Collaborating Hearing Aids

An Information-Theoretic Perspective

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Outline

Motivations (1/3)

Generalities

- Battery-operated sensing devices
- Types: behind-the-ear (BTE), in-the-ear (ITE), in-the-canal (ITC) and completely-in-the-canal (CTC)

- Analog vs. digital
- Few (omni-)directional microphones, 1 loudspeaker

Motivations (2/3)

Improve speech intelligibility with hearing aids

- Spectral shaping
- Beamforming
- Assistive listening devices

(a) (b)

Figure: Assistive listening devices. (a) Remote microphone. (b) Collaborating hearing aids.

Motivations (3/3)

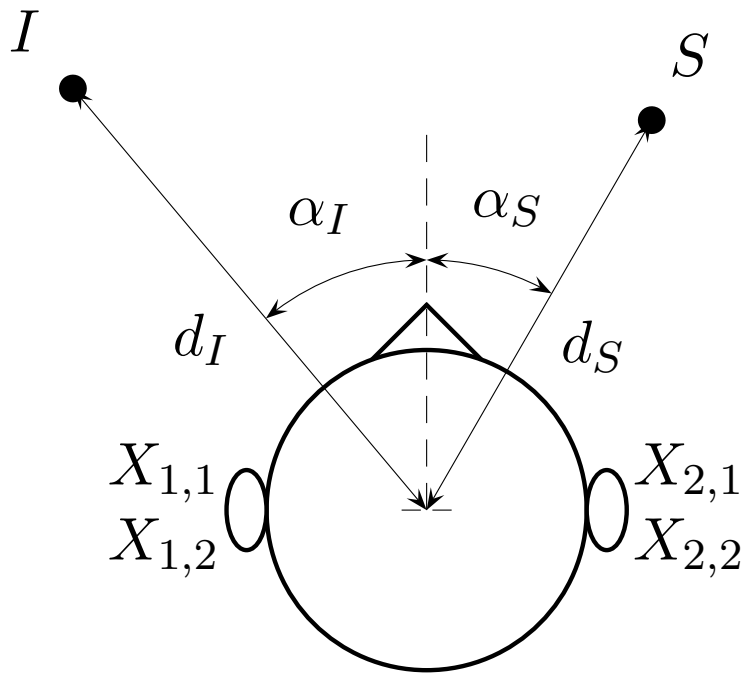
Wireless collaboration

- Analog vs. digital
- Transmission method (e.g. Bluetooth)
- Coding issues

Gain-Rate Tradeoff

Collaborating Hearing Aids (1/3)

