Collaborating Hearing Aids
An information-theoretic perspective

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1. Collaborating hearing aids

2. The problem from an information-theoretic perspective

3. Gain-rate analysis

4. Conclusions & future work
Some generalities about hearing aids

- Companies: Siemens, Phonak, Beltone, Philips, Widex, Clarity, Starkey, Oticon and many more...
- Types: behind-the-ear (BTE), in-the-ear (ITE), in-the-canal (ITC) and completely-in-the-canal (CTC)

- Analog vs. digital
- Battery-operated sensing devices
- Different colors
- Controls (volume, mode, etc.), 1 to 3 (omni-)directional microphones, 1 loudspeaker
What are the goals of hearing aids?

- **Spectral shaping**: frequency attenuation/amplification for hearing loss compensation
- **Beamforming**: signals acquired by multiple microphones are combined coherently
  - Allows to focus in one particular direction
  - Permits spatial noise reduction and rejection of interfering signals
  - Increases speech intelligibility in noisy environments
What is the need for collaboration?

- Most state-of-the-art systems involve two devices working independently of one another
  - Limited beamforming capability
  - Poor rejection of interfering signals
- Combining signals from microphones of both hearing aids would allow better beamforming capability (greater spatial extent)
- Collaboration by a wireless communication link between the hearing aids (e.g. Siemens e2e wireless technology)
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**Fundamental gain-rate tradeoff**
Signal observed at hearing aid $k$ ($k = 0, 1$)

$$X_k(t) = S_k(t) + I_k(t) + N_k(t)$$

$$= h_k(t) * S(t) + \tilde{h}_k(t) * I(t) + N_k(t)$$

$S$, $I$ and $N_k$ are assumed to be independent jointly Gaussian stationary random processes
Problem setup (2/3)

- Collaboration using a wireless link of rate $R_k$

\[\hat{S}_0 \quad \text{Enc} \quad R_0 \quad \text{Dec} \quad \hat{S}_1\]

- Distortion: mean-squared error criterion $E[\|S_k - \hat{S}_k\|^2]$
Symmetric problem: we look at it from the point-of-view of hearing aid 0 (left ear)

The setup reduces to a remote source coding problem with side information at the decoder:

We define the gain-rate function

\[ G(R) = \frac{D(0)}{D(R)} \]
Remote source coding with side information (1/4)

The problem from two different viewpoints: approximation and compression

- **Approximation**: the remote conditional Karhunen-Loève transform (rcKLT)
- **Compression**: the remote Wyner-Ziv problem for jointly Gaussian stationary sources
The coding intuition: what should be sent?

**Source coding:** encode $X_1$
Remote source coding with side information (2/4)

- The coding intuition: what should be sent?

**Remote source coding**: get the best estimate of $S_0$ based on $X_1$ and then encode this estimate
The coding intuition: what should be sent?

Source coding with side information: encode the part of $X_1$ that the decoder cannot predict with $X_0$
The coding intuition: what should be sent?

Remote source coding with side information: get the best estimate of $S_0$ based on the part of $X_1$ that the decoder cannot predict with $X_0$ and then encode this estimate
The optimal rate-distortion tradeoff is given by the reverse “water-filling” formula

\[ R(\theta) = \frac{1}{4\pi} \int_{-\infty}^{\infty} \max \left\{ 0, \log_2 \frac{\Phi_e(\Omega)}{\theta} \right\} d\Omega \quad [\text{b/s}] \]

\[ D(\theta) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \Phi_{S_0|X_0,X_1}(\Omega) d\Omega \]
\[ + \frac{1}{2\pi} \int_{-\infty}^{\infty} \min \{ \theta, \Phi_e(\Omega) \} d\Omega \quad [\text{MSE/s}] \]

where \( \Phi_e = \Phi_{S_0|X_0} - \Phi_{S_0|X_0,X_1} \) and \( \theta \in (0, \text{ess sup}_\Omega \Phi_e(\Omega)] \)

This allows to compute the optimal gain-rate tradeoff
Reverse “water-filling” bit allocation strategy

\[ \Phi_e(\Omega) \]
Gain-rate analysis (1/3)

- Flat power-spectrums over the frequency band $[-\Omega_0, \Omega_0]$
- The far-field case: source and ambient noise
  - We obtain as a function of the signal-to-noise ratio $\gamma$
    $$G(R, \gamma) = \frac{2\gamma + 1}{\gamma + 1} \left( \frac{\gamma}{\gamma + 1} 2^{-2\pi R/\Omega_0} + 1 \right)^{-1}$$
  - For $f_0 = \Omega_0 / 2\pi = 4000$ [Hz]
The far-field case: source, interferer and ambient noise

- The spatial extent naturally offered by the head allows a better rejection of interfering signals
- For $l = 2$ [cm] (dashed) and $l = 20$ [cm] (solid)
The near-field case with head shadowing: source, interferer and ambient noise

- The head is modelled as a sphere
- Normalized reconstruction error as a function of the position of the interferer
- For $R = 0$ [b/s/Hz] (dotted), $R = 0.1$ [b/s/Hz] (dashed) and $R = 1$ [b/s/Hz] (solid) at $f_0 = \Omega_0/2\pi = 3000$ [Hz]
Conclusions

- We have identified the problem of collaborating hearing aids from an information-theoretic perspective.
- The remote source coding problem with side information has been solved from both an approximation and a compression viewpoint.
- The optimal tradeoff between the communication bit-rate and the gain provided by collaboration has been given.
- The gain-rate function has been computed for various scenarios of interest (far-field, near-field, with/without head shadowing, etc.)
Future work

- Look at the same problem from a signal processing standpoint
- Investigate how the intuition acquired by the information-theoretic analysis can be used in the design of practical algorithms
- Explore coding techniques that take into account important perceptual factors
Thanks for your attention

Questions ?