Collaborating Hearing Aids

An information-theoretic perspective

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Joint work with Martin Vetterli

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Outline

1. Collaborating hearing aids
2. The problem from an information-theoretic perspective
3. Gain-rate analysis
4. Conclusions & future work

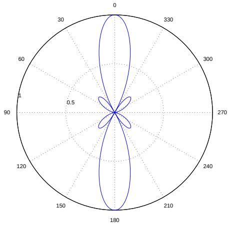
Some generalities about hearing aids

- 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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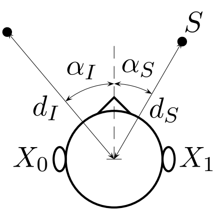
Fundamental gain-rate tradeoff

Problem setup (1/3)

- Signal observed at hearing aid k ($k = 0, 1$)

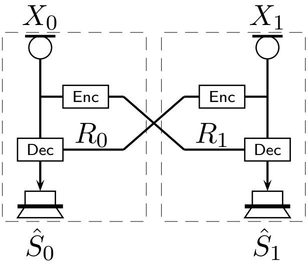
$$\begin{aligned} X_k(t) &= S_k(t) + I_k(t) + N_k(t) \\ &= h_k(t) * S(t) + \tilde{h}_k(t) * I(t) + N_k(t) \end{aligned}$$

- S, I and N_k are assumed to be independent jointly Gaussian stationary random processes



Problem setup (2/3)

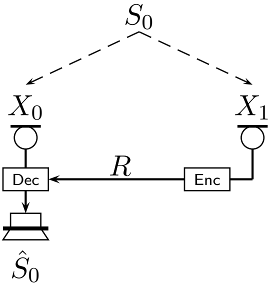
- Collaboration using a wireless link of rate R_k



- Distortion: mean-squared error criterion $\mathrm{E}[\|S_k - \hat{S}_k\|^2]$

Problem setup (3/3)

- 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

$$G(R) = D(0)/D(R)$$

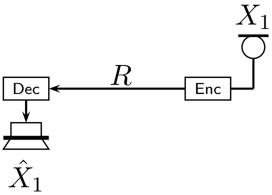
Remote source coding with side information (1/4)

- 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

Remote source coding with side information (2/4)

- The coding intuition: what should be sent?

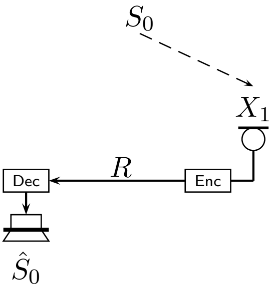
Source coding: encode X_1



Remote source coding with side information (2/4)

- The coding intuition: what should be sent?

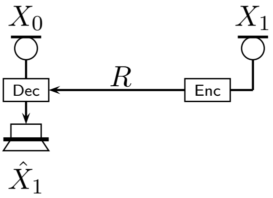
  Remote source coding: get the best estimate of S_0 based on X_1 and then encode this estimate



Remote source coding with side information (2/4)

- The coding intuition: what should be sent?

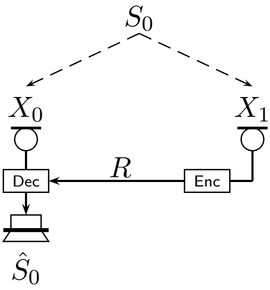
  Source coding with side information: encode the part of X_1 that the decoder cannot predict with X_0



Remote source coding with side information (2/4)

- 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



Remote source coding with side information (3/4)

- The optimal rate-distortion tradeoff is given by the reverse "water-filling" formula

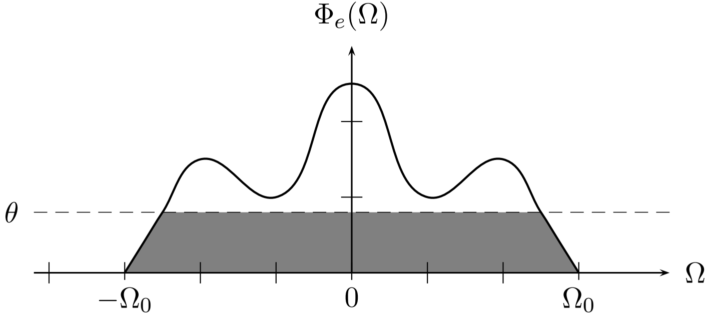
$$\begin{aligned} R(\theta) &= \frac{1}{4\pi}\int_{-\infty}^{\infty} \max\left\{0, \log_2 \frac{\Phi_e(\Omega)}{\theta}\right\} d\Omega \quad \text{[b/s]} \\ D(\theta) &= \frac{1}{2\pi}\int_{-\infty}^{\infty} \Phi_{S_0|X_0,X_1}(\Omega)\, d\Omega \\ &\quad + \frac{1}{2\pi}\int_{-\infty}^{\infty} \min\left\{\theta, \Phi_e(\Omega)\right\} d\Omega \quad \text{[MSE/s]} \end{aligned}$$

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

- This allows to compute the optimal gain-rate tradeoff

Remote source coding with side information (4/4)

- Reverse "water-filling" bit allocation strategy

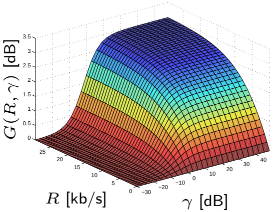


Gain-rate analysis (1/3)

- 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 γ

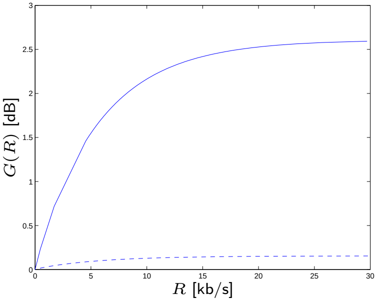
$$G(R,\gamma) = \frac{2\gamma+1}{\gamma+1}\left(\frac{\gamma}{\gamma+1}\,2^{-2\pi R/\Omega_0}+1\right)^{-1}$$

  - For $f_0 = \Omega_0/2\pi = 4000$ [Hz]



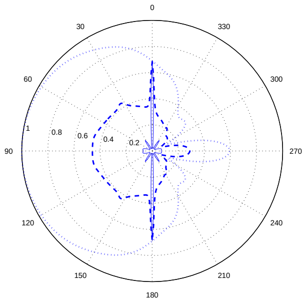
Gain-rate analysis (2/3)

- 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)



Gain-rate analysis (3/3)

- 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 infomation-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 ?