Primary Path Estimator based on Individual Secondary Path for ANC Headphones

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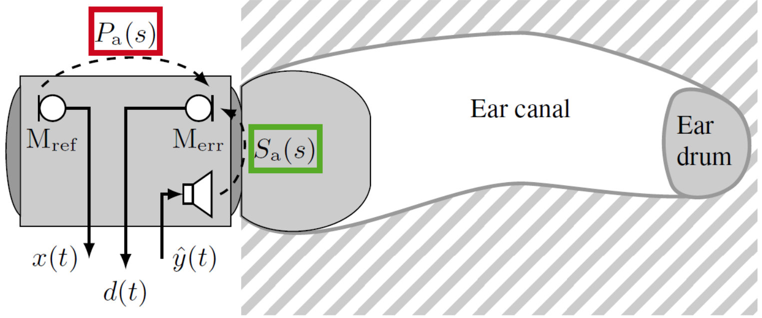
Use Case

- ANC headphones come with one-fits-all filter design
- ANC performance varies with individual ear physiology and fitting
- Add calibration step and individualize ANC filter
  - Measurement of secondary path $S_a(s)$ feasible by using inner loudspeaker
  - Measurement of primary path $P_a(s)$ not feasible and requires dedicated setup



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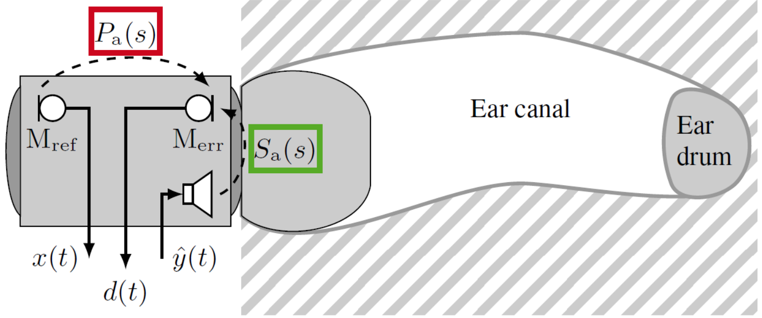
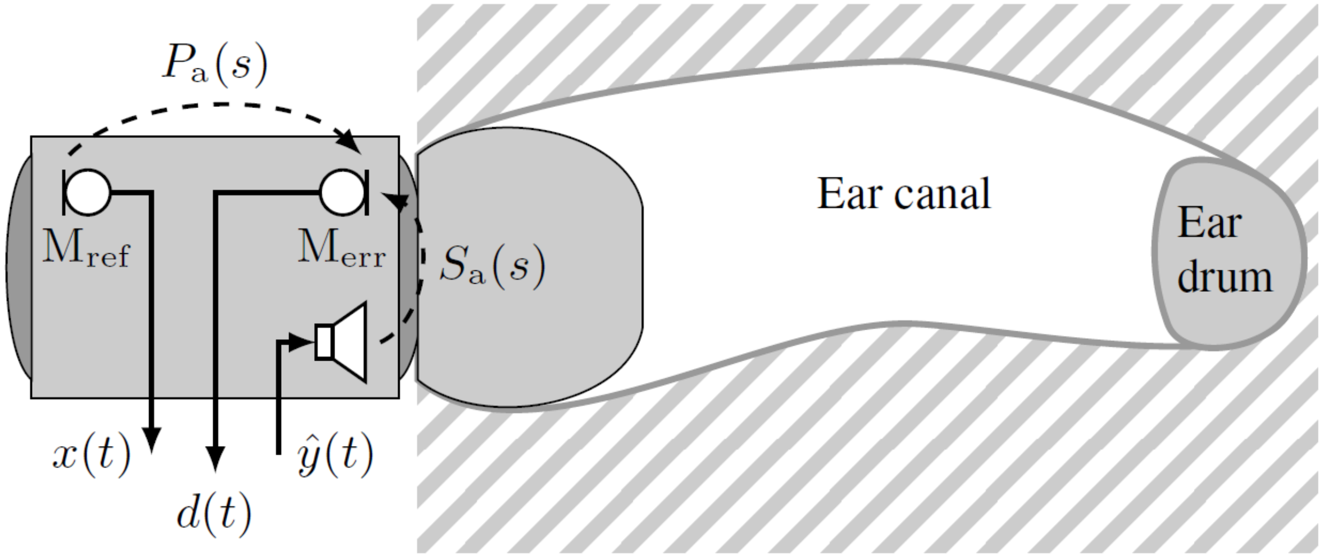


Use coherence of primary and secondary path to estimate primary path based on secondary path

→ Increase robustness of ANC with respect to individual fitting of headphone

Introduction

Headphone Model



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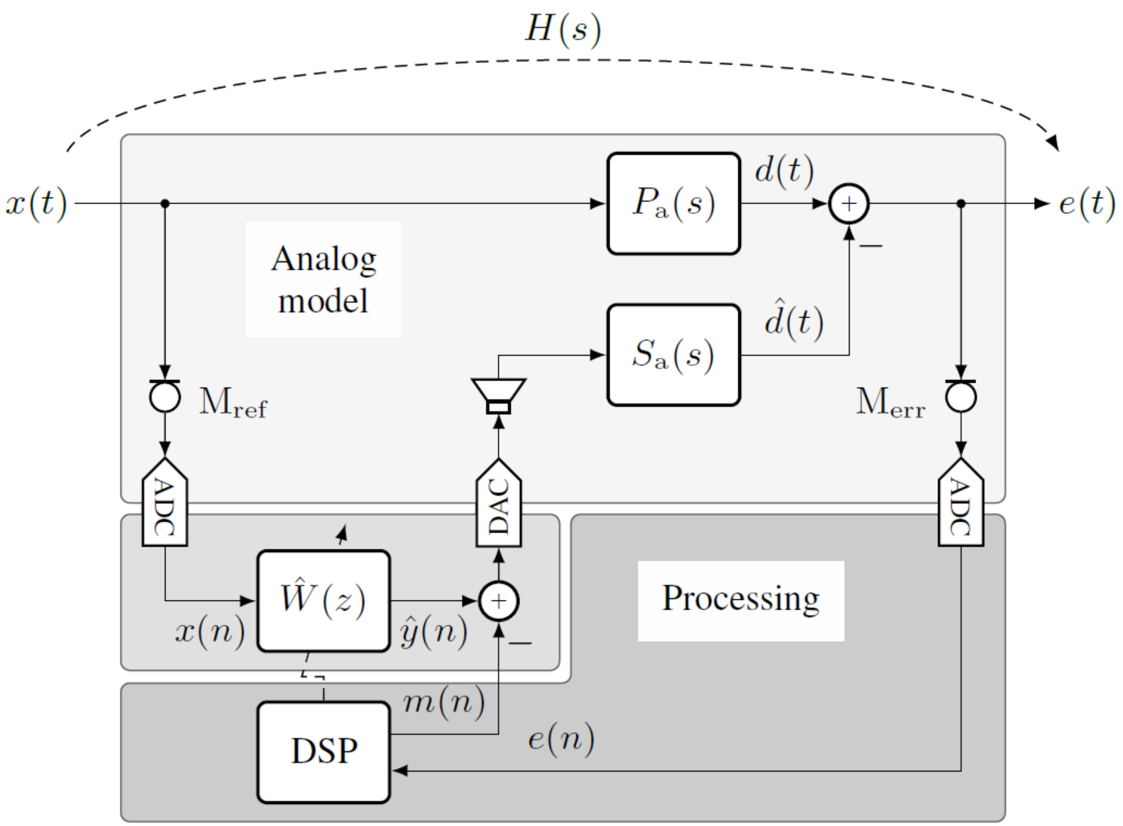
Feed-forward ANC Block Diagram



