FOR 1732
Research Unit Individualized Hearing Acoustics

Acoustically Transparent Hearing Device:

Towards Integration of Individualized Sound Equalization, Electro-Acoustic Modeling and Feedback Cancellation

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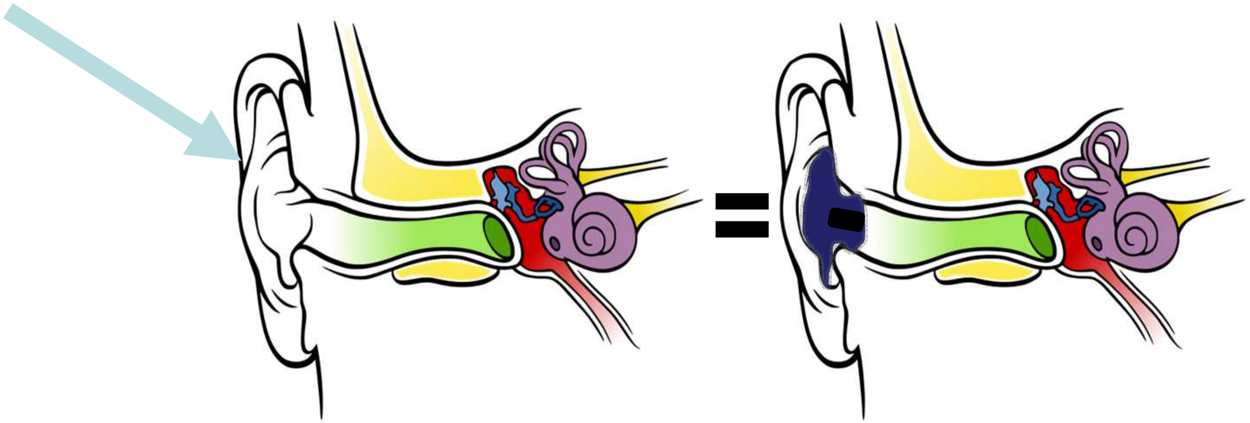
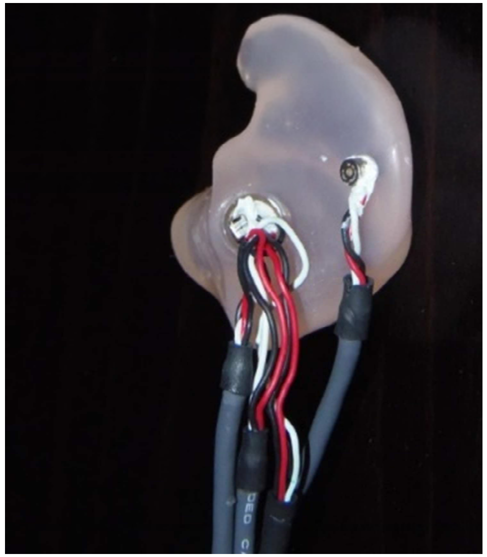
Motivation: *HiFi* Hearing Device

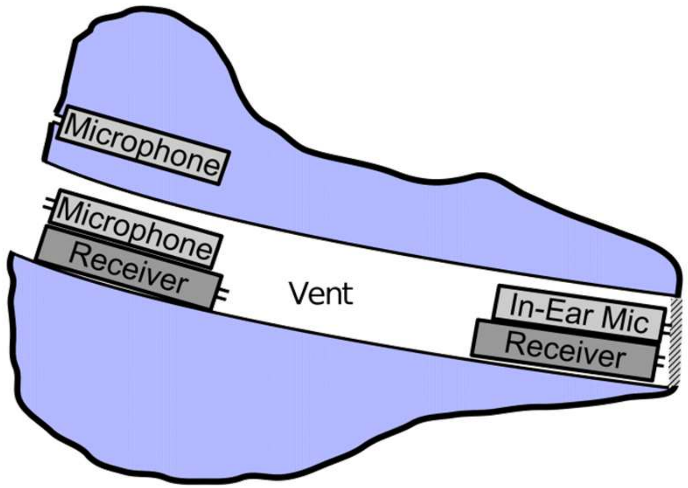
- Current hearing devices: sound quality still limited (e.g., distortion, non-individualized, own voice, spatial impression)
- Aim: construct a *scalable hearing device*
  - **Acoustically Transparent**: no degradation of perceived sound environment in „ground state"
  - Possibility to provide hearing support (e.g., amplification, DRC, noise reduction) when required



Hardware

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





[Denk et al., International Journal of Audiology, 2017]

