Beamformer with Post-filter in a Diffuse Noise Field

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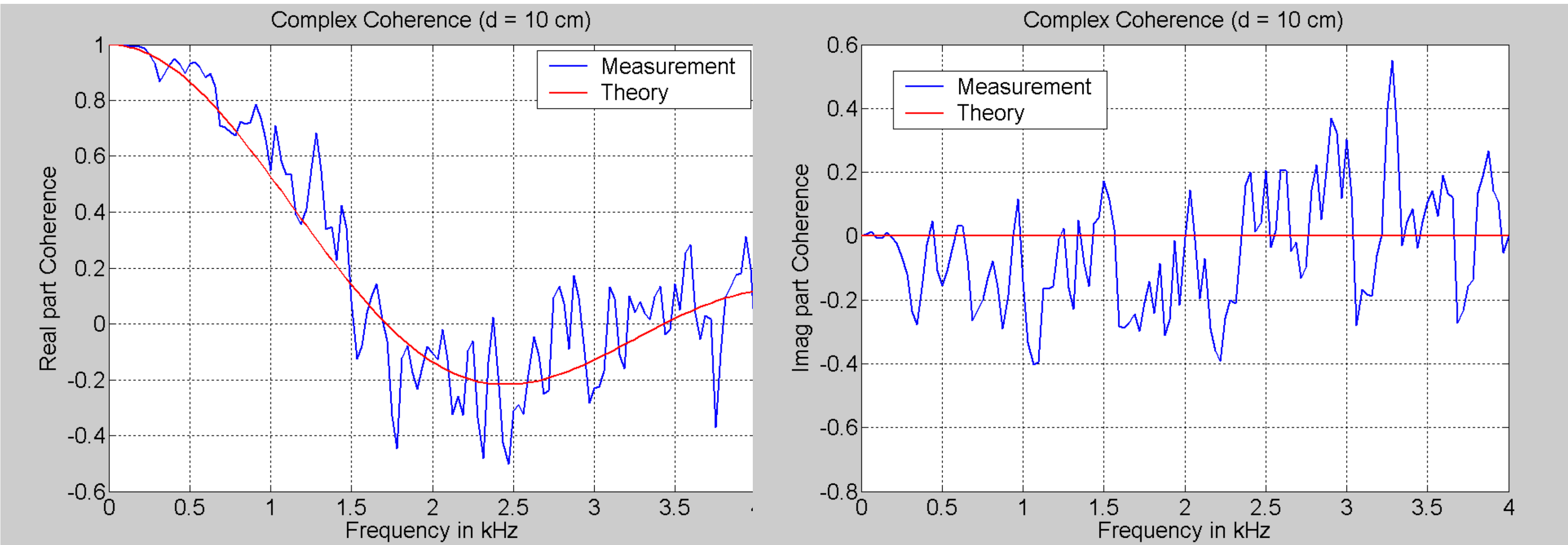
Outline:

1. Problem & Motivation
2. Optimal Solution
3. Real-World Solutions
4. Simulations and Results
5. Conclusion

Problem & Motivation

- Typical noise fields in rooms have
  - Diffuse characteristic (Coherence = si-function)

