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Beamforming-Based Multichannel Acoustic Echo Cancellation

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M.Sc. Thesis Seminar

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Outline

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Publication Info

- Y. Konforti, I. Cohen, and B. Berdugo, ”Array geometry optimization for region-of-interest broadband beamforming”, in Proc. IEEE International Workshop on Acoustic Signal Enhancement (IWAENC), pp. 1–5, 2022.
- Y. Konforti, I. Cohen, and B. Berdugo, ”Multichannel acoustic echo cancellation with beamforming in dynamic environments”, submitted to IEEE Open Journal of Signal Processing, 2023.

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Background and Motivation

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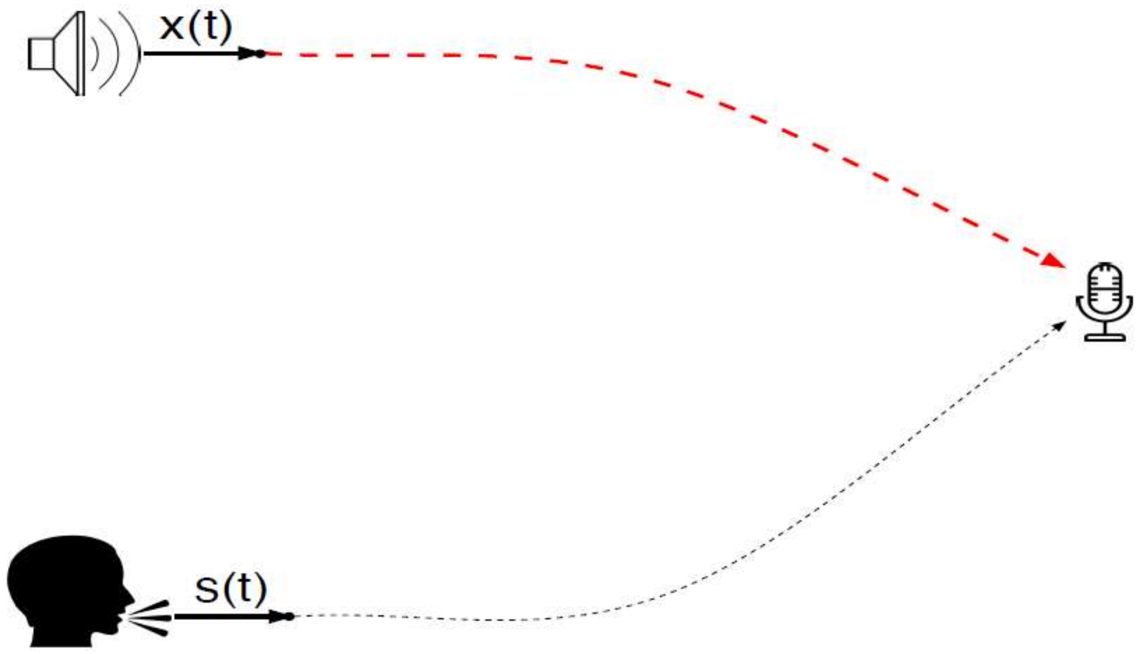
Acoustic Echo Cancellation

- Echo can interfere and disrupt conversations.
- Stems from the acoustic coupling between a loudspeaker and a microphone.
- Echo is eliminated with an acoustic echo canceller (AEC).
  - Usually solved by a normalized least-mean-square filter (NLMS) approach.
  - Involves a double-talk detector.



Applications

APPLE INC.