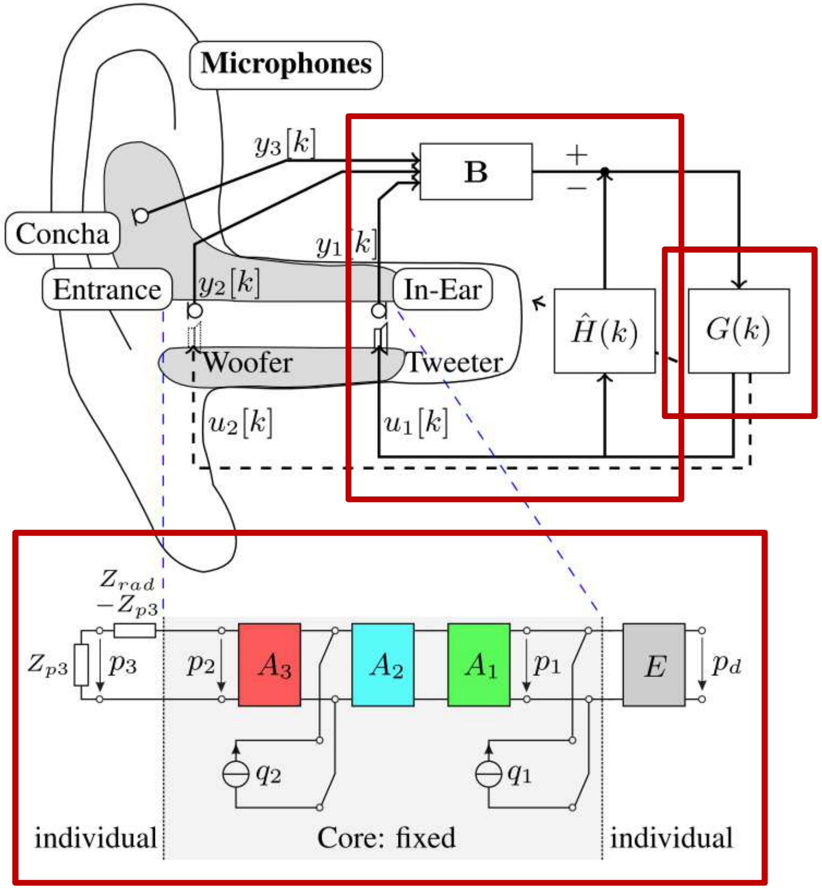
Transparent Hearing System

1. Transparent sound presentation:

- Natural sound quality by equalizing to open-ear target response at eardrum

2. Individualized Electro-Acoustic Model:

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



3. Acoustic Feedback cancellation

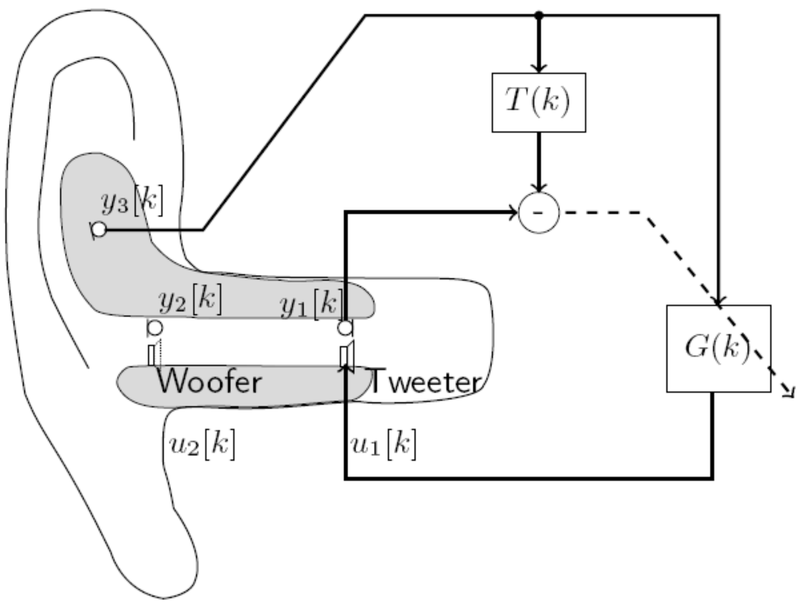
- Exploit multiple microphones to steer null towards position of receiver

4. Hearing support:

- Amplification and dynamic range compression
- Noise reduction (active/passive)
- Occlusion management