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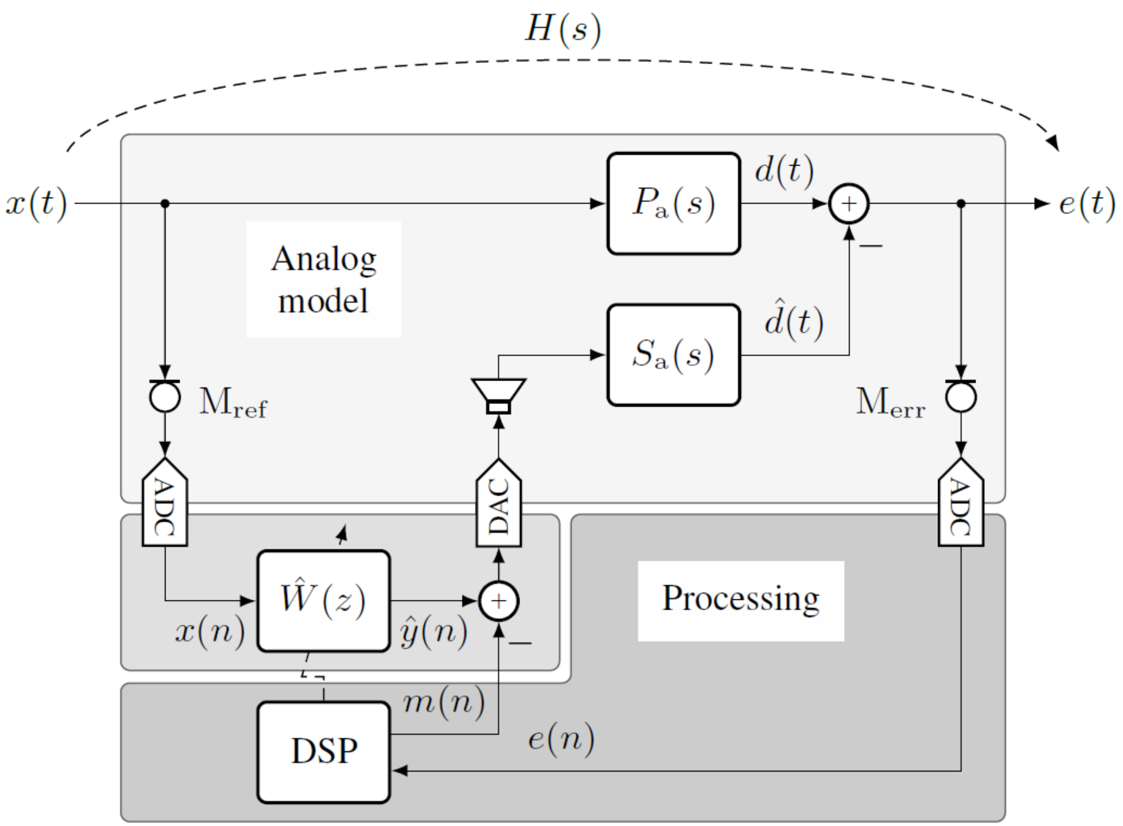

Analog model

Introduction

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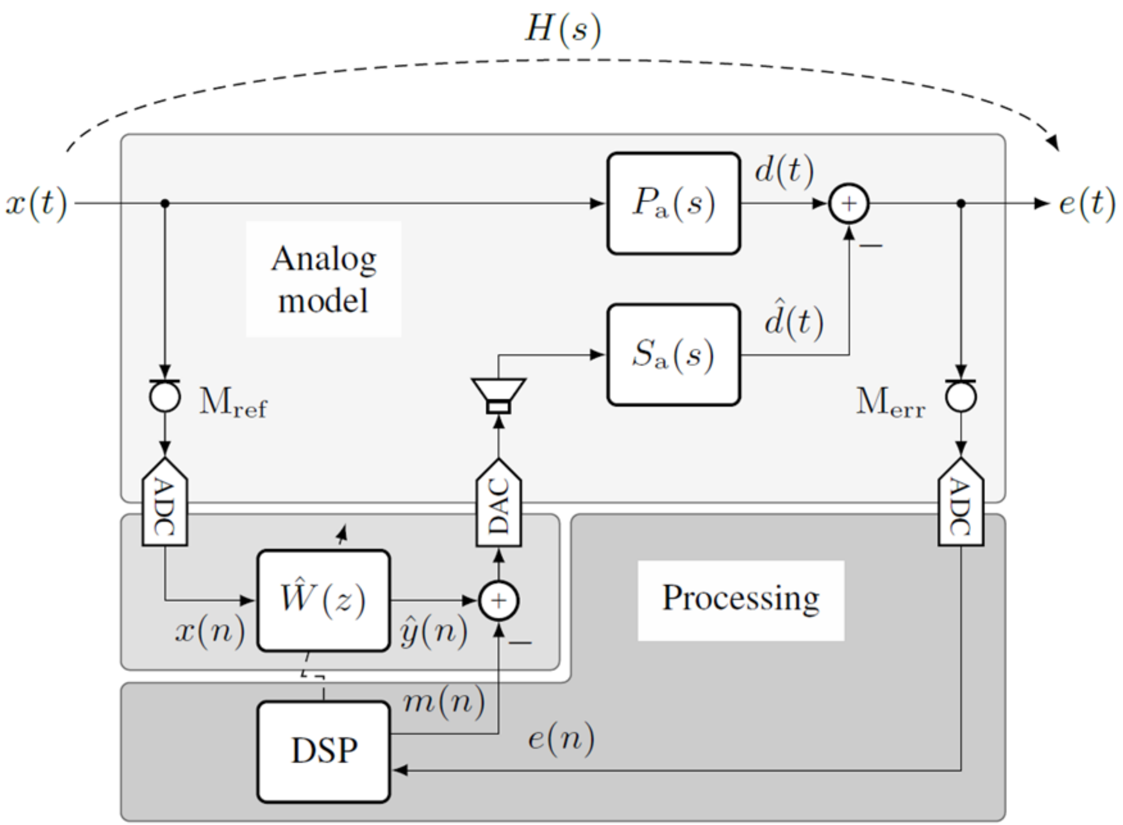

Analog model

Fast digital filter $\widehat{W}(z)$

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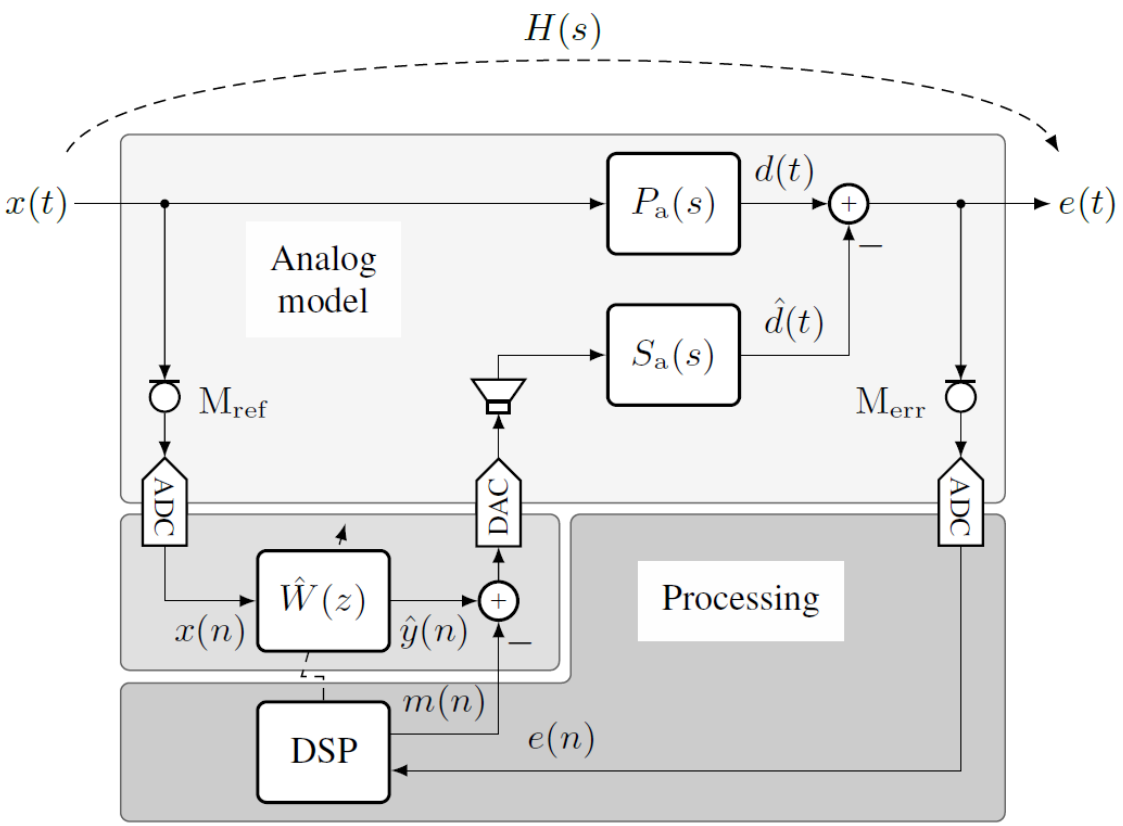