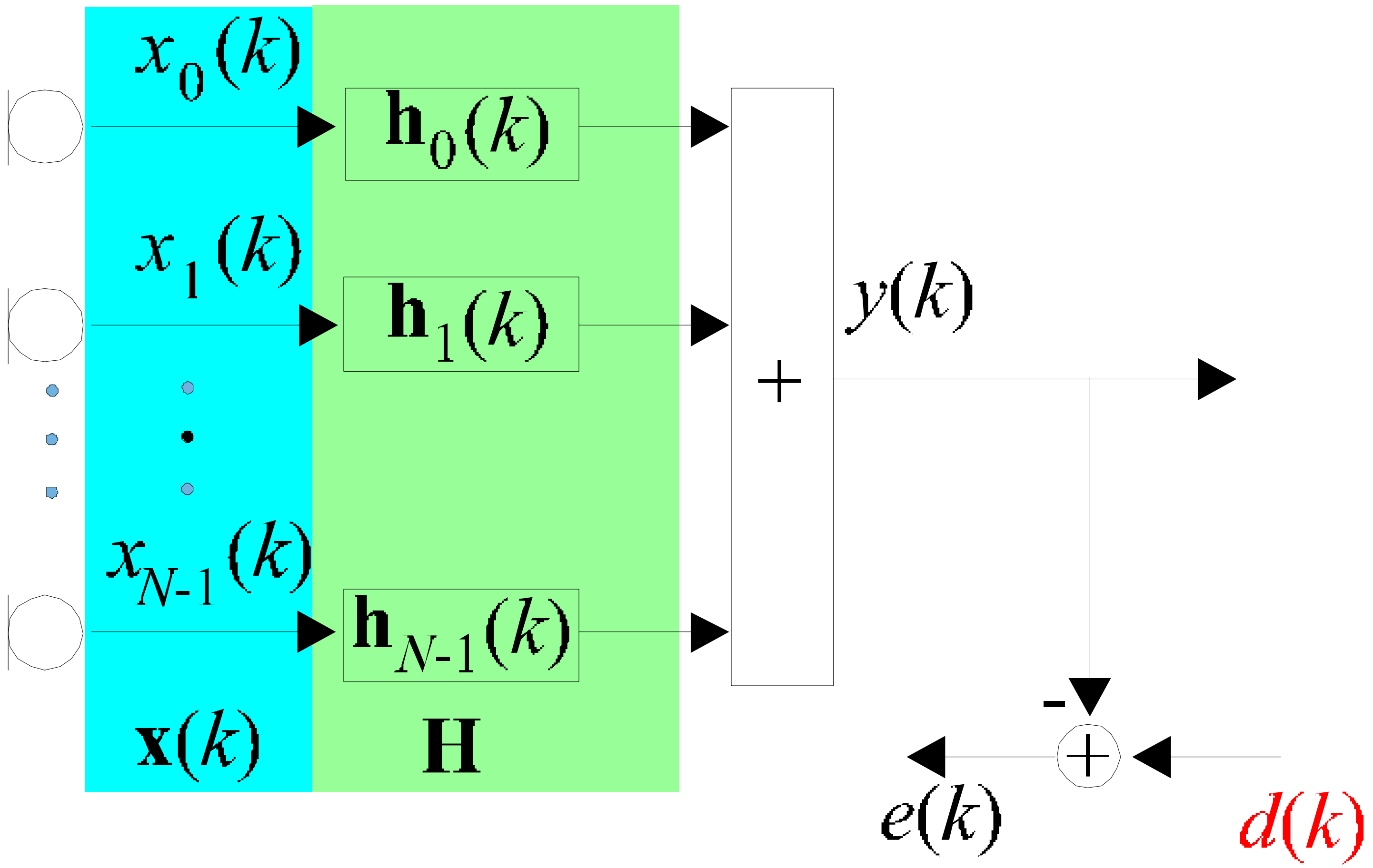


  - Low-pass characteristic

➔Problem: Reduction is very difficult for this kind of noise

Optimal Solution (MMSE)

Signal Model



Optimal Solution (MMSE)

- General solution is the multi-channel Wiener-Filter

$$\mathbf{H}(e^{j\omega}) = \mathbf{\Phi}^{-1}{}_{XX}(e^{j\omega})\mathbf{\Phi}_{XD}(e^{j\omega})$$

$\mathbf{\Phi}_{XX}(e^{j\omega})$ = PSD Matrix of the input signals

$\mathbf{\Phi}_{XD}(e^{j\omega})$ = Cross PSD vector between the input and the desired signal

- This can be decomposed into a single-channel Wiener-Filter and an MVDR-Beamformer

$$\mathbf{H}(e^{j\omega}) = \underbrace{\frac{\phi_{SS}(e^{j\omega})}{\phi_{SS}(e^{j\omega}) + \phi_{NN}(e^{j\omega})}}_{\text{Wiener-Filter}} \underbrace{\frac{\mathbf{\Phi}^{-1}{}_{NN}(e^{j\omega})\mathbf{d}}{\mathbf{d}^H \mathbf{\Phi}^{-1}{}_{NN}(e^{j\omega})\mathbf{d}}}_{\text{MVDR-Beamformer}}$$