Head-related configuration

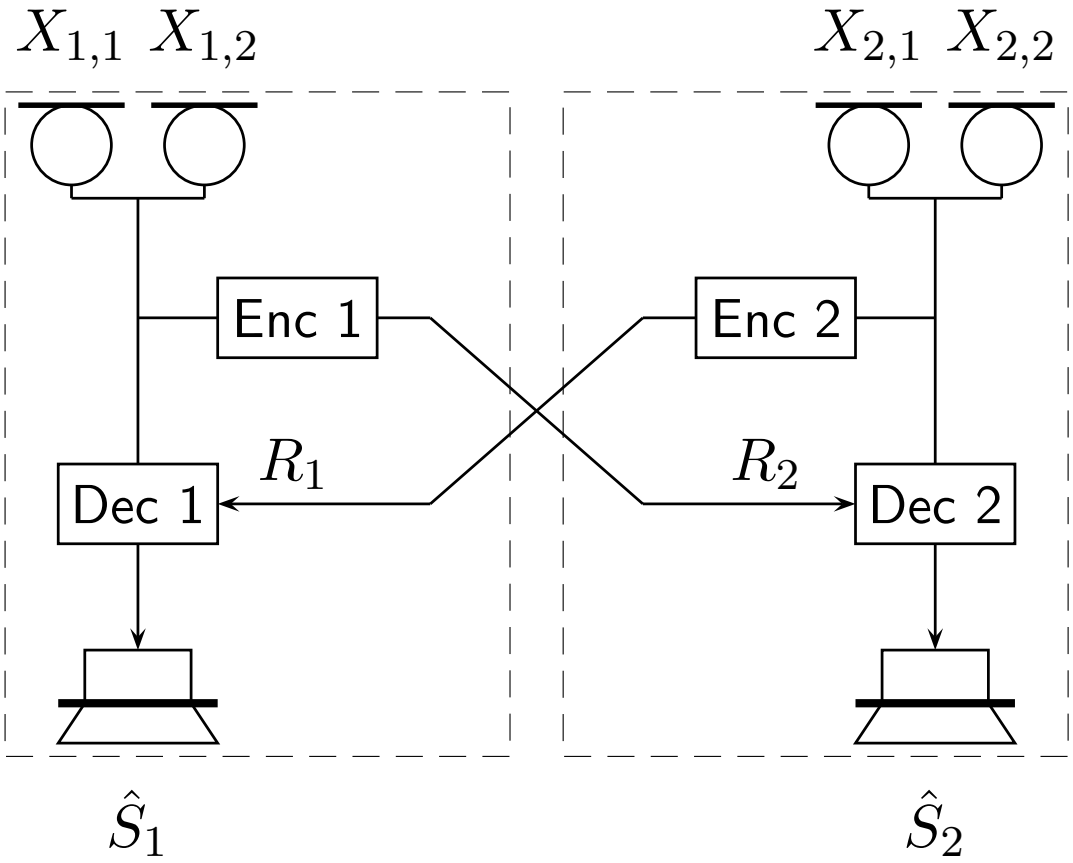


Recorded signals

$$X_{l,k}(t) = [h_{l,k} * S](t) + [g_{l,k} * I](t) + N_{l,k}(t), \quad \text{for } l, k = 1, 2$$

Collaborating Hearing Aids (2/3)

Wireless collaboration scheme



Weighted mean-squared error (MSE)

$$D_l = \mathrm{E}\left[\|A(S_l - \hat{S}_l)\|^2\right], \quad \text{for } l = 1, 2$$

Collaborating Hearing Aids (3/3)

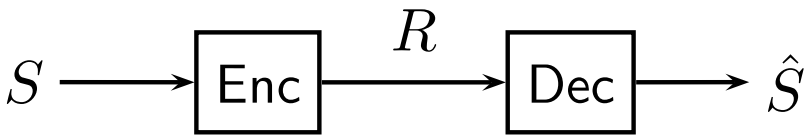
Goals

- Characterize the optimal rate-distortion tradeoffs
  - Local view: (R_1, D_1) and (R_2, D_2)
  - Global view: (R, D) where $R = R_1 + R_2$ and $D = D_1 + D_2$
- Compute rate allocation policies
  - How to distribute R_1 and R_2 among frequency bins?
  - How to share R between the hearing aids?
- Provide insights about implementation

Framework: information theory

Information-Theoretic Background (1/4)

Source coding in a nutshell



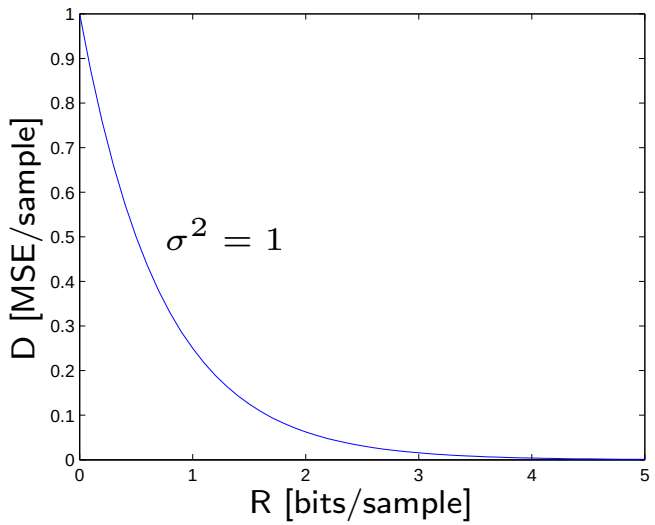
- Given: a source (or signal) S and a distortion criterion $d(S, \hat{S})$ (e.g. MSE)
- Question: for a given rate R, what is the minimum achievable distortion?
- Answer: the rate-distortion function
- Assumption: unbounded coding delay and complexity

Information-Theoretic Background (2/4)

Example: the Gaussian case

- We observe $X_1, X_2, \ldots$ where $X_k \sim \mathcal{N}(0, \sigma^2)$ i.i.d.
- Rate-distortion function given by

$$D(R) = \sigma^2 2^{-2R} \quad \text{[MSE/sample]}$$

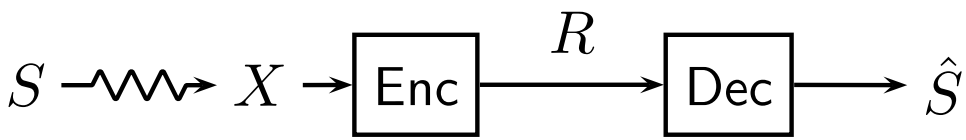


- simple 1-bit quantization $\approx 0.36\sigma^2$, optimal $= 0.25\sigma^2$

Information-Theoretic Background (3/4)