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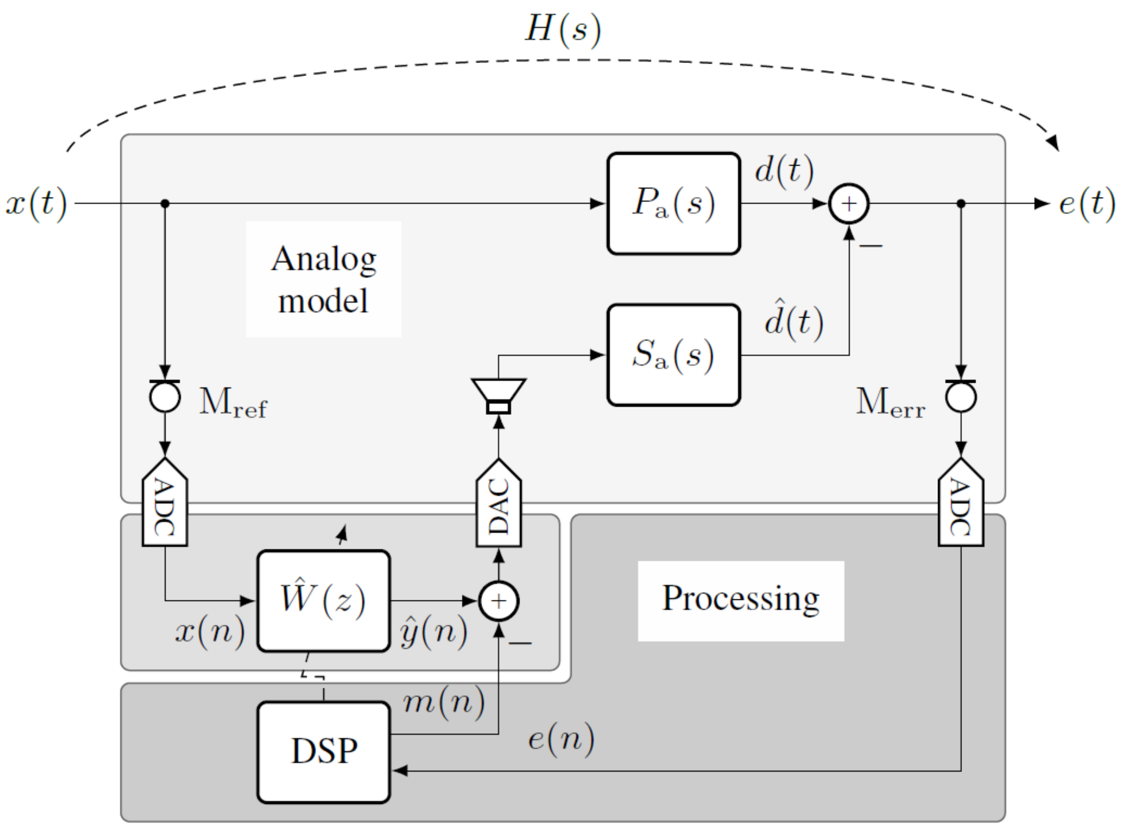
Fast digital filter $\widehat{W}(z)$

Processing unit

Feed-forward ANC Filter Design



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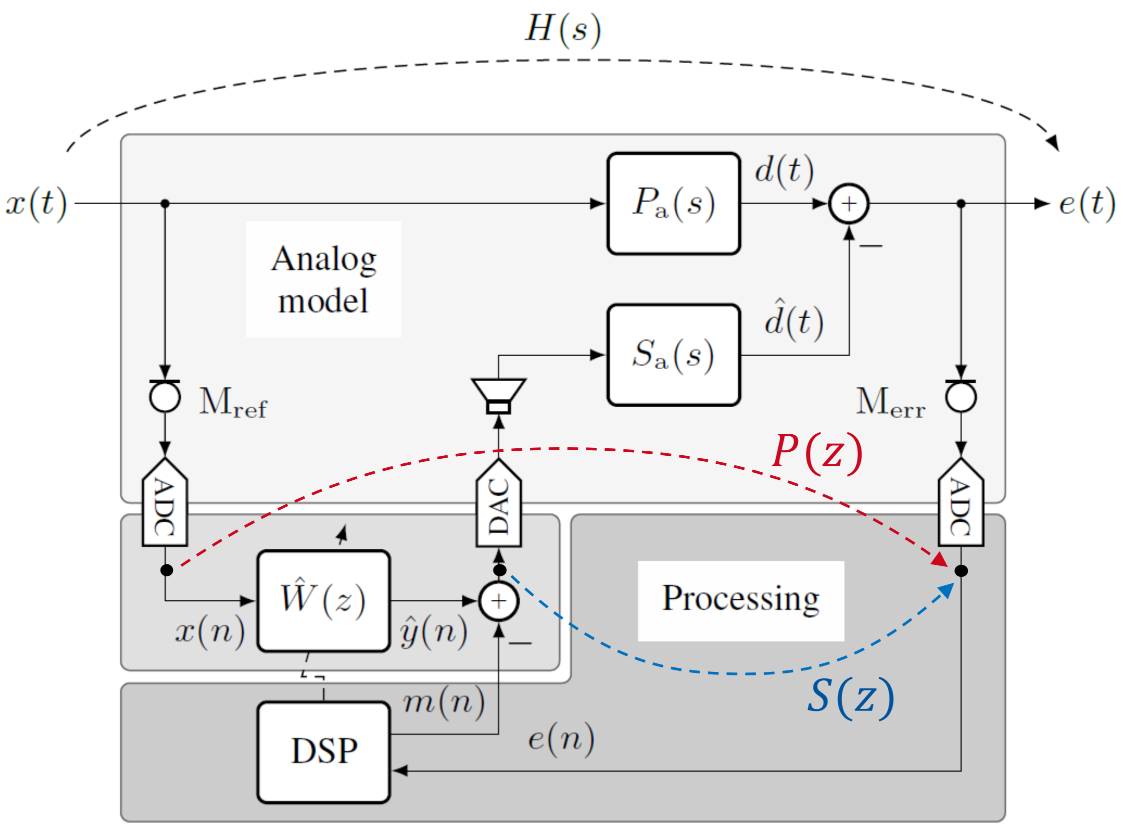

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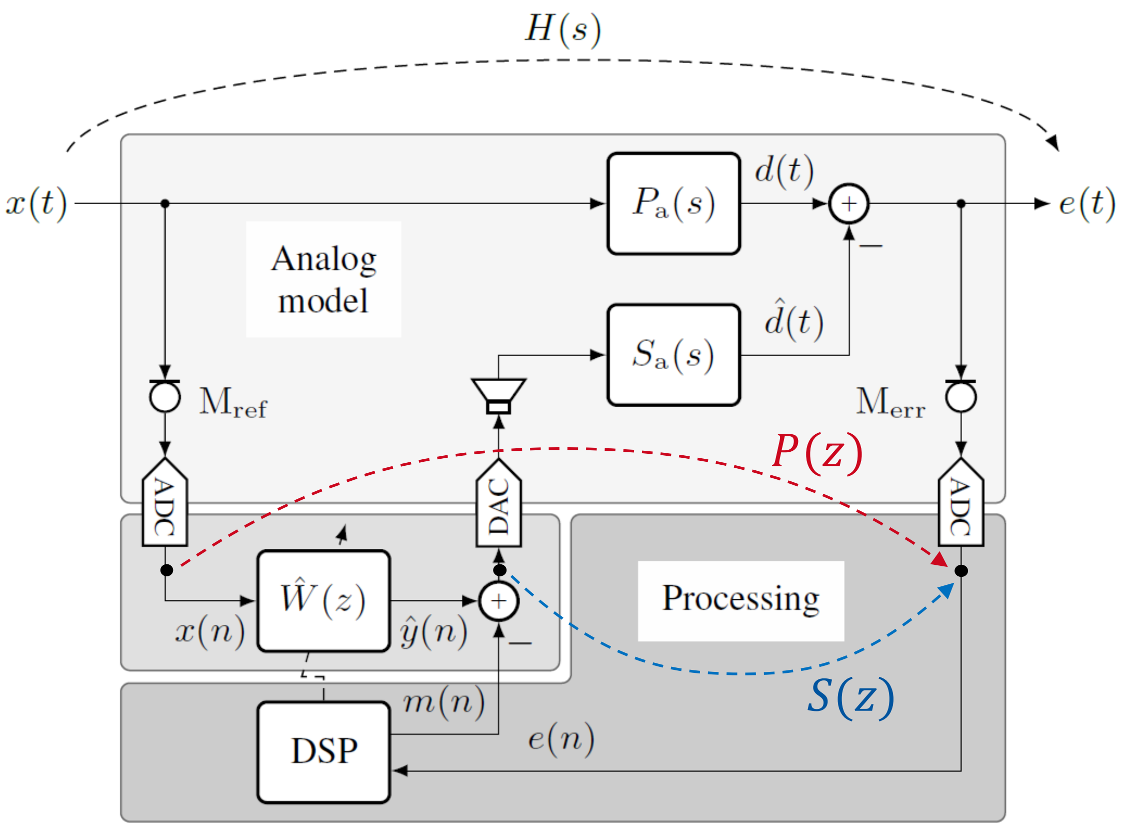