1. Transparent sound presentation

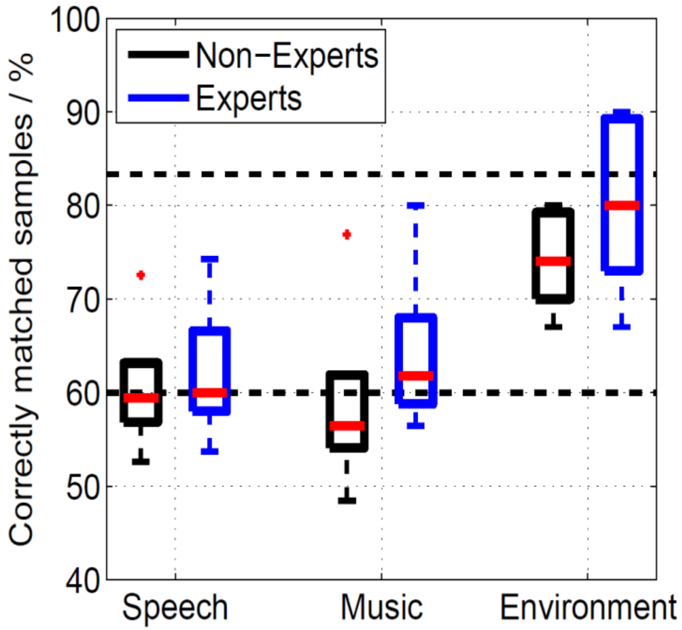
- **Target pressure at eardrum** = pressure that is (physically or perceptually) equal to pressure with open ear, i.e. individual head-related transfer function (HRTF)
  1. **Estimate target pressure** based on outer microphone(s), e.g., frequency-dependent gain *T*
  2. **Equalization with hearing device:** adjust filter *G(k)* such that direct sound + device output = target
- **In-Situ calibration routine,** assuming that pressure at in-ear microphone and eardrum are similar

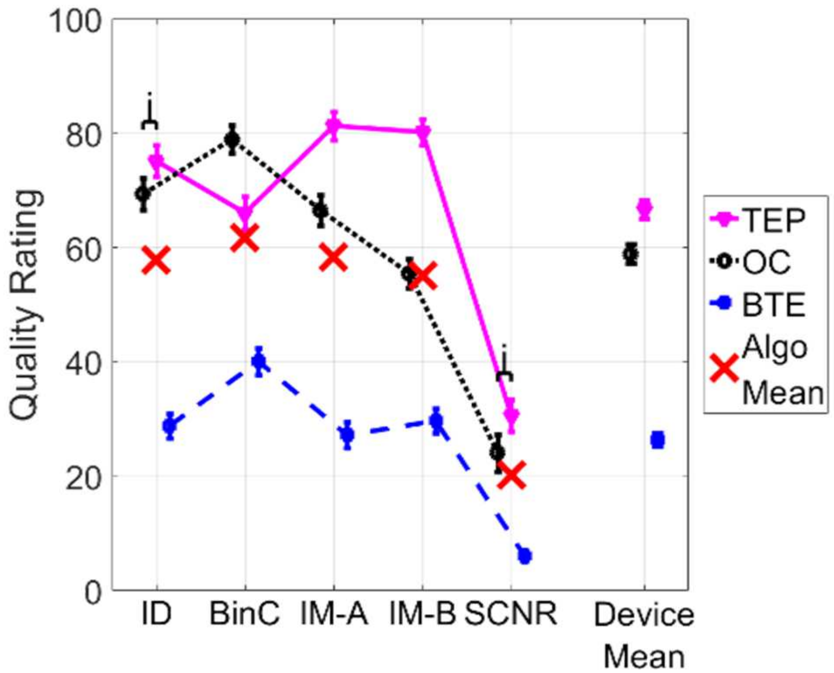


[Denk et al., International Journal of Audiology, 2017]

1. Transparent sound presentation

- **Perceptual sound quality evaluation (NH subjects):**
  - Transparency mode almost indistinguishable from (simulated) open ear canal condition, also in combination with HA processing
  - Significantly outperforms behind-the-ear (BTE)