Optimal MVDR-Beamformer in a diffuse noise field

- Insert the coherence matrix $\Gamma_{NN}(\omega)$ for a diffuse noise field

$$\Gamma_{N_1 N_2}(\omega) = \frac{\sin(\omega d_{12} / c)}{\omega d_{12} / c}$$

into the design equation

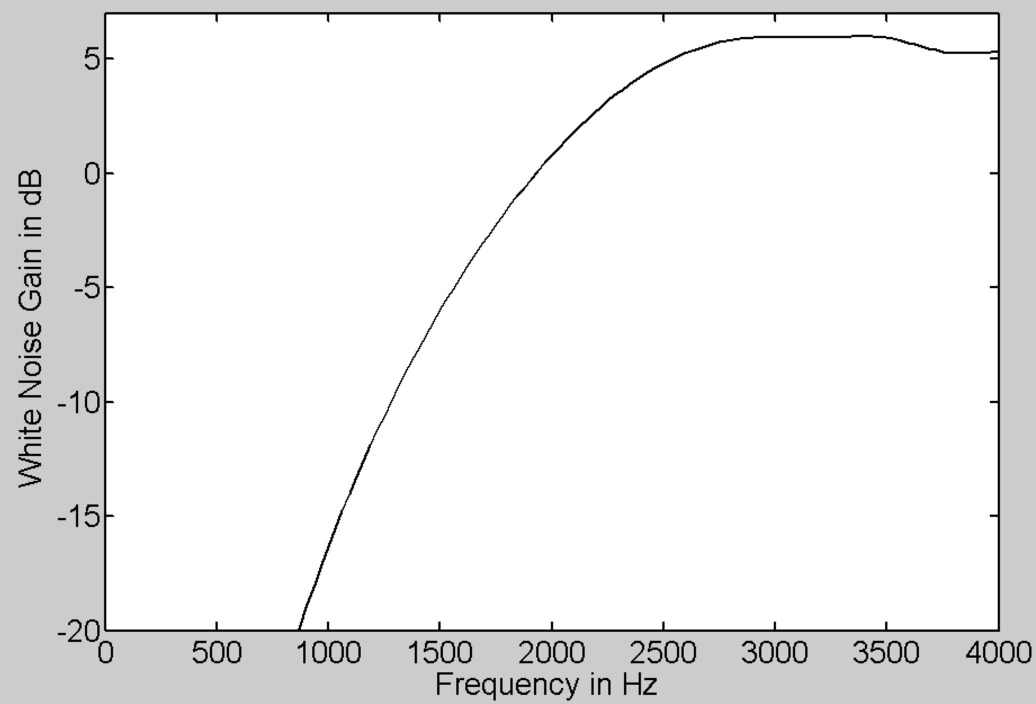
$$\mathbf{H}(\omega) = \frac{\Gamma^{-1}{}_{NN}(\omega)\mathbf{d}}{\mathbf{d}^H \Gamma^{-1}{}_{NN}(\omega)\mathbf{d}}$$

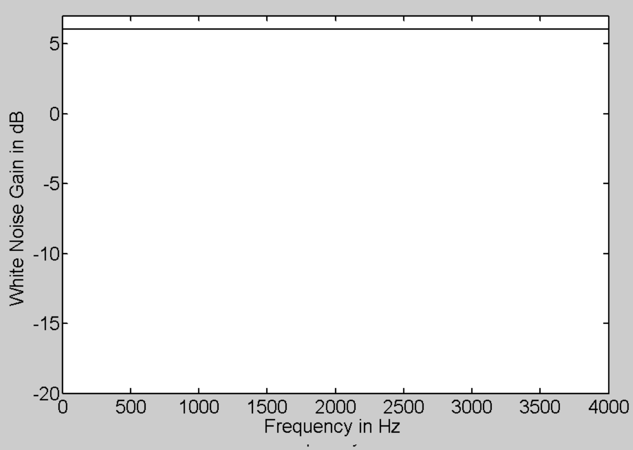
$\mathbf{d}$ = propagation vector

➔ Superdirective Beamformer

Analysis of the Superdirective Beamformer

- N = 4, d = 5cm, Endfire direction
- Typical measures of beamformer efficiency are:
  1. Beam-Pattern
  2. Directivity Index
  3. White Noise Gain