- Training set

$$\mathcal{T} = \{\boldsymbol{p}_j, \boldsymbol{s}_j \in \mathbb{R}^L \,|\, j = 1, \dots, J\}$$

of impulse responses

$$\boldsymbol{p} = [p(0), p(1), \dots, p(L-1)]^{\mathrm{T}}$$
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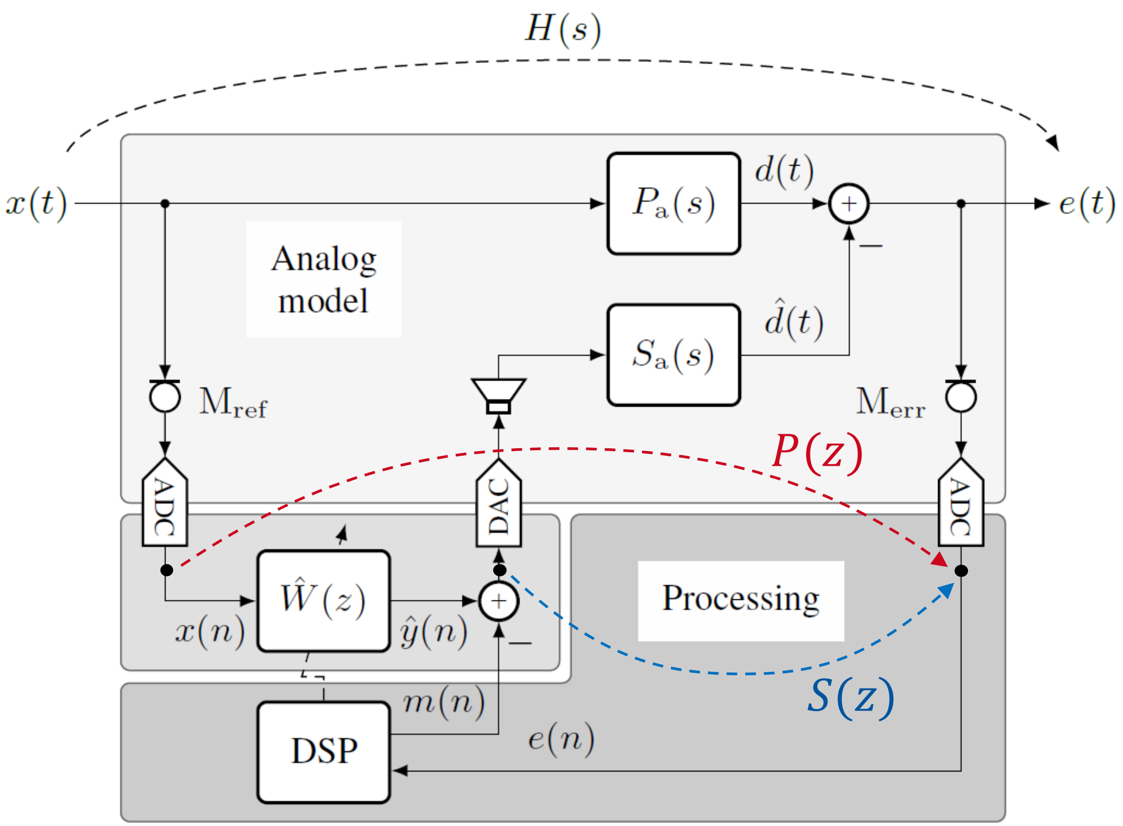
J Number of paths
L Filter length

Feed-forward ANC Filter Design



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$$\mathcal{C}_{\mathrm{w}} = \sum_{j \in \mathcal{T}} \left\| \boldsymbol{p}_j^0 - \underline{\boldsymbol{s}}_j \boldsymbol{w} \right\|^2$$

J Number of paths
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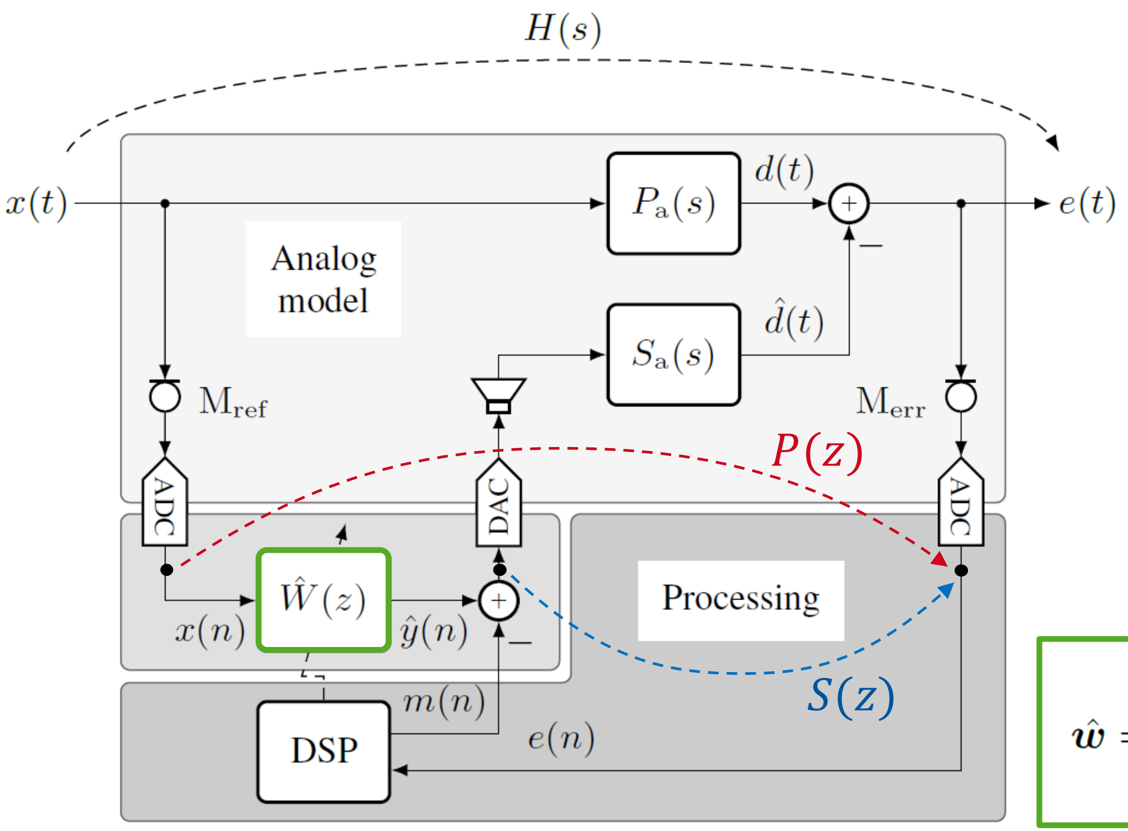
$\boldsymbol{p}^0$ Zero-padded prim. Path
$\underline{\boldsymbol{s}}$ Sec. path convolution matrix
$\hat{\boldsymbol{w}}$ ANC FIR filter

Introduction

Filter Design



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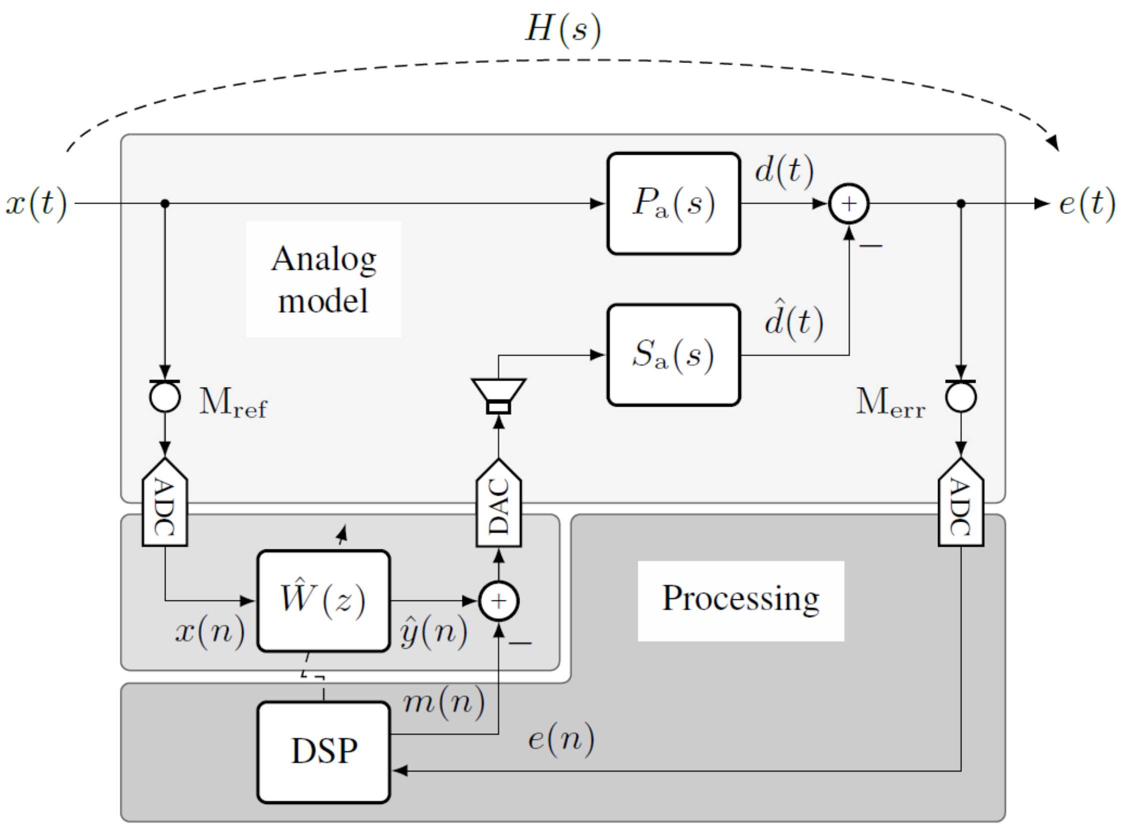
$$\hat{\boldsymbol{w}} = \arg\min_{\boldsymbol{w}} \mathcal{C}_{\mathrm{w}} = \left(\sum_{j \in \mathcal{T}} \underline{\boldsymbol{s}}_j^{\mathrm{T}} \underline{\boldsymbol{s}}_j \right)^{-1} \sum_{i \in \mathcal{T}} \underline{\boldsymbol{s}}_i^{\mathrm{T}} \boldsymbol{p}_i^0$$