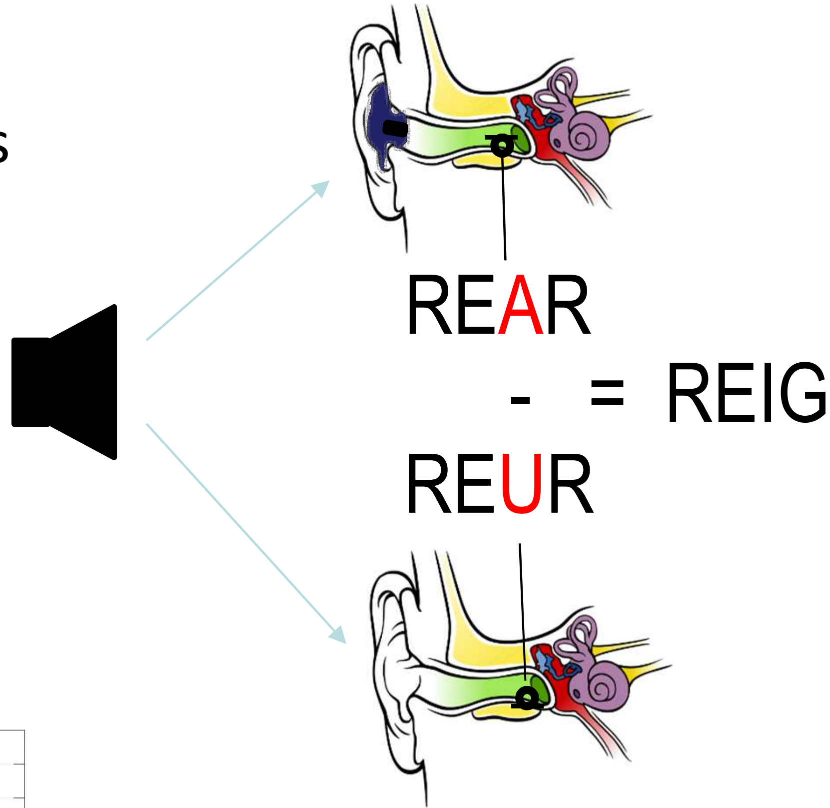


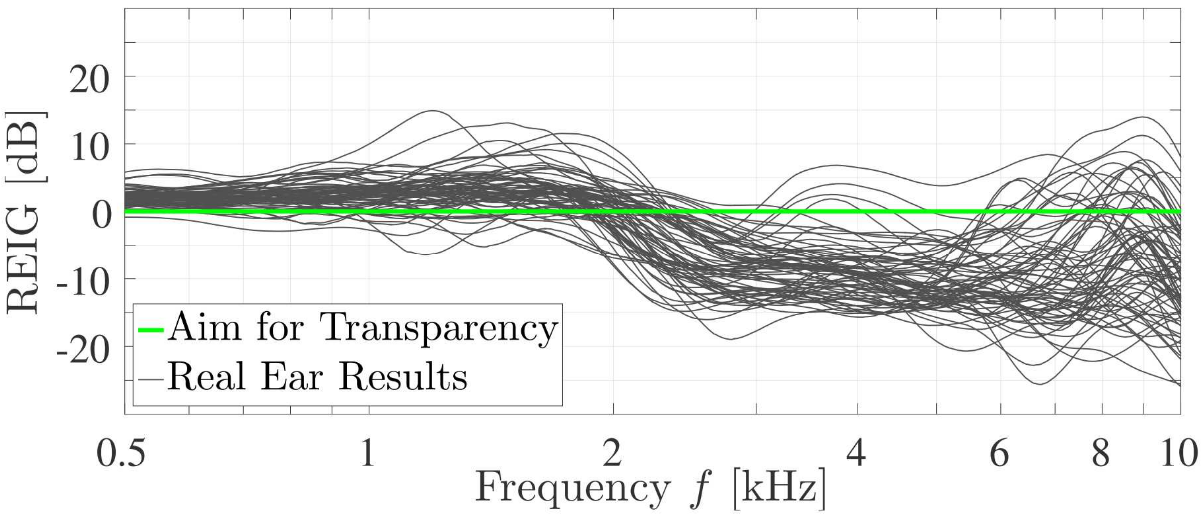


[Denk et al. 2017, IJA] [Denk et al. 2017, AES Conf. Headphone Technology]

1. Transparent sound presentation

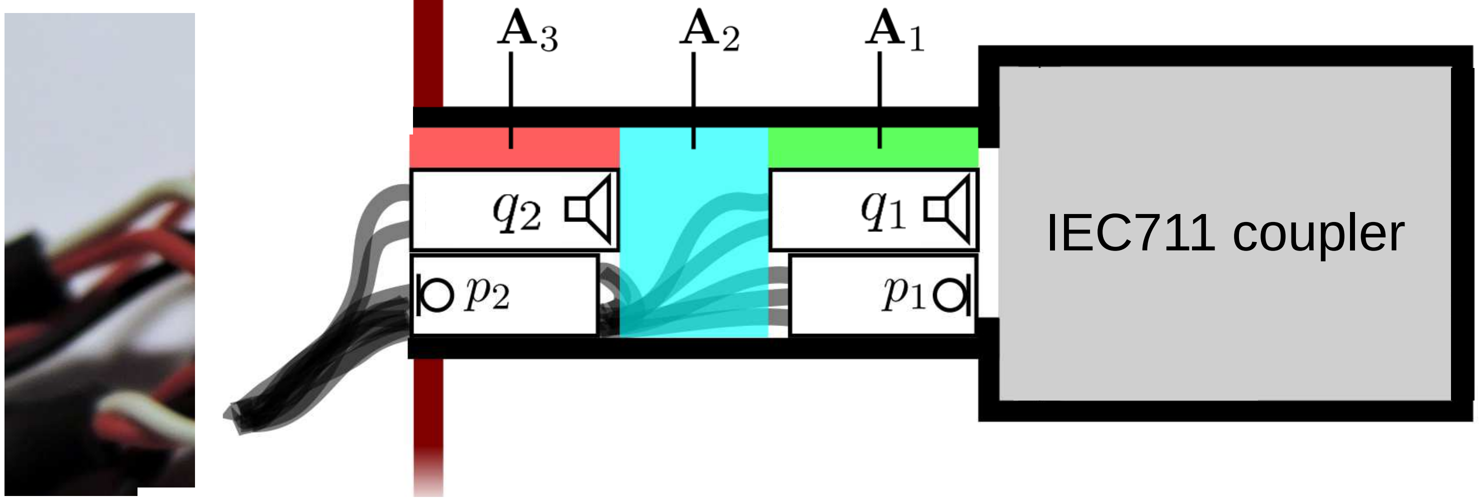
- **Physical Evaluation:**
  - Real-ear measurements on 12 subjects
  - Real Ear Insertion Gain (REIG): 0 dB for transparency
- **Potential error sources:**
  - Estimation of target response
  - Calibration: estimation of pressure at the eardrum ≠ inner-ear mic