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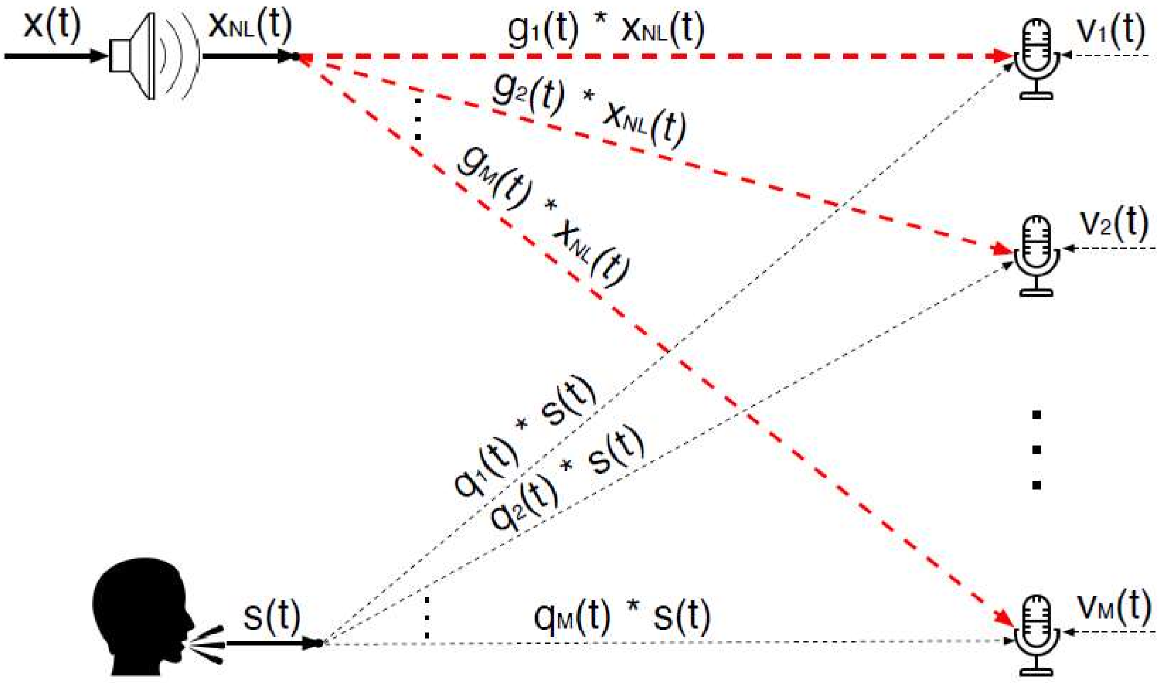
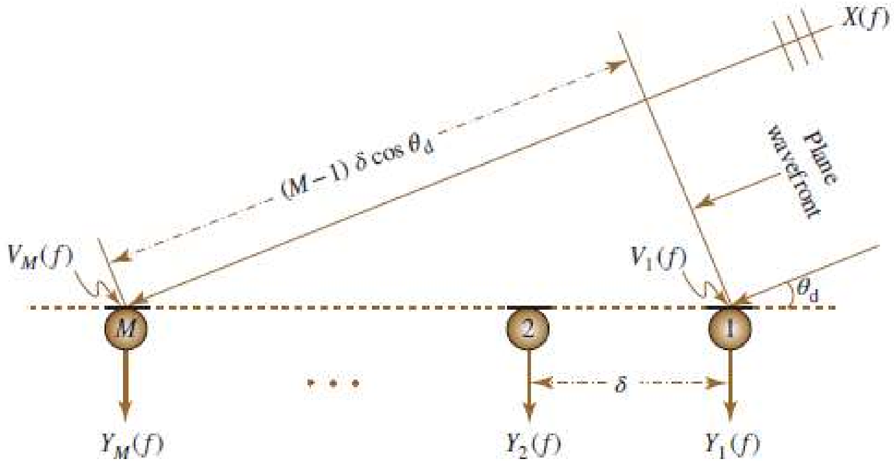
Multichannel Acoustic Echo Cancellation

- In real environments two phenomena worsen performance:
  - Nonlinear loudspeaker distortion
  - Background noise
- Multichannel AEC can be used to mitigate these effects.



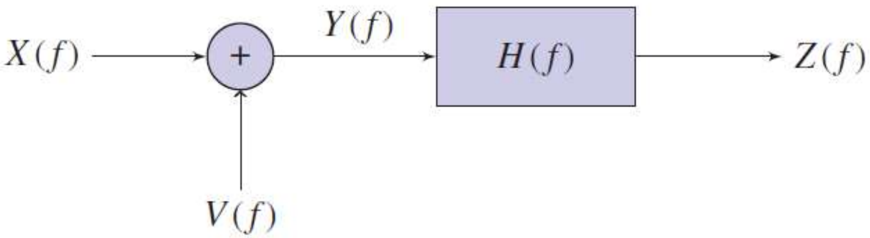
Spatial Filtering



- A signal is propagated in space.
- The signal arrives from a certain direction.
- A sensor array is utilized. The time difference of arrival (TDOA) between the sensors is in accordance with the direction.

