Comparison of Parameter Estimation Methods for Single-Microphone Multi-Frame Wiener Filtering

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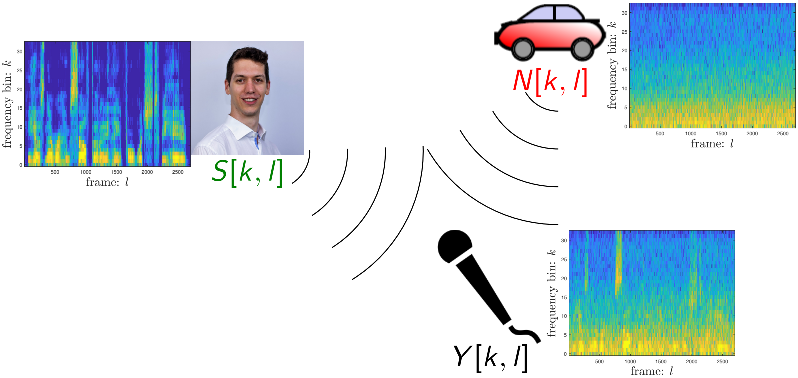
05 September 2019

The work and travel costs were funded by the **DEGA Young Scientist Grant**, the **Deutsche Forschungsgemeinschaft** (DFG, German Research Foundation) - Projektnummer 352015383 - SFB 1330 B2, and Cluster of Excellence 1077 **Hearing4all**

Scenario

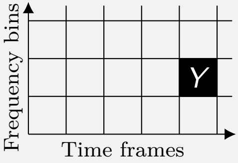


Recorded signal consists of speech and additive noise

$$\boxed{Y[k,l] = S[k,l] + N[k,l]}$$

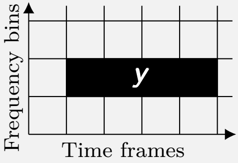
Assumption: speech and noise are uncorrelated with eachother

Single-Frame Signal Model



Assumption: speech and noise are uncorrelated over time frames

Multi-Frame Signal Model



Assumption: speech is correlated over time frames [1]

[1] J. Benesty, J. Chen, and E. A. P. Habets, Speech enhancement in the STFT domain. Springer Science & Business Media, 2011.

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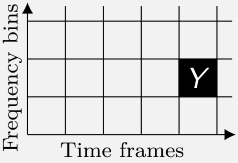


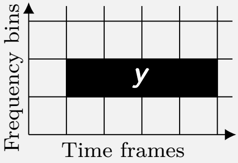
Signal Model

$$Y = S + N$$

Estimate speech

$$\hat{S} = HY$$

Multi-Frame Signal Model



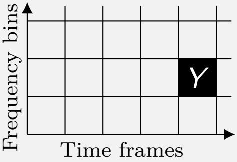
Signal Model

$$\boldsymbol{y} = \boldsymbol{s} + \boldsymbol{n}$$

Estimate speech

$$\hat{S} = \boldsymbol{h}^H \boldsymbol{y}$$

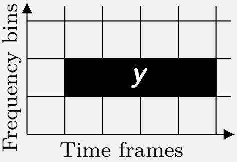
Single-Frame Signal Model



Typical parameters

- Frame length: 16 - 32 ms
- Overlap: 50 %

Multi-Frame Signal Model



Typical parameters

- Frame length: 4 - 8 ms
- Overlap: $\geq$ 75 %
- Vector length: 6 - 24 ms

Multi-Frame Signal Model

- Decomposition of speech vector $\boldsymbol{s}$ [2]

$$\boxed{\boldsymbol{s} = \underbrace{\gamma_{\boldsymbol{s}} S}_{\text{correlated speech}} + \underbrace{\boldsymbol{x}'}_{\text{uncorrelated speech}}}$$

with normalized correlated speech vector

$$\gamma_{\boldsymbol{s}} = \frac{\mathbb{E}[\boldsymbol{s} S^*]}{\mathbb{E}[|S|^2]} = \frac{\boldsymbol{r}_{\boldsymbol{s}}}{\phi_S}$$

[2] Y. Huang and J. Benesty, "A multi-frame approach to the frequency-domain single-channel noise reduction problem," IEEE TASLP, vol. 20, no. 4, pp. 1256–1269, May 2012.