J	Number of paths
L	Filter length
$\boldsymbol{p}^0$	Zero-padded prim. Path
$\underline{\boldsymbol{s}}$	Sec. path convolution matrix
$\hat{\boldsymbol{w}}$	ANC FIR filter

Motivation

Secondary Path Measurement



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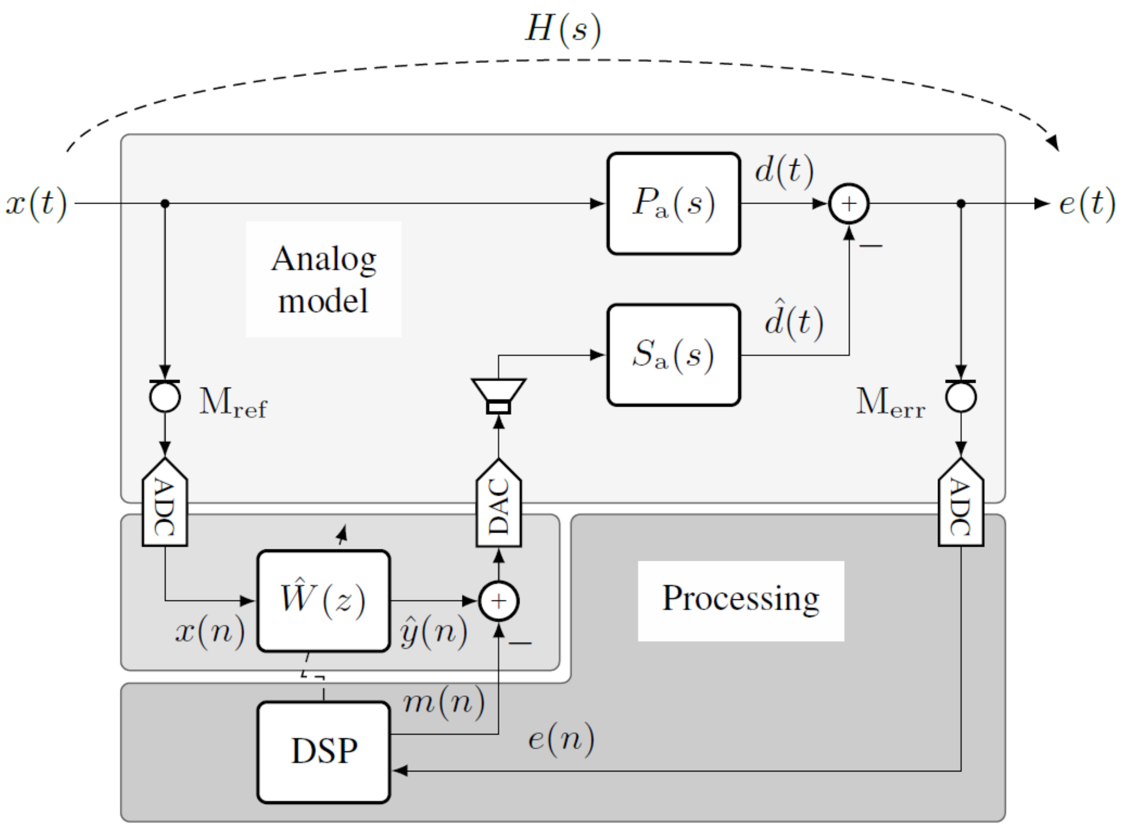


Filter design

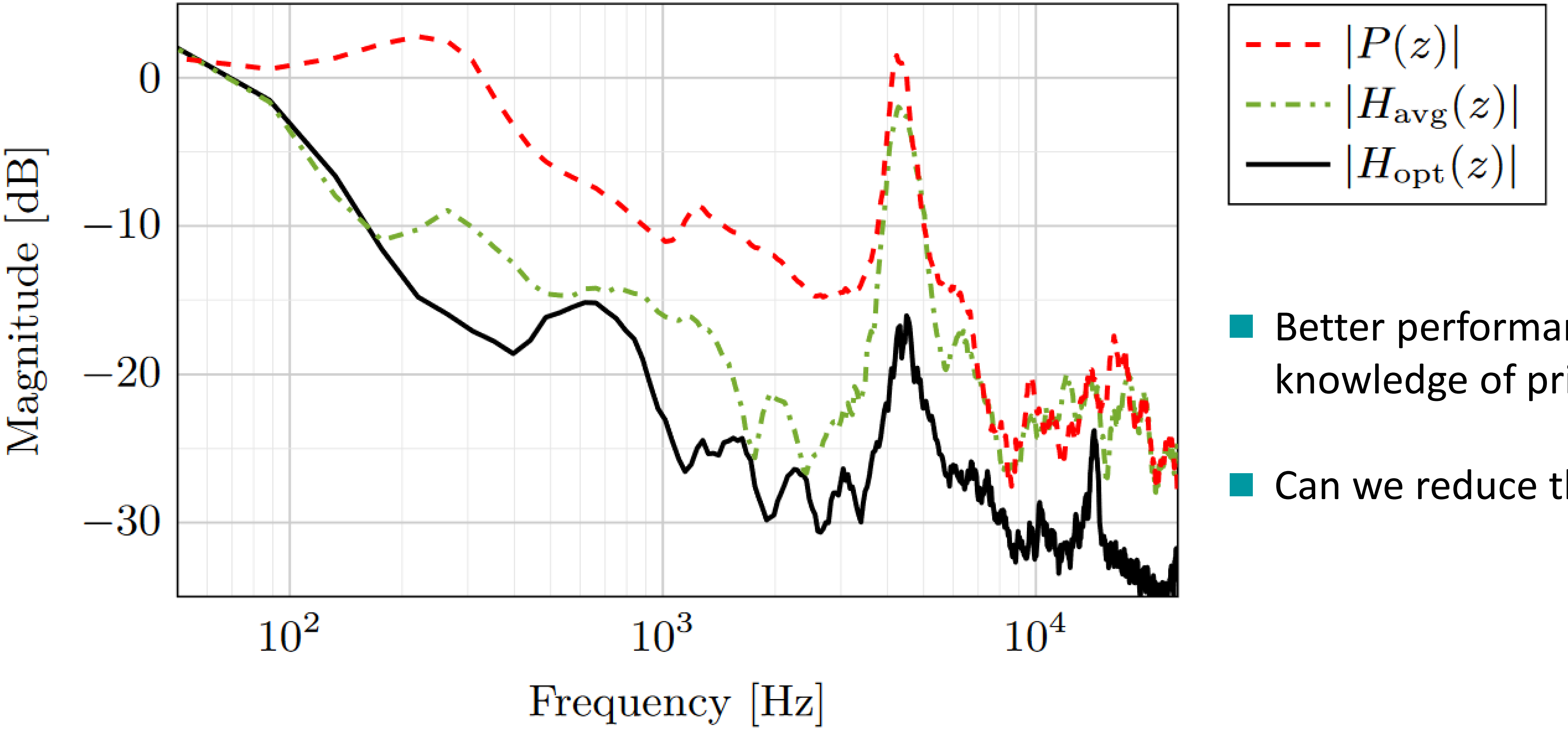
$$\hat{\boldsymbol{w}}_{\mathrm{avg}} = \left(\underline{\boldsymbol{s}}^{\mathrm{T}}\underline{\boldsymbol{s}}\right)^{-1}\underline{\boldsymbol{s}}^{\mathrm{T}}\overline{\boldsymbol{p}}^{0}$$

based on individual secondary path and averaged primary path

$$\overline{\boldsymbol{p}} = \frac{1}{J}\sum_{j\in\mathcal{J}}\boldsymbol{p}_j$$