For comparison Delay and Sum Beamformer

Real-World Algorithms

- Constrain the white noise gain

➔ Optimal solution for the theortically defined noise field

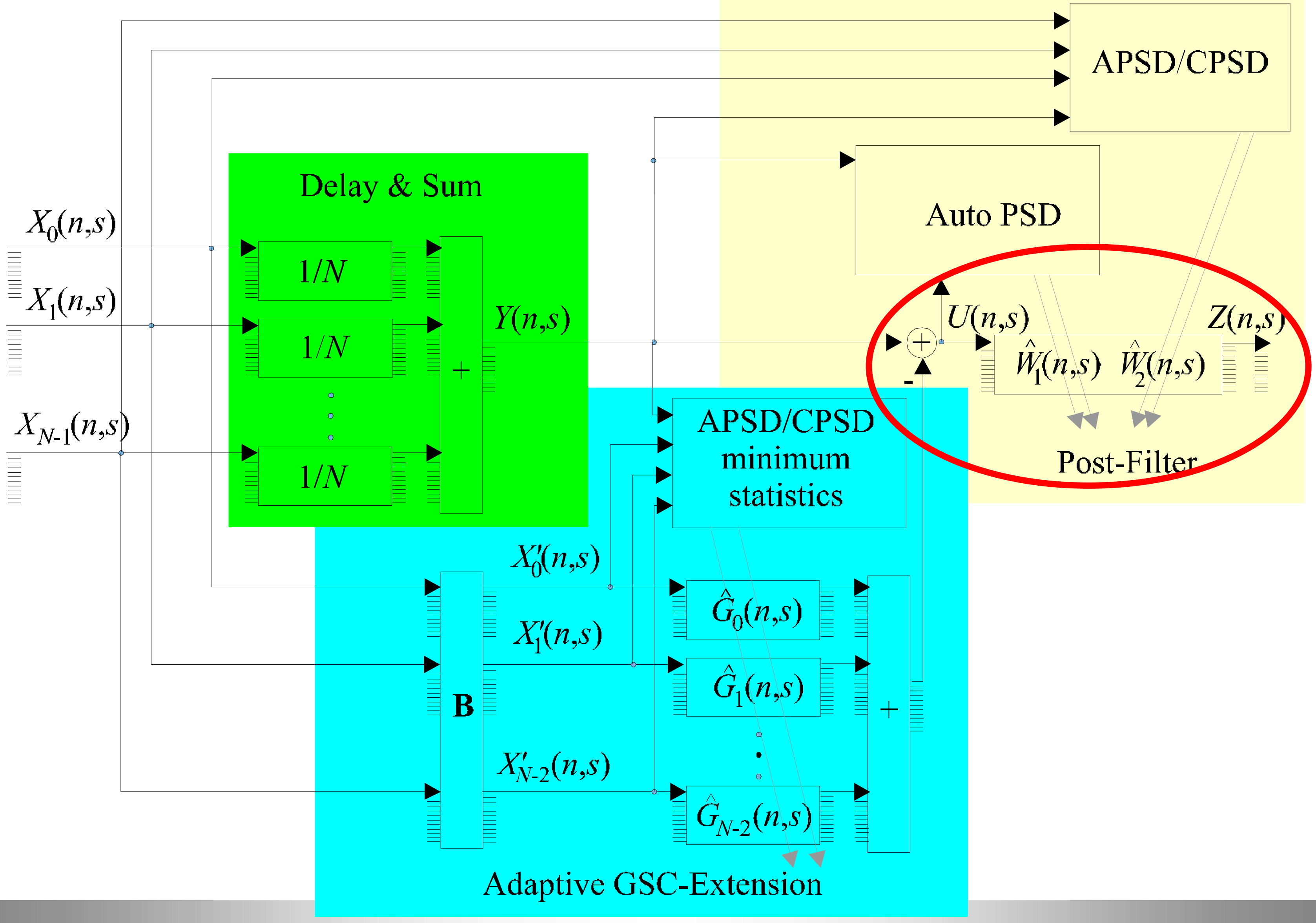
- However, real-world noise-fields consist of a mixture of coherent and diffuse sources