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- Multi-frame signal model

$$\boxed{\boldsymbol{y} = \boldsymbol{\gamma_s} S + \underbrace{\boldsymbol{x}' + \boldsymbol{n}}_{\text{undesired: } \boldsymbol{u}}}$$

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Muti-Frame Wiener Filter (MFWF)

- Cost-Function

$$\boldsymbol{h}^{\mathrm{MFWF}} = \underset{\boldsymbol{h}}{\operatorname{argmin}} \left\{ \mathbb{E}\left[|\boldsymbol{h}^H \boldsymbol{y} - S|^2 \right] \right\}$$

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- MFWF solution [2],[3]

$$\boxed{\begin{aligned} \boldsymbol{h}^{\mathrm{MFWF}} &= \boldsymbol{R}_{\boldsymbol{y}}^{-1} \boldsymbol{\gamma}_{\boldsymbol{s}} \phi_S \\ &= \underbrace{\frac{\boldsymbol{R}_{\boldsymbol{y}}^{-1} \boldsymbol{\gamma}_{\boldsymbol{s}}}{\boldsymbol{\gamma}_{\boldsymbol{s}}^H \boldsymbol{R}_{\boldsymbol{y}}^{-1} \boldsymbol{\gamma}_{\boldsymbol{s}}}}_{\text{MF-MPDR}} \; \underbrace{\frac{\phi_S}{\phi_Y^{\mathrm{out}}}}_{\text{postfilter}} \end{aligned}}$$

Noisy correlation matrix: $\boldsymbol{R}_{\boldsymbol{y}} = \mathbb{E}[\boldsymbol{y}\boldsymbol{y}^H]$
Output noisy PSD: $\phi_Y^{\mathrm{out}} = (\boldsymbol{\gamma}_{\boldsymbol{s}}{}^H \boldsymbol{R}_{\boldsymbol{y}}^{-1} \boldsymbol{\gamma}_{\boldsymbol{s}})^{-1}$
Distortionless assumption: $\phi_S = \phi_S^{\mathrm{out}}$

[2] Y. Huang and J. Benesty, "A multi-frame approach to the frequency-domain single-channel noise reduction problem," IEEE TASLP, vol. 20, no. 4, pp. 1256–1269, May 2012.
[3] D. Fischer and T. Gerkmann, "Single-microphone speech enhancement using MVDR filtering and Wiener post-filtering," in Proc. IEEE ICASSP, Shanghai, China, Mar. 2016, pp. 201–205.

Parameter Estimation

$$\boxed{\boldsymbol{h}^{\mathrm{MFWF}} = \underbrace{\frac{\boldsymbol{R}_{\boldsymbol{y}}^{-1}\boldsymbol{\gamma}_{\boldsymbol{s}}}{\boldsymbol{\gamma}_{\boldsymbol{s}}^{H}\boldsymbol{R}_{\boldsymbol{y}}^{-1}\boldsymbol{\gamma}_{\boldsymbol{s}}}}_{\text{MF-MPDR}} \underbrace{\frac{\phi_S}{\phi_Y^{\mathrm{out}}}}_{\text{postfilter}}}$$

2 parameters to estimate in MF-MPDR filter

- Noisy correlation matrix $\boldsymbol{R}_{\boldsymbol{y}}$
  (2 existing approaches)
- Normalized speech correlation vector $\boldsymbol{\gamma}_{\boldsymbol{s}}$
  (2 existing approaches + 1 proposed approach)

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2 parameters to estimate in postfilter *(refer to paper)*

- Speech PSD ϕ_S
- Noisy output PSD ϕ_Y^{out}

Parameter Estimation for MF-MPDR

2 existing approaches to estimate either $\boldsymbol{R_y}$ or $\boldsymbol{\gamma_s}$

- **Direct**: estimate correlation $\hat{\boldsymbol{r}}$ in main filterbank
- **Indirect**: Wiener Khinchin based estimation of correlation [4]

$$\boxed{\text{IDFT of PSD } \hat{\phi} \text{ is correlation } \hat{\boldsymbol{r}}}$$

