commercial hearables**
  - 3 hearing support: **Devices A-C**
  - 4 wireless earbuds: **Devices D-G**
- **2 research prototypes**
  - UOL Commodity: consumer hardware based hearing aid prototype [Schädler 2017, Buhl, Denk et al. 2019]
  - UOL Acoustically Transparent Earpiece: Adaptation to individual ear acoustics [Denk et al. 2018, Schepker, Denk et al. 2019]



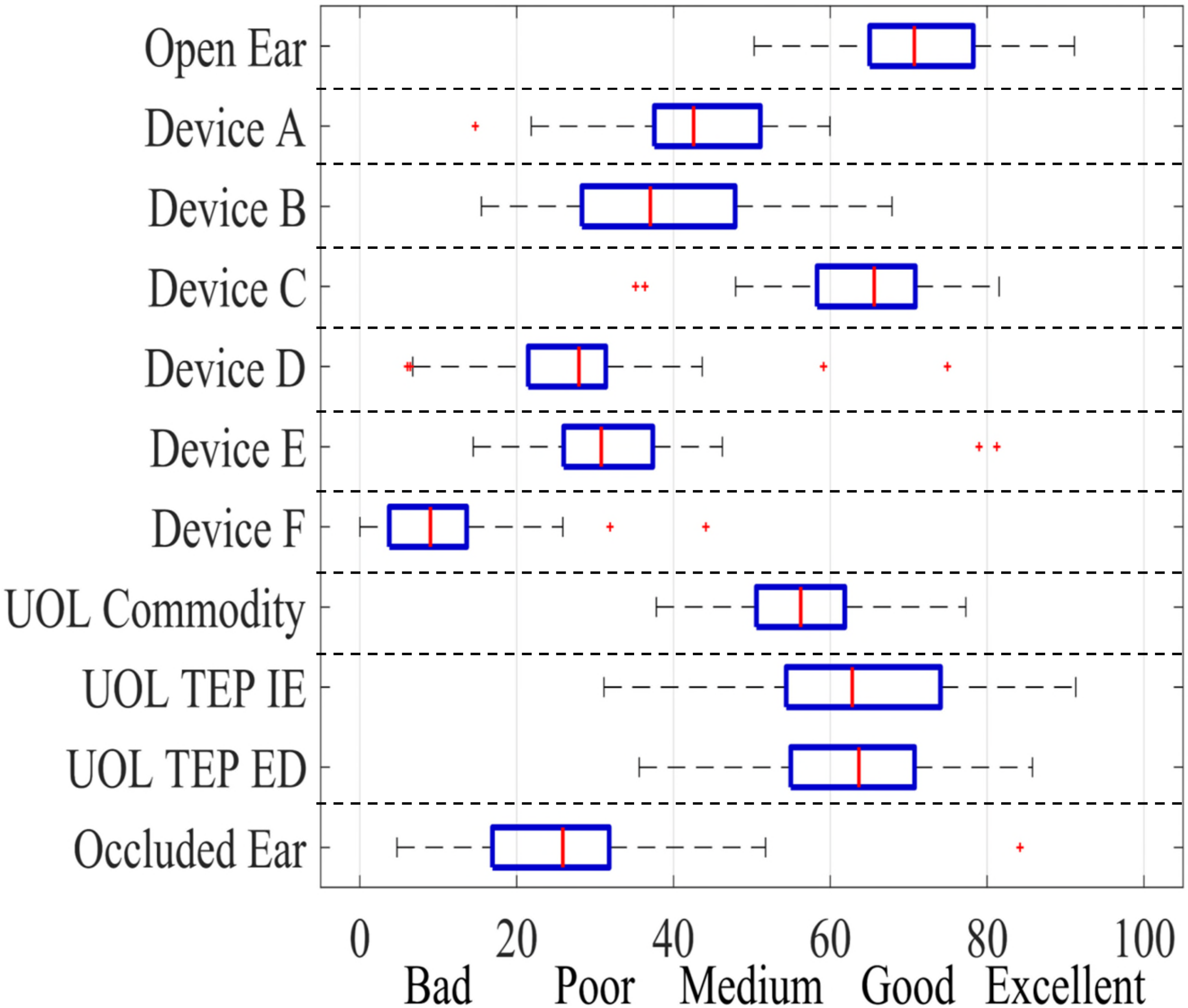
[Denk et al., J. Audio Eng. Soc., 2020] [Schepker et al., J. Audio Eng. Soc., 2020]

Results: Open-ear reference given



	Response Match	Comb Filters
Open Ear		
Device A	+	-
Device B	-	+
Device C	++	++
Device D	--	++
Device E	-	++
Device F	--	-
UOL Commodity	+	-
UOL TEP IE / UOL TEP ED	++	-
Occluded Ear	--	++

Results: *No* reference given



	Response Match	Comb Filters
Device A	+	-
Device B	-	+
Device C	++	++
Device D	--	++
Device E	-	++
Device F	--	-
UOL Commodity	+	-
UOL TEP IE / UOL TEP ED	++	-
Occluded Ear	--	++

[Schepker et al., J. Audio Eng. Soc., 2020]