Variations on a theme

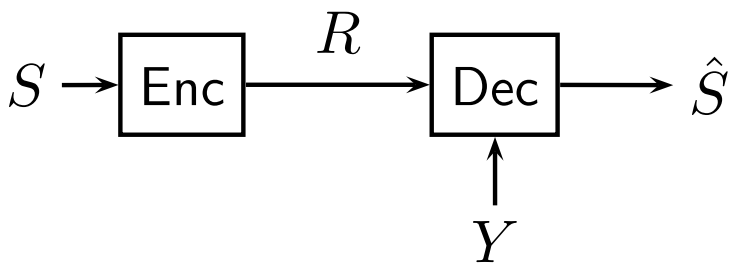
- Remote source coding



Information-Theoretic Background (3/4)

Variations on a theme

- Source coding with side information at the decoder



Information-Theoretic Background (3/4)

Variations on a theme

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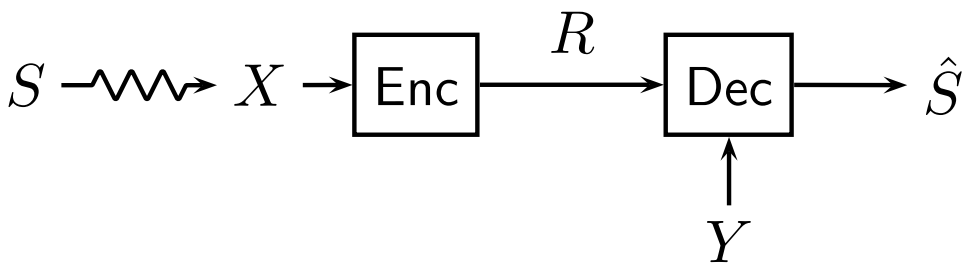
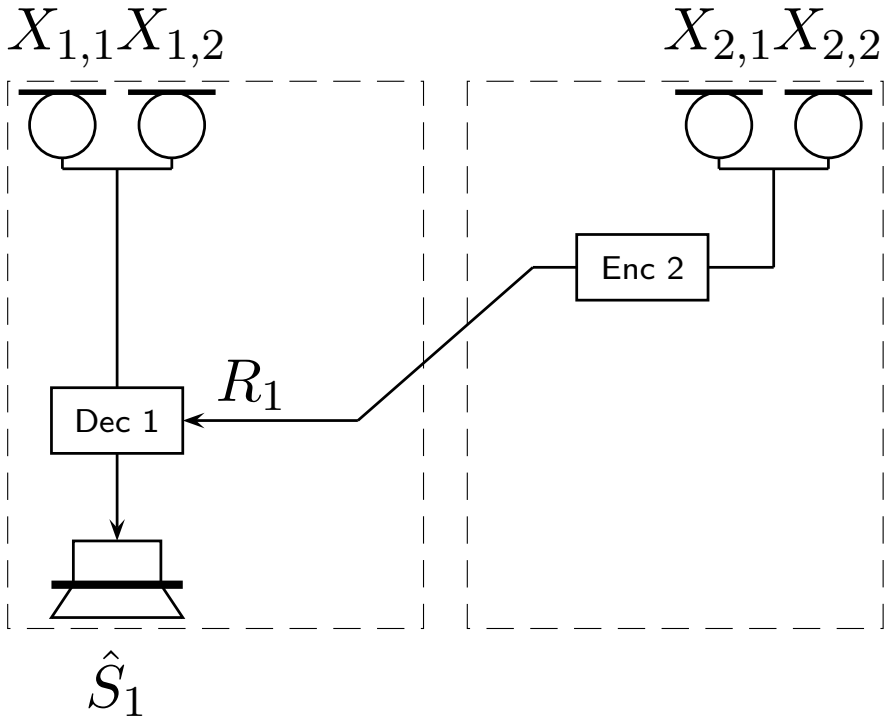


Information-Theoretic Background (4/4)

What about collaborating hearing aids? Local view



- We define the gain-rate function at hearing aid 1

$$G_1(R_1) = \frac{D_1(0)}{D_1(R_1)}$$

Information-Theoretic Background (4/4)