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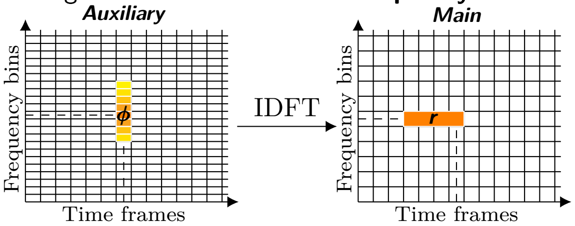
2 STFT filterbanks used for parameter estimation:

- ***Auxiliary***: high time resolution & **high frequency resolution**
- ***Main***: high time resolution & **low frequency resolution**



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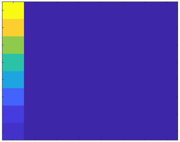

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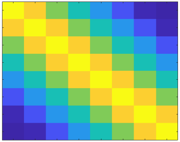

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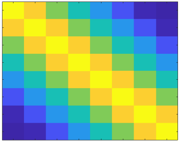

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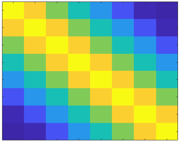

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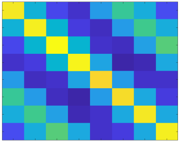

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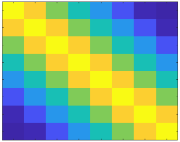

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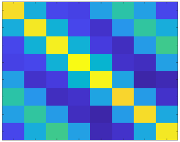

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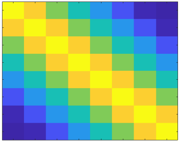

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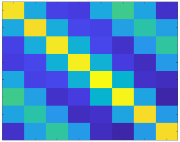

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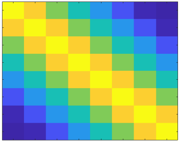

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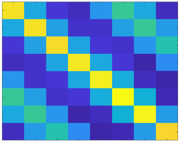

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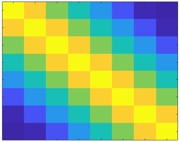

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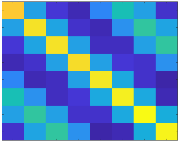

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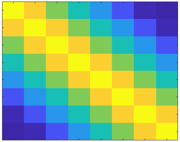

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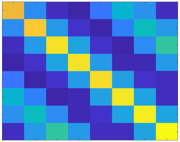

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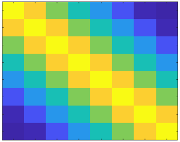

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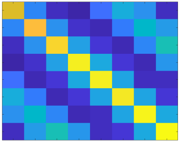

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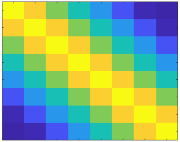

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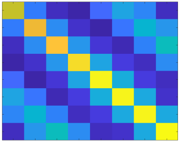

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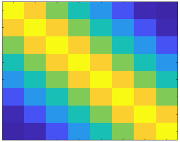

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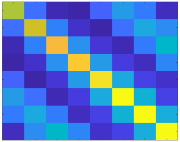

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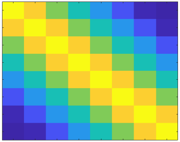

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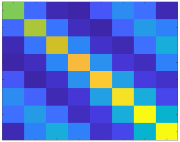

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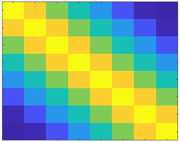

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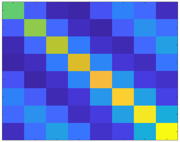

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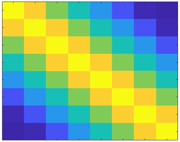

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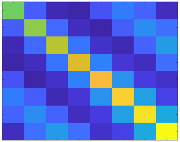

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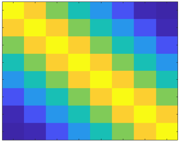

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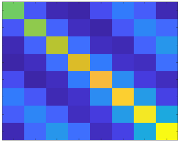