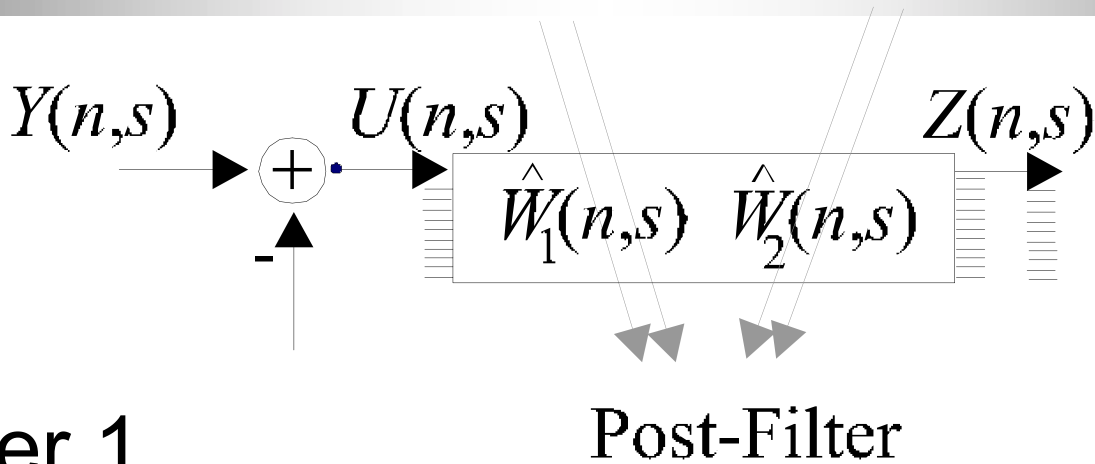
➔ Adaptive Beamformers are necessary. A good solution is the Generalized Sidelobe Canceller (GSC) in a robust implementation

Post-Filter Estimation

- How to estimate the Wiener-Filter?
  - Known algorithms are
    - Zellinski
    - Simmer
    - Generalized Simmer/Zellinski (Marro et al.)
  - Problem:
    All these algorithms cannot be combined with superdirective coefficients, due to the inherent assumption of an uncorrelated noise field
  - Solution:
    New estimation procedure, which is independent of the beamformer coefficients.

- Post-Filter Algorithm in the GSC-Structure (APEAB):





- Filter 1

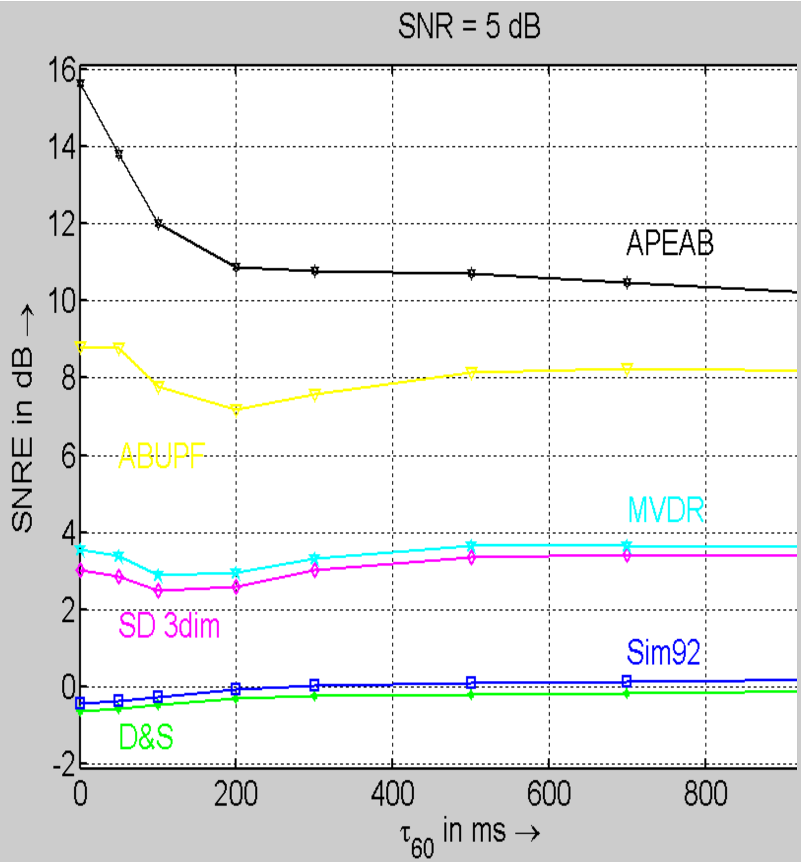
$$\hat{W}_1(n,s) = \frac{\phi_{UU}(n,s)}{\phi_{YY}(n,s)}$$