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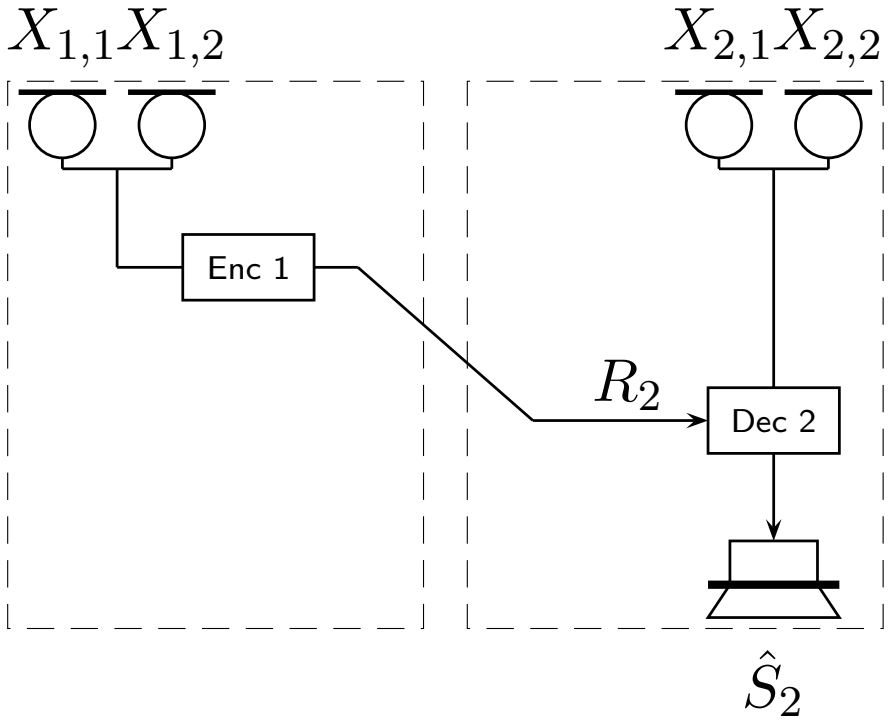
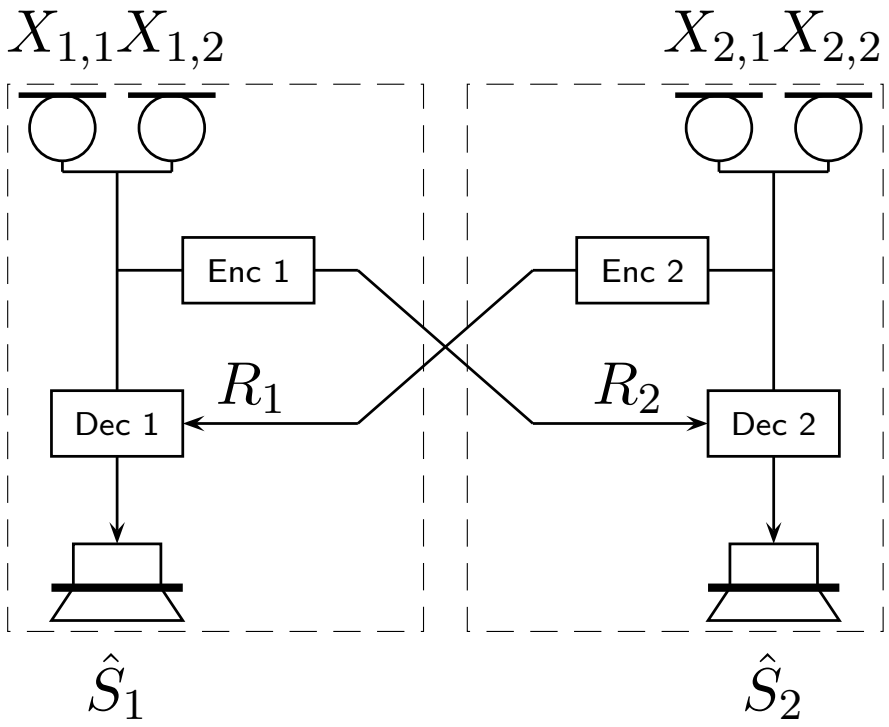


- We define the gain-rate function at hearing aid 2

$$G_2(R_2) = \frac{D_2(0)}{D_2(R_2)}$$

Information-Theoretic Background (4/4)