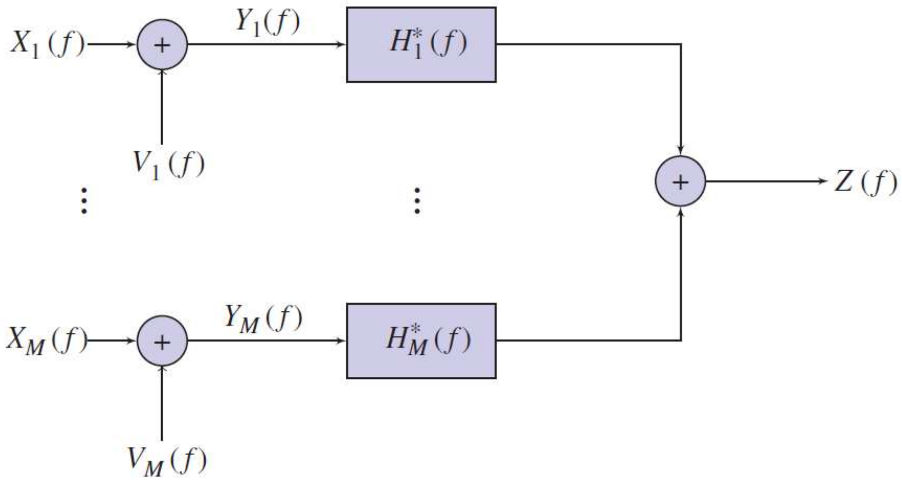
Beamforming – a Sum of Digital Filters

- With one sensor:



$$Z(f) = H(f)Y(f)$$

- With multiple sensors:



$$Z(f) = \sum_{m=1}^{M} H_m^*(f)Y_m(f)$$
$$= \mathbf{h}^H(f)\mathbf{y}(f)$$

Sensor Array Beamforming

- We define the steering vector

$$\mathbf{d}\left(f, \cos\theta\right) = \begin{bmatrix} 1 & e^{-\jmath 2\pi f \tau_0 \cos\theta} & \cdots & e^{-\jmath (M-1) 2\pi f \tau_0 \cos\theta} \end{bmatrix}^T$$

- Each sensor utilizes a digital filter $H_m(f)$.
- The response is measured by the beampattern:
  - Angle dependent.
  - Frequency dependent.

$$\mathcal{B}\left[\mathbf{h}(f), \cos\theta\right] = \mathbf{d}^H\left(f, \cos\theta\right)\mathbf{h}(f) = \sum_{m=1}^{M} H_m(f) e^{\jmath (m-1) 2\pi f \tau_0 \cos\theta}$$

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Multiframe Filtering

- In the short-time fourier transform (STFT) domain, speech signals are correlative between frames.
- The inter-frame correlations must be updated, as they highly vary in time.
- Multiframe and Multichannel filters were used for speech separation and noise reduction(*), yet not for AEC.

(*) E. A. P. Habets, J. Benesty, and J. Chen, "Multi-microphone noise reduction using interchannel and interframe correlations," in Proc. IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), pp. 305–308, 2012.
(*) Z. Zhang, Y. Xu, M. Yu, S. X. Zhang, L. Chen, D. S. Williamson, and D. Yu, "Multi-channel multi-frame ADL-MVDR for target speech separation," IEEE/ACM Transactions on Audio, Speech, and Language Processing, vol. 29, pp. 3526–3540, 2021.
(*) M. Tammen and S. Doclo, "Deep multi-frame MVDR filtering for binaural noise reduction," in Proc. International Workshop on Acoustic Signal Enhancement (IWAENC), 2022.