Motivation

Median Individual Performance

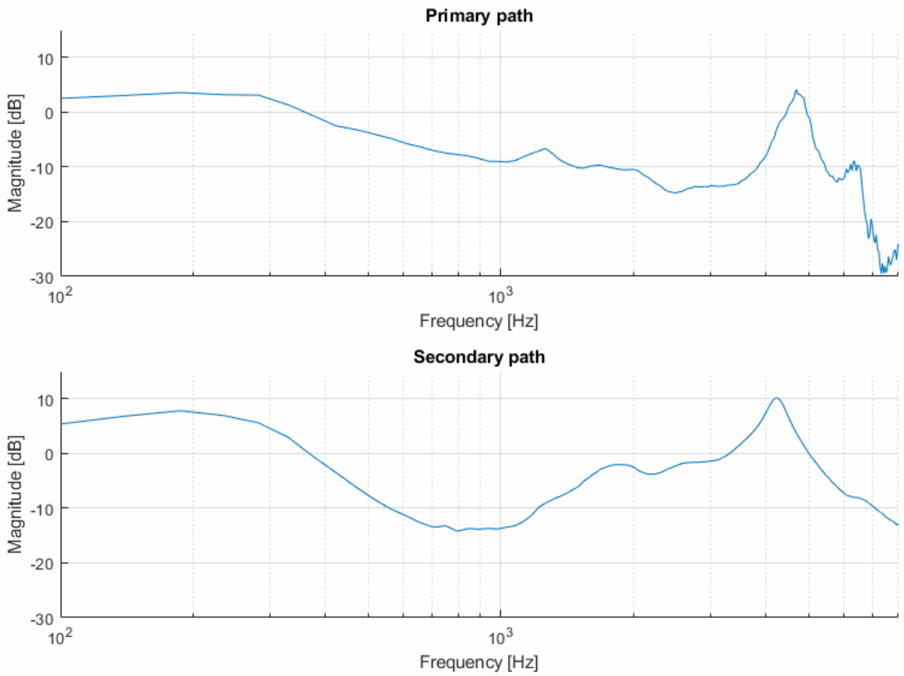


- Better performance for perfect knowledge of primary path
- Can we reduce the gap?

Motivation

Acoustic Paths

- Measurements of Bose QC20 for 25 subjects and different headphone fittings in anechoic chamber
- Strong coherence of primary and secondary paths in frequency domain



Primary Path Estimator

Goal

- Estimate primary path based on features from secondary path measurement

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Design Contrains

- Limited training data
  - Prevent overfitting
  - Ensure robustness
- Freq. regions of deterministic change

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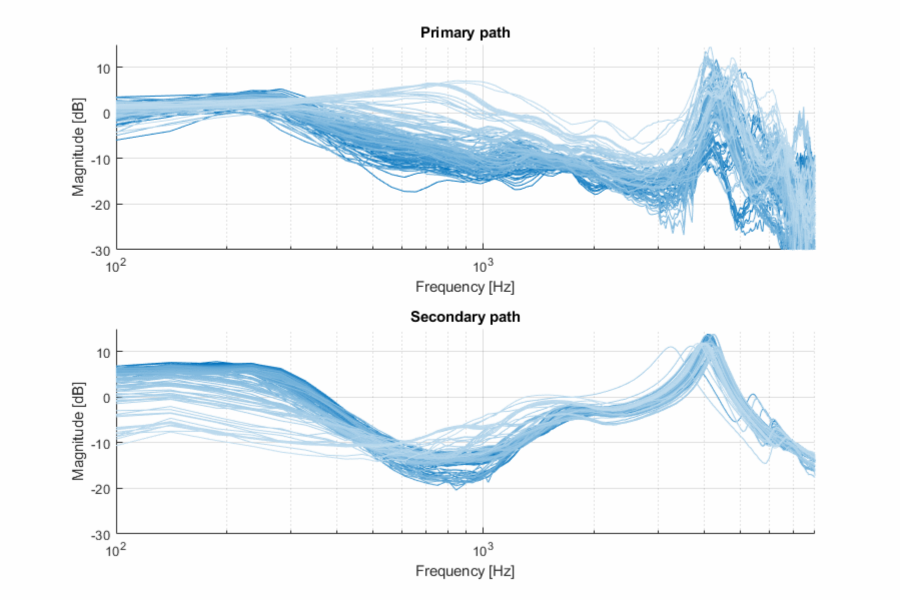

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- Extract freq. regions

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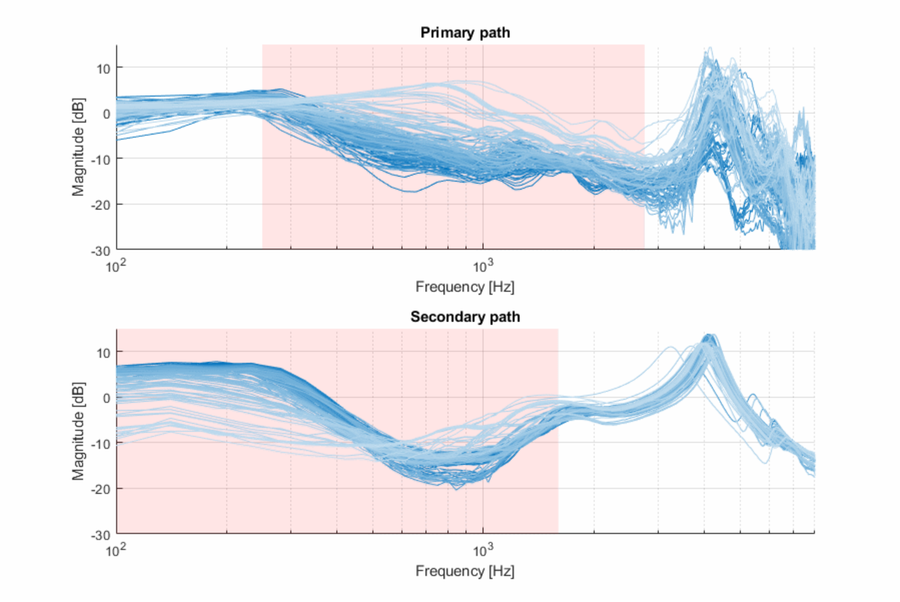


Design Contrains

- Limited training data → Perform dimensionality reduction
  - Prevent overfitting
  - Ensure robustness
  - Principal component analysis
- Freq. regions of deterministic change → Extract freq. regions

Primary Path Estimator

Training: Principal Component Analysis (PCA)

- Extract regions by applying frequency domain window

$$P_{\mathrm{q}}(z) = Q_{\mathrm{p}}(z)P(z)$$
$$S_{\mathrm{q}}(z) = Q_{\mathrm{s}}(z)S(z)$$

- Perform PCA and dimensionality reduction on single-sided frequency domain vectors $\boldsymbol{P}_{\mathrm{q},j}, \boldsymbol{S}_{\mathrm{q},j} \in \mathcal{T}$
- With $\hat{\boldsymbol{P}}_{\mathrm{q},j} = \overline{\boldsymbol{P}}_{\mathrm{q}} + \underline{\boldsymbol{U}}_{\mathrm{p}} \boldsymbol{g}_{\mathrm{p},j}$ obtain PCA gain vector by utilizing orthogonality of components

$$\boldsymbol{g}_{\mathrm{p},j} = \underline{\boldsymbol{U}}_{\mathrm{p}}^{\mathrm{H}} \left(\boldsymbol{P}_{\mathrm{q},j} - \overline{\boldsymbol{P}}_{\mathrm{q}}\right)$$

and analogously for secondary path

Primary Path Estimator

Training: Linear Mapping

- Find matrix $\underline{\boldsymbol{a}} \in \mathbb{C}^{K_\mathrm{p} \times K_\mathrm{s}}$ that linearly maps secondary path PCA gains to primary path PCA gains
- Least squares cost function

$$\mathcal{C}_\mathrm{a} = \sum_{j \in \mathcal{T}} \left\| \tilde{\boldsymbol{g}}_{\mathrm{p},j} - \underline{\boldsymbol{a}} \tilde{\boldsymbol{g}}_{\mathrm{s},j} \right\|^2 \longrightarrow \hat{\underline{\boldsymbol{a}}} = \arg\min_{\underline{\boldsymbol{a}}} \mathcal{C}_\mathrm{a} = \sum_{j \in \mathcal{T}} \tilde{\boldsymbol{g}}_{\mathrm{p},j} \tilde{\boldsymbol{g}}_{\mathrm{s},j}^\mathrm{H} \left(\sum_{i \in \mathcal{T}} \tilde{\boldsymbol{g}}_{\mathrm{s},j} \tilde{\boldsymbol{g}}_{\mathrm{s},j}^\mathrm{H} \right)^{-1}$$

- Estimate primary path PCA gain

$$\hat{\boldsymbol{g}}_\mathrm{p} = \overline{\boldsymbol{g}}_\mathrm{p} + \underline{\boldsymbol{a}} \boldsymbol{g}_\mathrm{s}$$