What about collaborating hearing aids? Global view



Results (1/5)

Local view

- Gain-rate tradeoffs

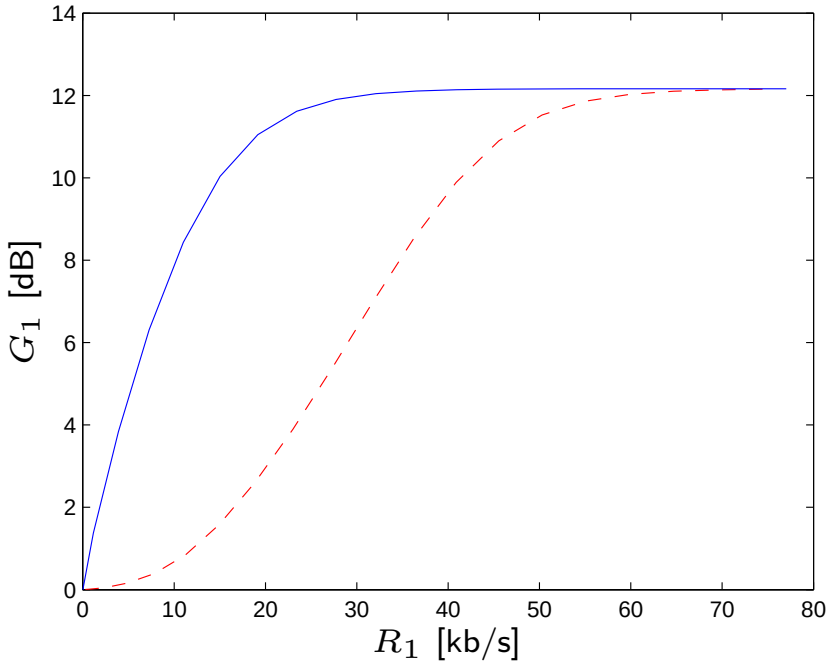
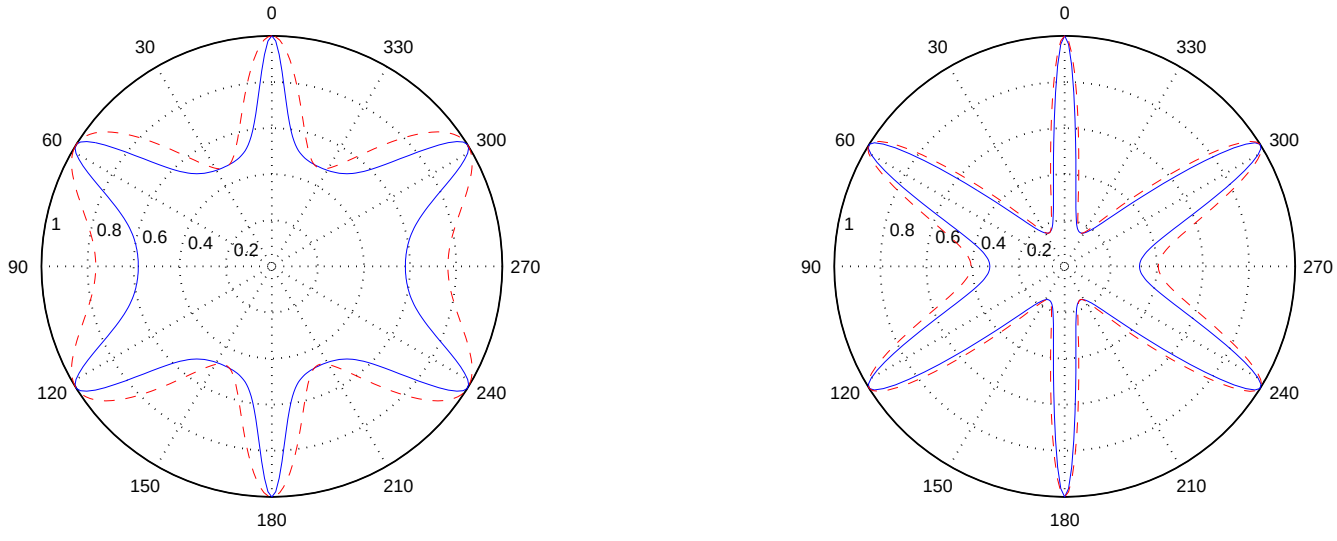


Figure: Example of gain-rate tradeoffs (two classes of coding strategies).