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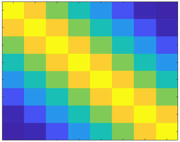

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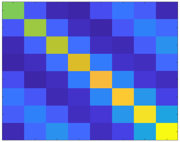

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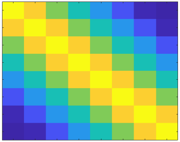

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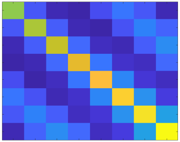

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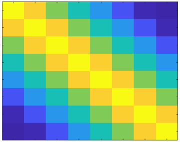

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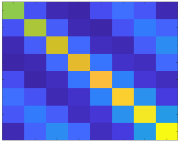

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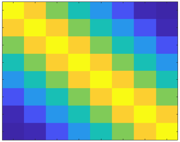

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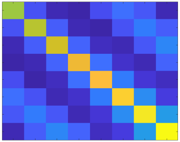

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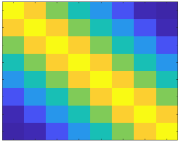

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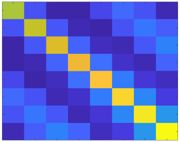

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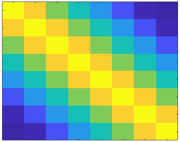

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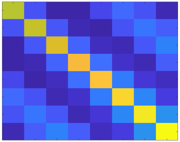

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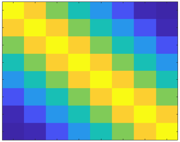

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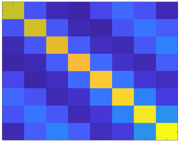

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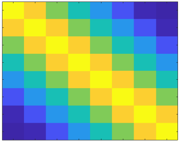

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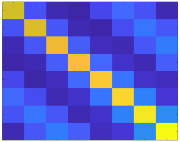

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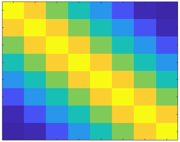

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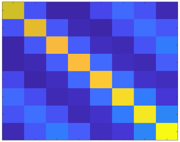

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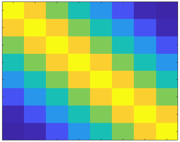

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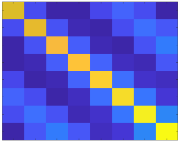

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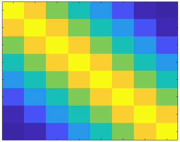

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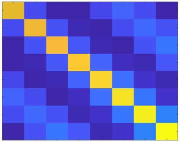

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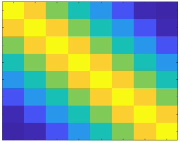

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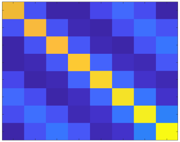

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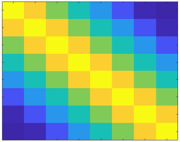

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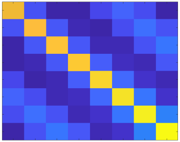

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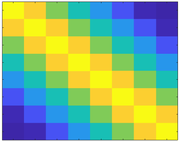

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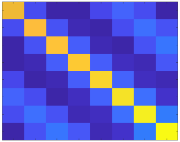

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Proposed method:

3. **Combined**: using indirectly estimated (***time-varying***) noise correlation vector estimate $\hat{\boldsymbol{\gamma}}_{\boldsymbol{n}}$

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- Speech material: 176 s (92 s female, 84 s male) from TIMIT database [6]
- 5 noise signals: babble, white Gaussian noise (WGN), traffic, modulated WGN, crossroad noise
- SNRs: 0, 5, 10 dB

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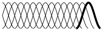
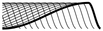
Main	1 ms	4 ms 
Auxiliary	1 ms	16 ms 