Primary Path Estimator

Application summary

1. Measure individual secondary path
2. Calculate windowed single-sided frequency domain vector $S_{\mathrm{q}}(z) = Q_{\mathrm{s}}(z)S(z)$
3. Calculate secondary path PCA gain and estimate primary path PCA gain $\hat{\boldsymbol{g}}_{\mathrm{p}} = \overline{\boldsymbol{g}}_{\mathrm{p}} + \underline{\boldsymbol{a}}\boldsymbol{g}_{\mathrm{s}}$
4. Calculate primary path estimate $\hat{\boldsymbol{P}} = \overline{\boldsymbol{P}} + \underline{\boldsymbol{U}}_{\mathrm{p}}\hat{\boldsymbol{g}}_{\mathrm{p}}$
5. Design feed-forward filter using individual primary and secondary path

Evaluation

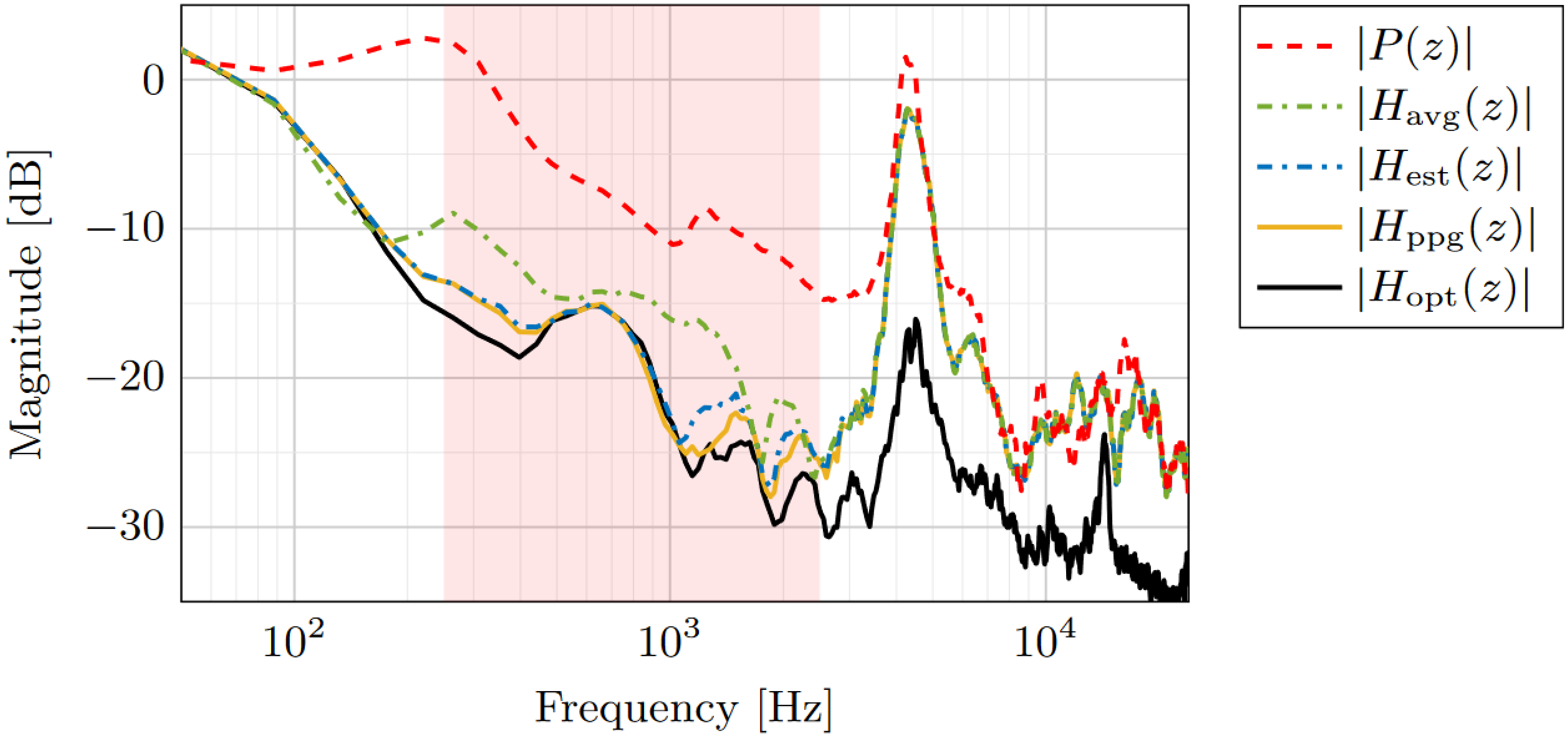
Settings

- Set $\mathcal{M}$ of $J = 173$ acoustic paths pairs for 25 subjects and different fittings
- Split $\mathcal{M}$ randomly into training subset $\mathcal{T}$ and validation subset $\mathcal{V}$
  - $\mathcal{T}$ contains 80% of $\mathcal{M}$
  - $\mathcal{V}$ contains remaining 20% of $\mathcal{M}$
- Train estimator based on $\mathcal{T}$ and evaluate transfer function $H(z)$ for $\mathcal{V}$
- Repeat for 100 iterations

Length of acoustic paths: $L = 1024$
Length of feed-forward filter: $L_w = 64$
Sample rate: $f_s = 48$ kHz
Number of prim. path comp.: $K_\mathrm{p} = 1$
Number of sec. path comp.: $K_\mathrm{s} = 3$

Evaluation

Median Individual Performance



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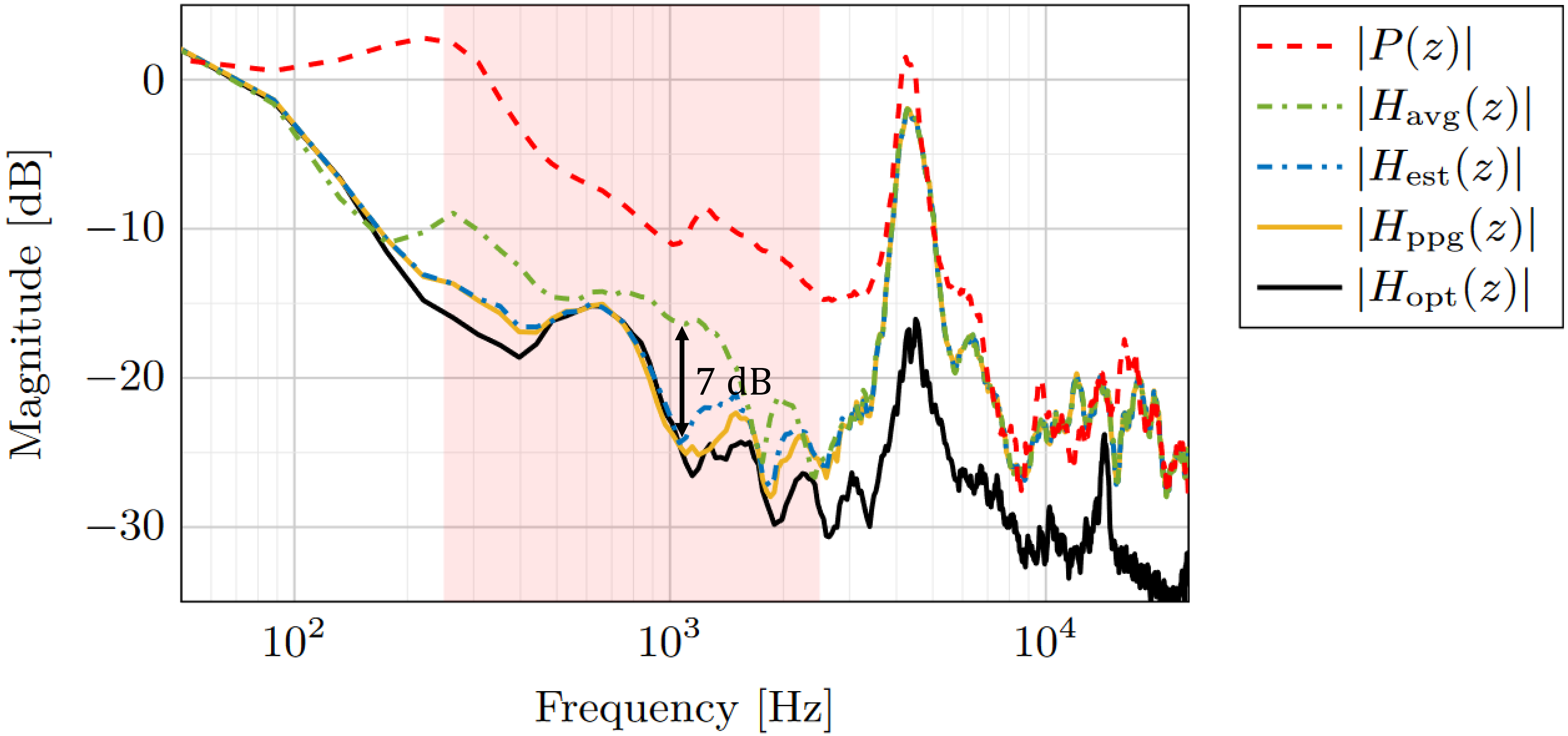