Results (2/5)

Local view

- Rate-constrained directivity patterns



(a) (b)

Figure: Example of rate-constrained directivity patterns (two different rates, two classes of coding strategies).

Results (3/5)

Local view

- Rate allocation across frequencies

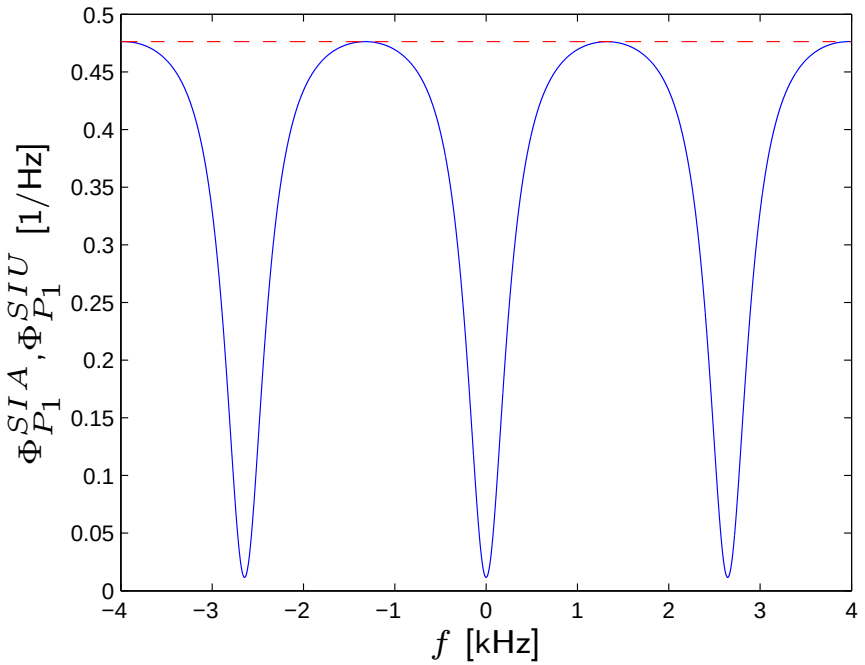


Figure: Allocation of the rate R_1 across frequencies (two classes of coding strategies)

Results (4/5)

Global view

- Rate allocation between the hearing aids

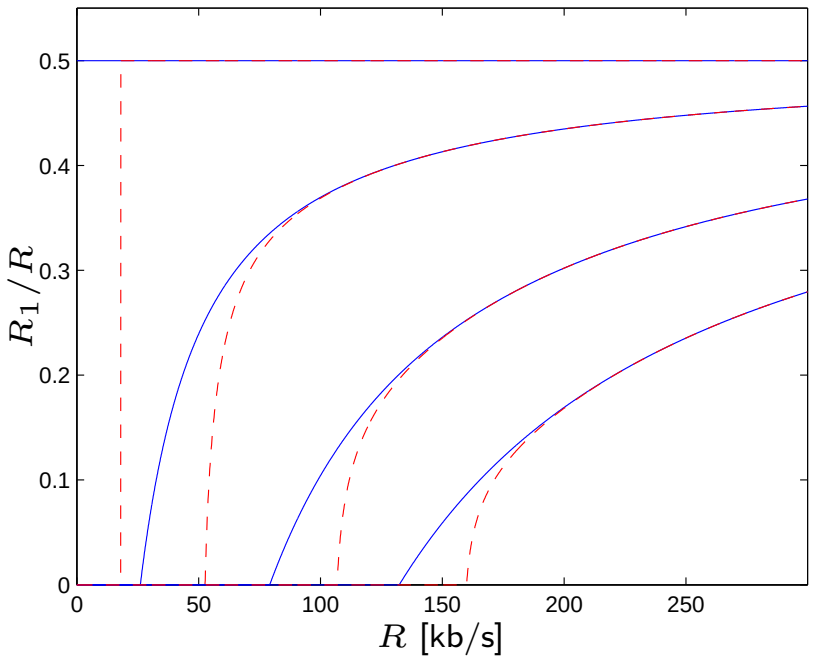


Figure: Fraction of the total rate benefiting to hearing aid 1 (different signal-to-noise ratios, two classes of coding strategies)

Conclusions

- Identification of the problem of collaborating hearing aids
- Information-theoretic analysis
  - Gain-rate tradeoffs
  - Rate allocation
  - Rate-constrained directivity patterns

  $\Rightarrow$ Allows to benchmark the performance of practical schemes

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Thanks for your attention!!