AEC Performance Measures

- Echo-return loss enhancement (ERLE):
  - $y_1(t)$ - Echo component at reference microphone.
  - $y_{re}(t)$- Residual echo component.

$$\xi(t) = \frac{\mathrm{LPF}\left\{y_1^2(t)\right\}}{\mathrm{LPF}\left\{y_{\mathrm{re}}^2(t)\right\}}$$

- Distortion Index (DI):
  - $u_1(t)$ - Desired component at reference microphone.
  - $u_f(t)$ - Filtered desired component.

$$\nu(t) = \frac{\mathrm{LPF}\left\{\left[u_1(t) - u_{\mathrm{f}}(t)\right]^2\right\}}{\mathrm{LPF}\left\{u_1^2(t)\right\}}$$

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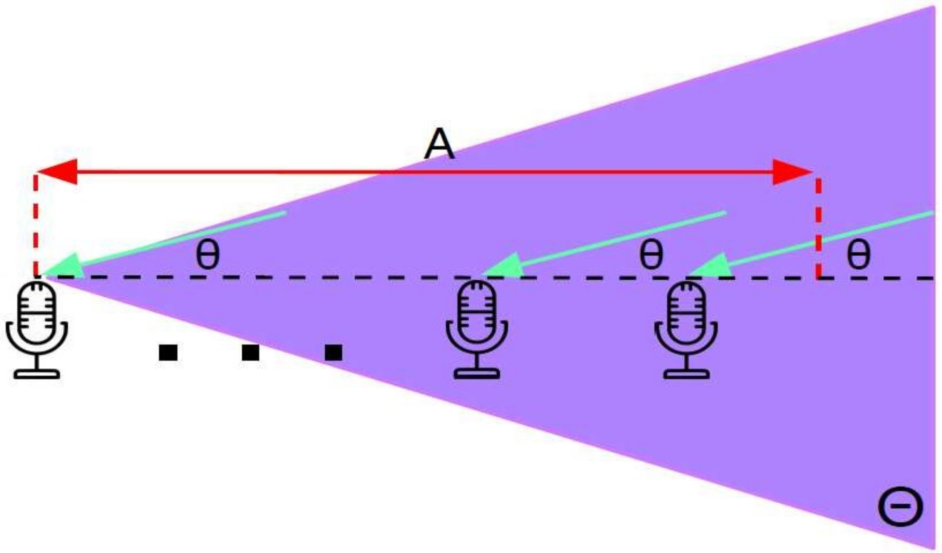
Region-of-Interest Beamforming



- In many applications, the source location is unknown, but it can be assumed it is in a region-of-interest (ROI).
- Source localization / Direction-of-arrival (DOA) estimation may be employed to track a moving source.
- While the coefficients change, the array geometry is preserved.

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Applications

Array Geometry Optimization

- Typically, the beamforming coefficients are found per given geometry. Usually symmetric geometries are considered:
  - Uniform Linear Arrays (ULAs).
  - Rectangular Arrays.
  - Uniform Circular Arrays (UCAs).
  - Uniform Concentric Circular Arrays (UCCAs).
- Differential Microphone Arrays (DMAs) produce an approximate frequency invariant (FI) response.
- The geometry of a microphone array has an important impact on beamforming performance.

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Optimization Methods

- Two common methods for array geometry optimization:
  - Greedy-based approaches.
  - Genetic Algorithms.
- Greedy-based approaches find the best position for the placed microphone in each step, but the overall result may not be optimal.
- Genetic algorithms are unstable and may also converge to nonoptimal results.
- The study in (*) optimize the geometry for a ROI, but only for narrowband signals.

(*) X. Chen, C. Pan, J. Chen, and J. Benesty, "Planar array geometry optimization for region sound acquisition," in *Proc. IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pp. 756–760, 2021.

Beamforming Performance Measures

- White Noise Gain: $$\mathcal{W}\left[\mathbf{h}(\mathrm{x},\omega,\theta)\right] \triangleq \frac{\left|\mathbf{d}^H(\mathrm{x},\omega,\theta)\,\mathbf{h}(\mathrm{x},\omega,\theta)\right|^2}{\mathbf{h}^H(\mathrm{x},\omega,\theta)\,\mathbf{h}(\mathrm{x},\omega,\theta)}$$
- Directivity Factor (DF): $$\mathcal{D}\left[\mathbf{h}(\mathrm{x},\omega,\theta)\right] \triangleq \frac{\left|\mathbf{d}^H(\mathrm{x},\omega,\theta)\,\mathbf{h}(\mathrm{x},\omega,\theta)\right|^2}{\mathbf{h}^H(\mathrm{x},\omega,\theta)\,\mathbf{\Gamma}(\mathrm{x},\omega)\,\mathbf{h}(\mathrm{x},\omega,\theta)}$$