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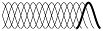
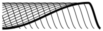
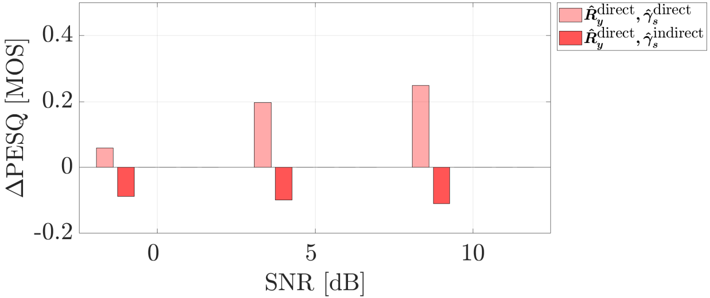
Main	1 ms	4 ms 
Auxiliary	1 ms	16 ms 

- Length of correlation vectors and matrices: 8 frames (corresponding to 11 ms of data)
- Speech quality measured using PESQ improvement over noisy signal, using clean speech as reference [7]

[6] J. S. Garofolo, "DARPA TIMIT acoustic-phonetic speech database," in NIST, 1988.
[7] "ITU-T recommendation P.862. Perceptual evaluation of speech quality (PESQ): an objective method for end-to-end speech quality assessment of narrow-band telephone networks and speech codecs," Feb. 2001.

Evaluation of MF-MPDR Filter



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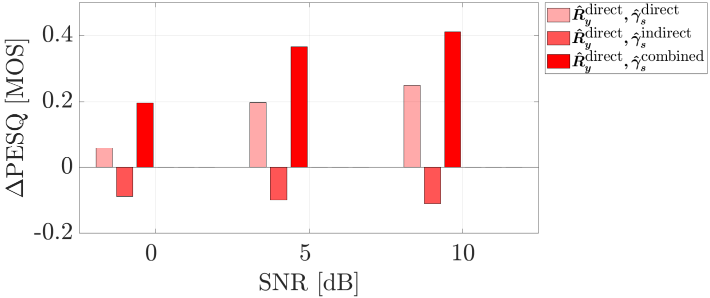

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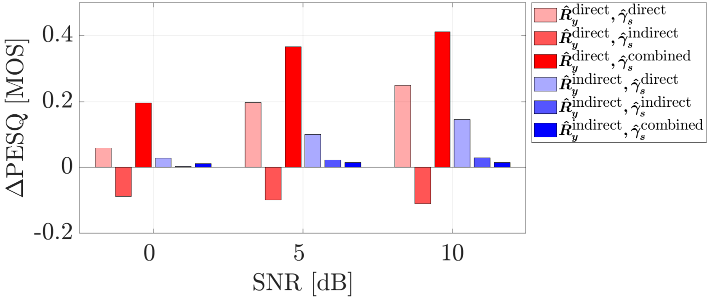

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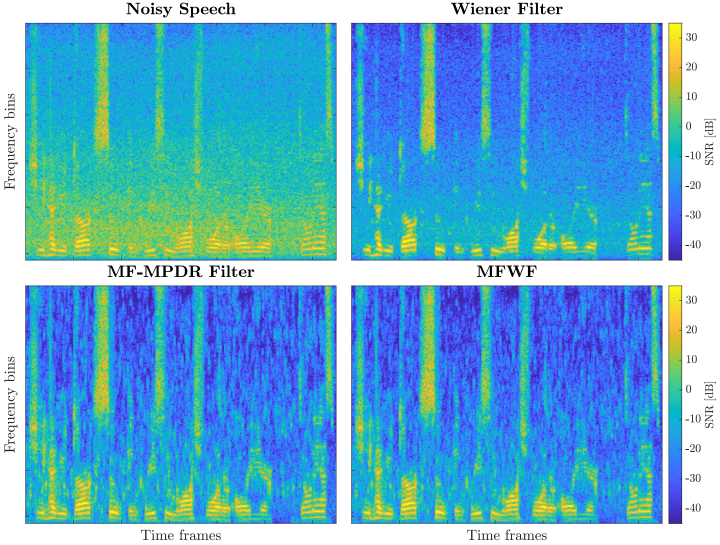

Speech: ☐ Noisy: ☐ WF: ☐ MF-MPDR Filter: ☐ MFWF: ☐

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- Applying a Wiener postfilter ***can*** further improve speech quality *(refer to paper)*