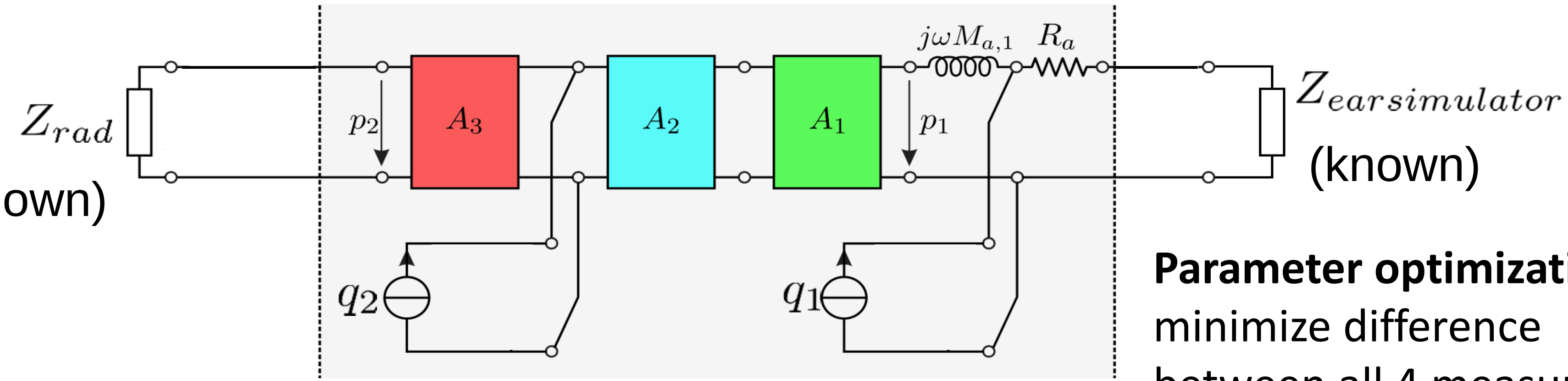




2. Electro-acoustic model

- Earpiece Model (Fixed)

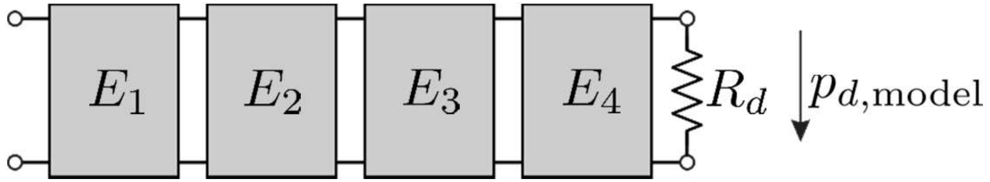


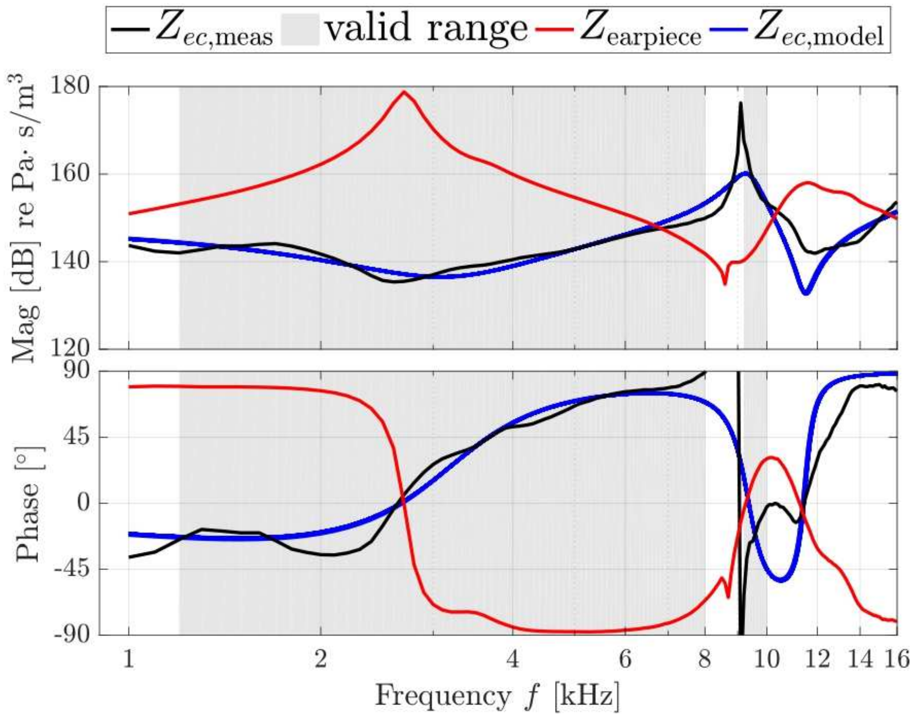


Parameter optimization:
minimize difference between all 4 measured and modeled transfer functions