  where $$\Gamma_{i,j}(\mathrm{x},\omega) = \frac{\sin\left(\omega\left(x_i - x_j\right)/c\right)}{\omega\left(x_i - x_j\right)/c}, \quad 1 \le i,j \le M$$
- Directivity Index: $$\mathcal{DI}_{[\omega_L,\omega_H]}\left[\mathbf{h}(\mathrm{x},\omega,\theta)\right] \triangleq \frac{\int_{\omega_L}^{\omega_H}\left|\mathbf{d}^H(\mathrm{x},\omega,\theta)\,\mathbf{h}(\mathrm{x},\omega,\theta)\right|^2 d\omega}{\int_{\omega_L}^{\omega_H}\mathbf{h}^H(\mathrm{x},\omega,\theta)\,\mathbf{\Gamma}(\mathrm{x},\omega)\,\mathbf{h}(\mathrm{x},\omega,\theta)\,d\omega}$$

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Multichannel Acoustic Echo Cancellation with Beamforming in Dynamic Environments

A Beamforming-Based Approach

- $\boldsymbol{y}(k,n)$- Echo component received by the array.
- $\boldsymbol{u}(k,n)$- Desired component received signal by the array.
- $\boldsymbol{v}(k,n)$- Background noise received signal by the array.
- $\boldsymbol{d}(k,n)$- total received signal by the array.

$$\hat{U}(k,n) = \mathbf{h}^H(k,n)\,\mathbf{d}(k,n)$$

$$\mathbf{d}(k,n) = \mathbf{y}(k,n) + \mathbf{u}(k,n) + \mathbf{v}(k,n)$$

Linear-Constraint-Minimum-Variance Beamforming

- Theoretically enforces:
  - Complete echo cancellation.
  - No distortion.
  - Minimum residual noise.
- Ideal ERLE and DI.
- Requires accurate estimates of $\boldsymbol{g}(k)$ and $\boldsymbol{q}(k)$.

$$\mathbf{h}^*(k,n) = \underset{\mathbf{h}(k,n)}{\arg\min} \|\mathbf{h}(k,n)\|^2$$

$$\text{s.t.} \quad \mathcal{C}_1[\mathbf{h}(k,n)] : \mathbf{h}^H(k,n)\,\mathbf{g}(k) = 0$$

$$\mathcal{C}_2[\mathbf{h}(k,n)] : \mathbf{h}^H(k,n)\,\mathbf{q}(k) = 1$$

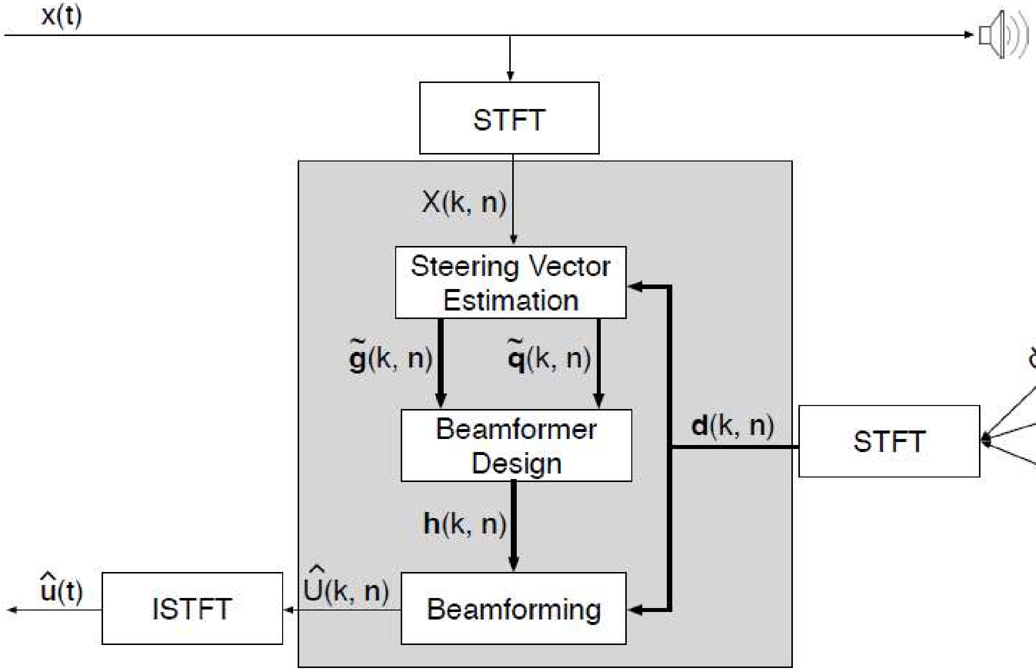
$$\mathbf{h}^*(k,n) = \mathbf{C}(k)\left[\mathbf{C}^H(k)\,\mathbf{C}(k)\right]^{-1}\mathbf{i}_c$$