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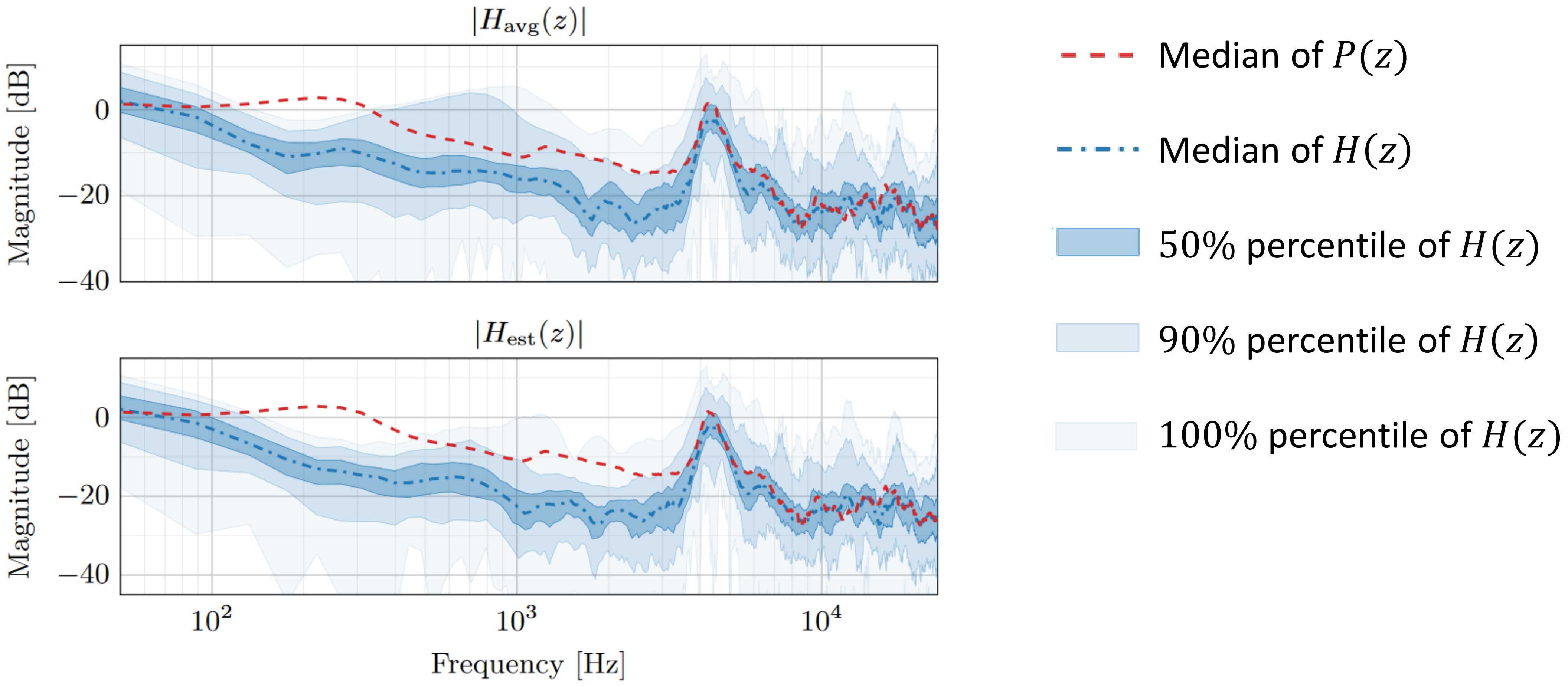
Uncertainty

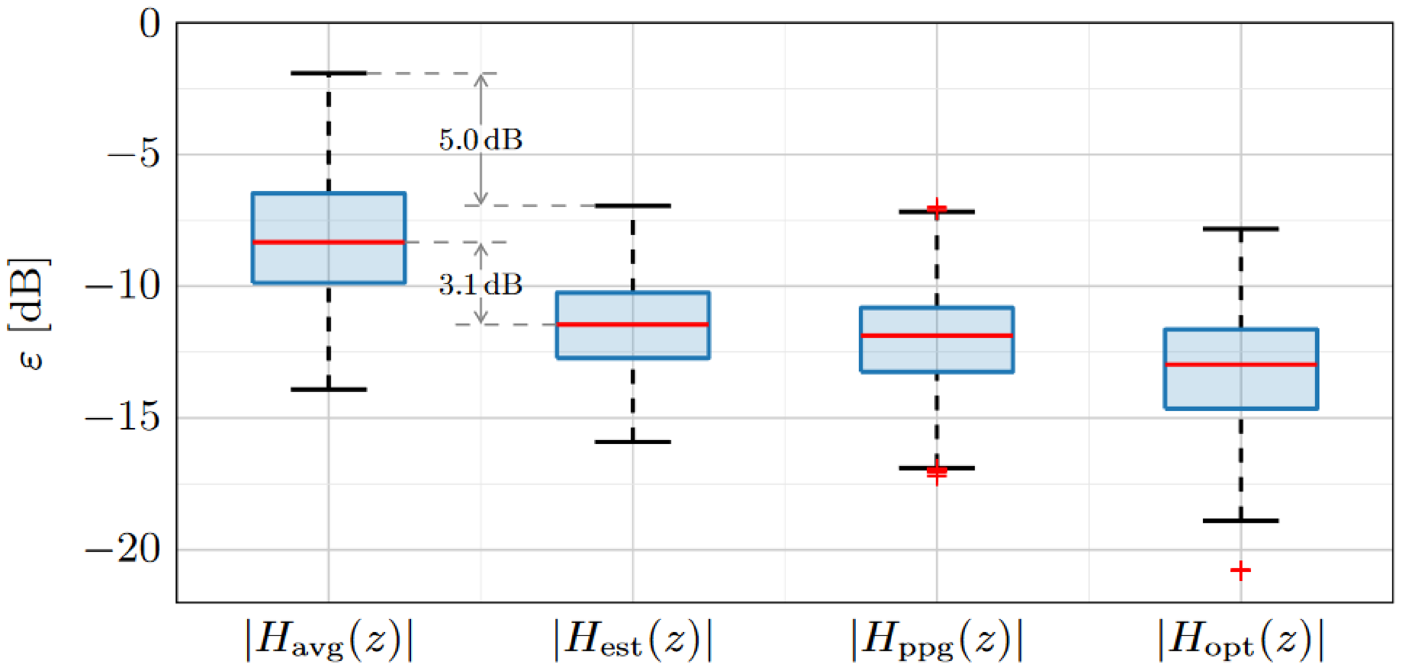


Evaluation

Uncertainty

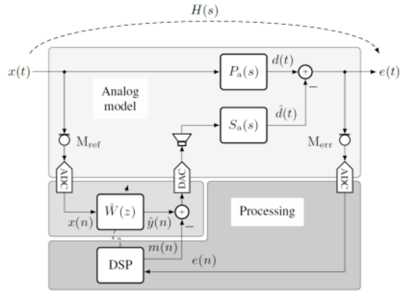
- Attenuation in deterministic region of primary path

- $$\varepsilon_j = \frac{\oint |H_{\mathrm{q},j}(z)|^2 \,\mathrm{d}z}{\oint |P_{\mathrm{q},j}(z)|^2 \,\mathrm{d}z}$$



Conclusion

- Primary path estimator for individualization of ANC



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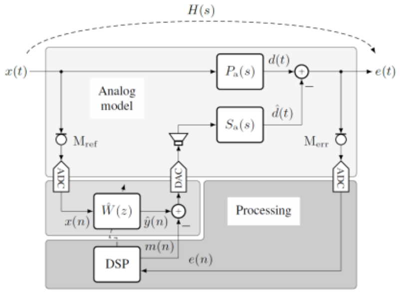
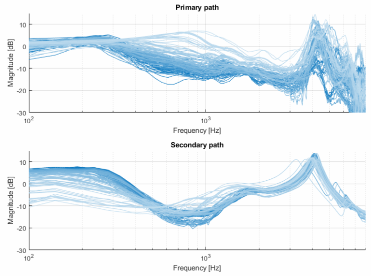
- Based on features from secondary path measurement





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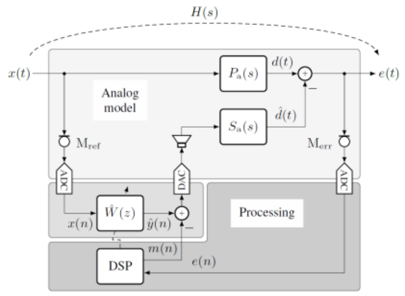

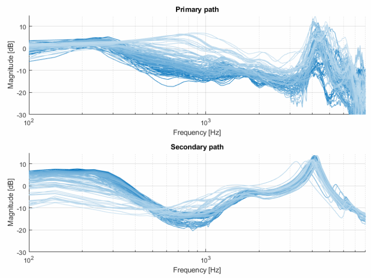

Conclusion

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- Based on features from secondary path measurement
- Requires training stage
- Simulations show increased robustness of ANC