2. Electro-acoustic model

- Ear Canal Model (Individualized)





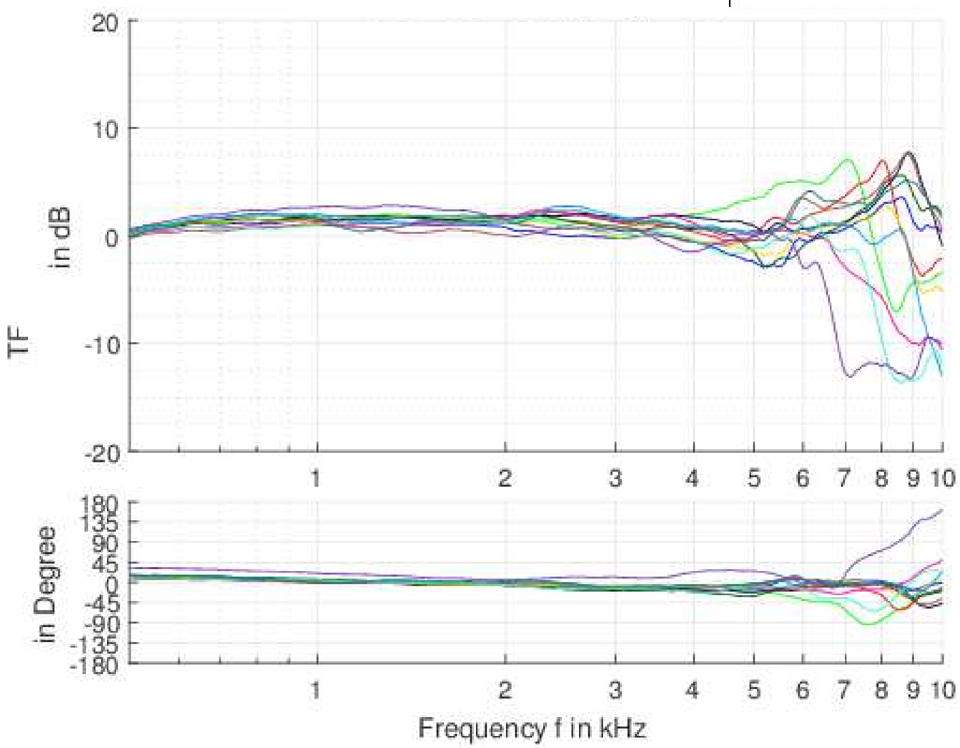
Parameter optimization (4 radii, 1 length, 1 resistive load) by minimizing the difference between measured and modeled ear canal (Nelder-Mead simplex optimization procedure):