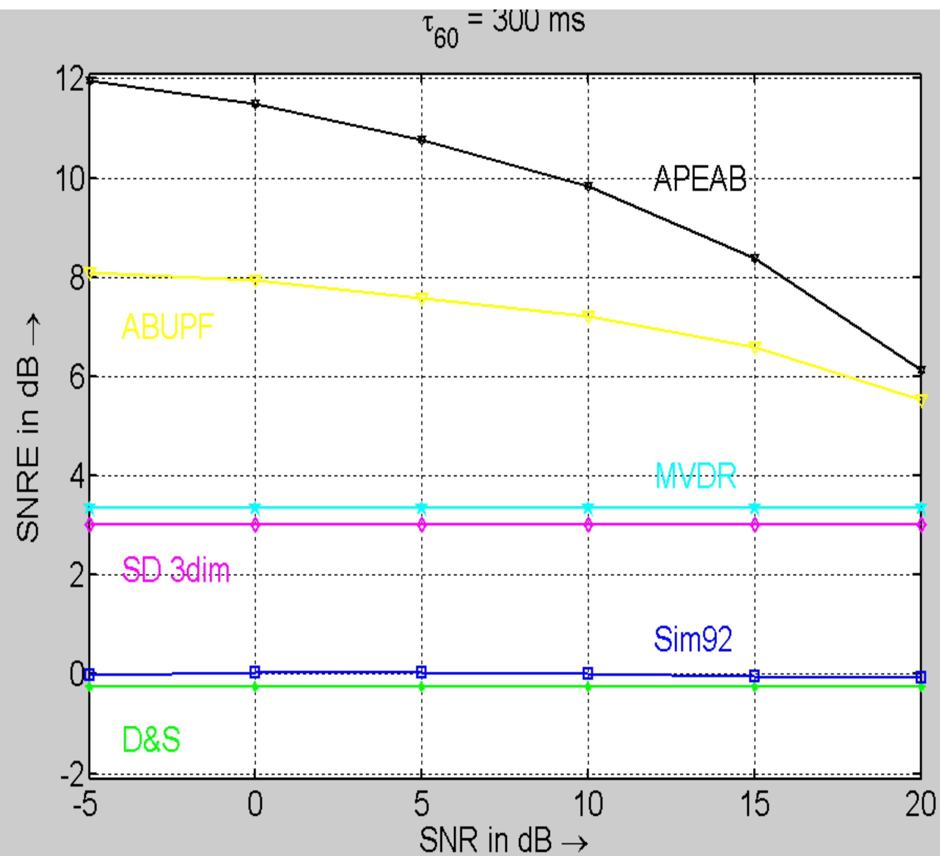
- Filter 2: Simmer Post-Filter

$$\hat{W}_2(n,s) = \frac{2}{N^2 - N} \frac{\Re\left\{ \sum_{i=0}^{N-2} \sum_{j=i+1}^{N-1} \phi_{X_i X_j}(n,s) \right\}}{\phi_{YY}(n,s)}$$

Simulation and Results

- Analysis of SNR-Enhancement vs. Reverb. Time and Input SNR (N = 4, d = 5cm, Endfire)





Audio Demonstration

- Simulated noise field (Tau_60 = 300ms, 4 mics, d = 5cm, SNR = 5dB)
  - 1 Microphone
  - Delay and Sum Beamformer
  - Superdirectional Beamformer
  - Single-Channel Solution
  - Simmer Post-Filter
  - APEAB

Conclusion

- Noise reduction in a diffuse noise field with a low-pass characteristic background noise is very difficult
- Superdirective Beamformers do not reduce noise enough

  ➔Post-Filter extensions are necessary and theoretically motivated
- A robust solution has been proposed
- However:
  - Is this algorithm suitable for Hearing Aids?
  - Can it be used as a starting point for further developments?