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

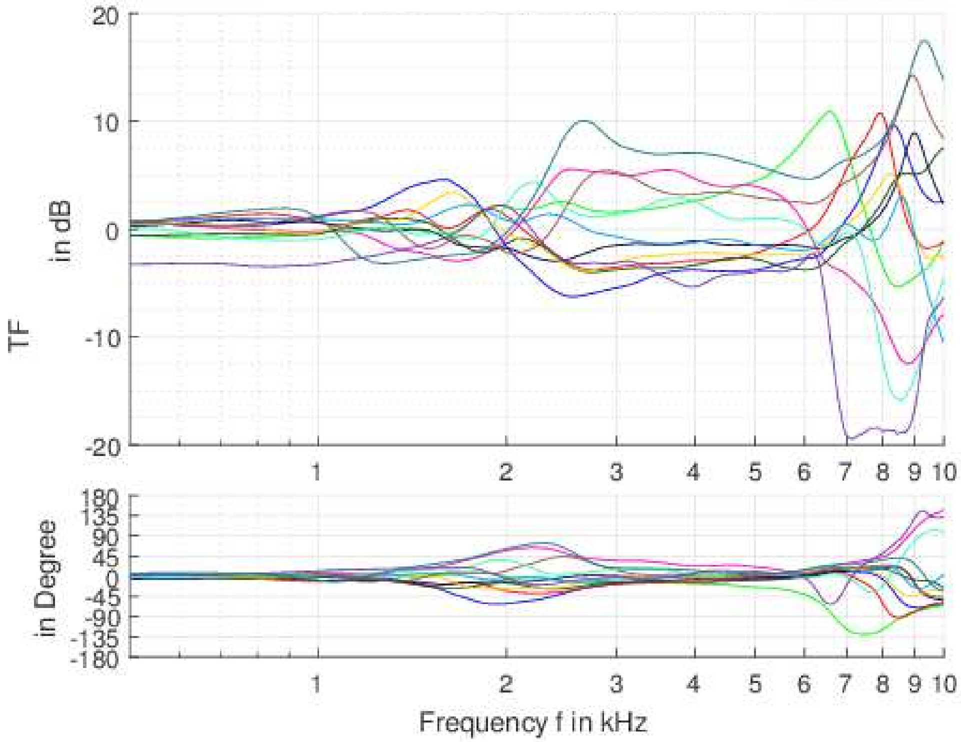
2. Electro-acoustic model

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

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



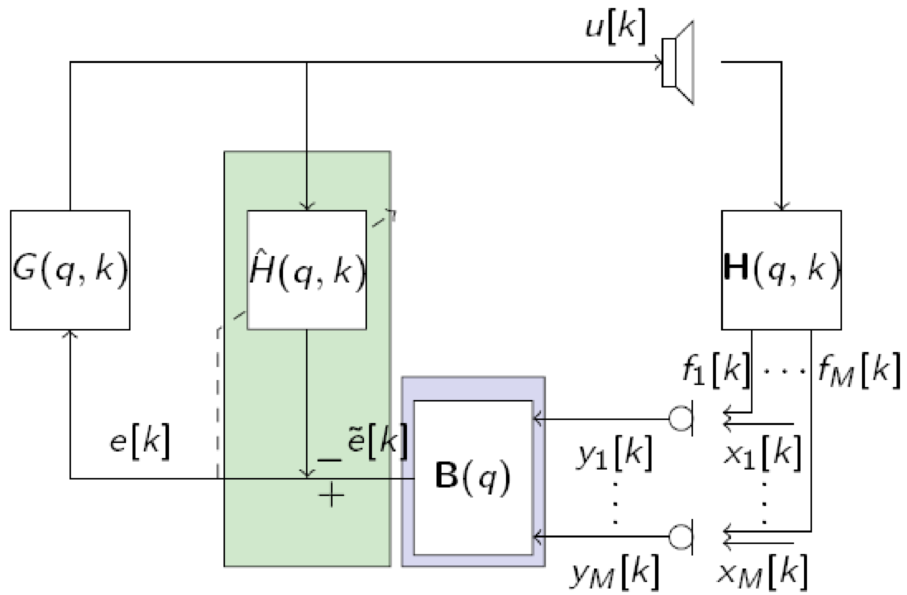
$$\frac{p_{d,\text{from average correction of p1 (i.e. non-individualized)}}}{p_{d,\text{Probe Tube Meas}}}$$



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

3. Acoustic feedback cancellation

- **Several approaches** for acoustic feedback cancellation in hearing aids:
  1. Feedforward suppression
  2. Adaptive feedback cancellation (prediction error method, probe noise)
  3. **Spatial filtering methods** exploiting multiple microphones
- **Approach:** fixed beamformer steering spatial null towards position of hearing aid receiver → theoretically perfect feedback cancellation possible
- **Extension:** reduction of residual feedback using adaptive filter



[Schepker et al., IWAENC 2016, ITG 2016, ICASSP 2017, EUSIPCO 2017]

3. Acoustic feedback cancellation

- **Assumptions:**
  - Time-invariance of the acoustic feedback paths
  - Availability of multiple (measured) acoustic feedback paths
- **Different optimization criteria**: compute coefficients **b** of null-steering beamformer by minimizing cost function (least-squares, minimax)
- Increase **robustness** by including all available feedback paths $\mathbf{H}_i$, *i=1…I*

$$\min_{\mathbf{b}} \quad J(\mathbf{b}) \qquad \text{subject to} \quad B_{m_0}(q) = q^{-L_d}$$

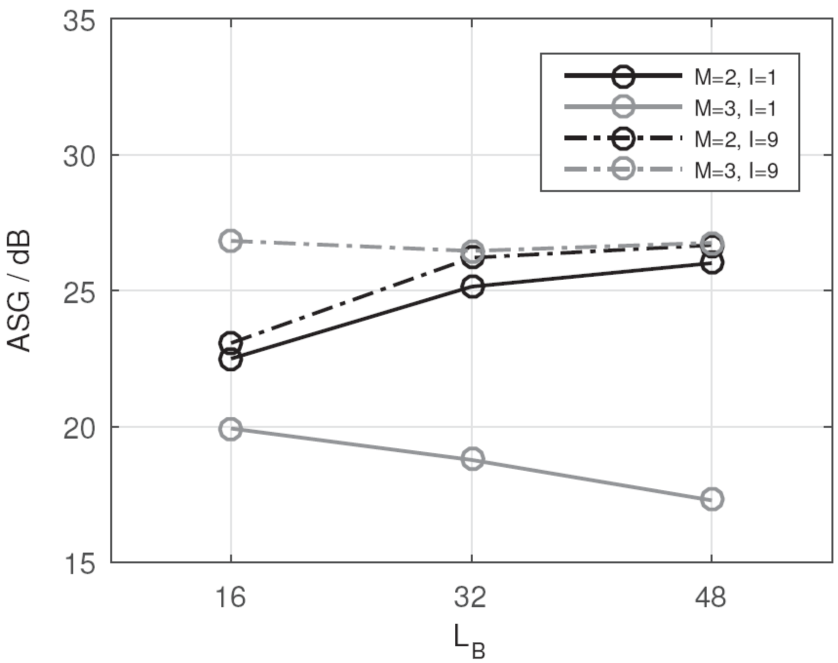
$$J_{rLS}(\mathbf{b}) = \sum_{i=1}^{I} \sum_{n=0}^{N_{FFT}-1} |\mathbf{H}_i^H(\omega_n)\mathbf{B}(\omega_n)|^2$$

$$J_{rMM}(\mathbf{b}) = \max_{\omega_n, i=1,\ldots,I} |\mathbf{B}^H(\omega_n)\mathbf{H}_i(\omega_n)|^2$$

- *Note:* directional response of beamformer for external signals is not explicitly constrained/optimized

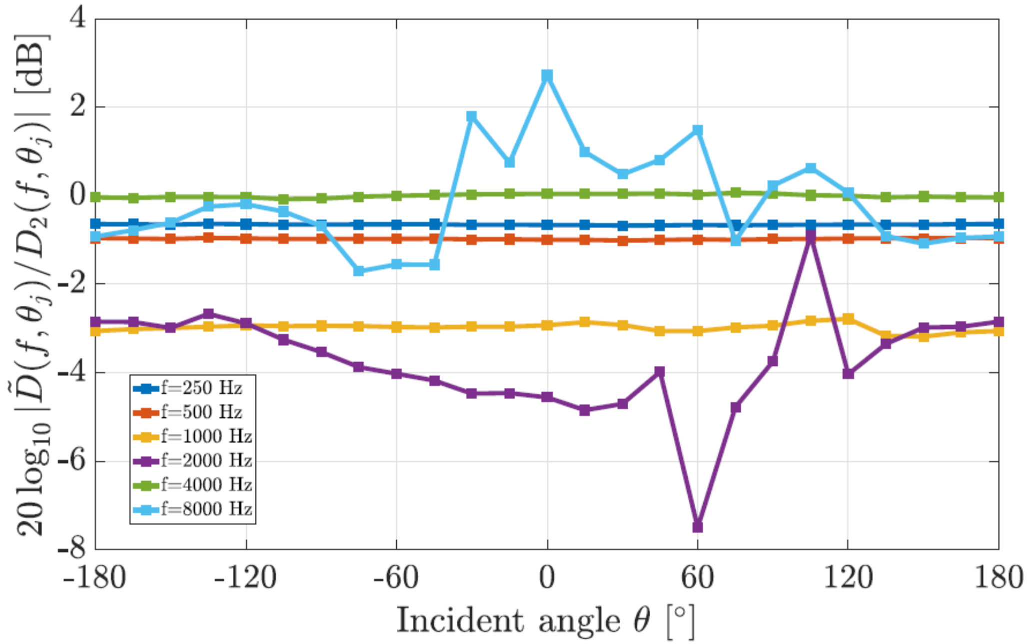
3. Acoustic feedback cancellation

- **Feedback cancellation performance** [Schepker et al., ITG2016]



(robust) average ASG improvement of more than 20 dB

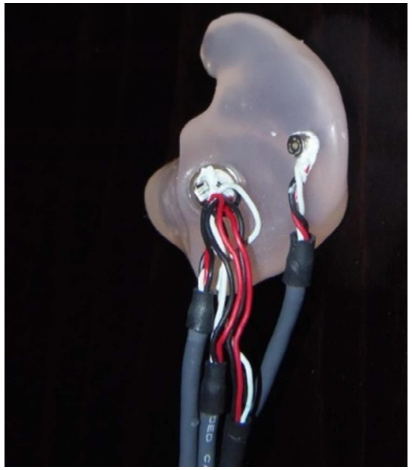
- **Directional response of beamformer** (relative to entrance microphone)



small variations in directional response of approximately ± 4dB

Conclusion and outlook

- **Acoustically transparent hearing device:**
  - Earpiece with multiple integrated microphones and receivers
  - Allows for individualized sound pressure equalization and beamforming for acoustic feedback cancellation
    - **Transparency mode almost indistinguishable from open ear canal**
    - **Robust ASG improvement of more than 20 dB**
  - Real-time demonstrator available



- **Outlook:**
  - Integration of individualized electro-acoustic model into equalization procedure
  - Combined solutions for equalization and acoustic feedback cancellation (exploting multiple receivers)
  - Integration with hearing support (e.g., noise suppression) and occlusion management

Acknowledgments / references





- Denk, F. et al. (2017) An Individualised Acoustically Transparent Earpiece for Hearing Devices, *International Journal of Audiology (Early Online).*
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