where $\mathbf{C}(k,n) = [\mathbf{q}(k), \mathbf{g}(k)]$

$$\mathbf{i}_c = [1,0]^T$$

AEC Scheme

- Procedure:
  1. Steering vectors $\boldsymbol{g}(k)$ and $\boldsymbol{q}(k)$ are estimated.
  2. Beamformer $\boldsymbol{h}(k,n)$ is designed.
  3. Estimate $\widehat{U}(k,n)$ is produced.
- No double talk detection used.



Utilizing Multiple Sensors – A Frame Invariant Expression

- Neglecting nonlinear loudspeaker distortion.
- Neglecting background noise.
- Assuming a static environment in the last L frames.
- Utilizing the Multiplicative Transfer Function (MTF) approximation (*).

$$D_m(k, n-l+1) = G_m(k)\,X(k, n-l+1) + Q_m(k)\,S(k, n-l+1)$$

- For any two microphones m_1 and m_2:

$$\frac{Q_{m_1}(k)}{Q_{m_2}(k)} = \frac{D_{m_1}(k, n-l+1) - G_{m_1}(k)\,X(k, n-l+1)}{D_{m_2}(k, n-l+1) - G_{m_2}(k)\,X(k, n-l+1)}$$

(*) Y. Avargel and I. Cohen, "On multiplicative transfer function approximation in the short-time fourier transform domain," *IEEE Signal Processing Letters*, vol. 14, pp. 337–340, 2007.

Utilizing Multiple Frames

- For any two recent frames l_1 and l_2:

$$\frac{D_{m_1}(k,n-l_1+1)-G_{m_1}(k)X(k,n-l_1+1)}{D_{m_2}(k,n-l_1+1)-G_{m_2}(k)X(k,n-l_1+1)}=\frac{D_{m_1}(k,n-l_2+1)-G_{m_1}(k)X(k,n-l_2+1)}{D_{m_2}(k,n-l_2+1)-G_{m_2}(k)X(k,n-l_2+1)}$$

- Quadratic elements of $G_{m_1}(k)G_{m_2}(k)$ are reduced.
- A linear equation with respect to $G_{m_1}(k)$ and $G_{m_2}(k)$ is obtained:

$$\begin{aligned}&G_{m_1}(k)\left[X(k,n-l_1+1)D_{m_2}(k,n-l_2+1)-X(k,n-l_2+1)D_{m_2}(k,n-l_1+1)\right]+\\&G_{m_2}(k)\left[X(k,n-l_2+1)D_{m_1}(k,n-l_1+1)-X(k,n-l_1+1)D_{m_1}(k,n-l_2+1)\right]=\\&D_{m_1}(k,n-l_1+1)D_{m_2}(k,n-l_2+1)-D_{m_1}(k,n-l_2+1)D_{m_2}(k,n-l_1+1)\end{aligned}$$

A Linear Set of Equations

- Overall, for any pick of $1 \leq m_1, m_2 \leq M$ and $1 \leq l_1, l_2 \leq L$, we get such an equation.
- Uninformative equations:
  - $m_1 = m_2$
  - $l_1 = l_2$
  - Swapping $m_1 \Leftrightarrow m_2$
  - Swapping $l_1 \Leftrightarrow l_2$
- Must have more equations than variables: $M \leq \binom{M}{2}\binom{L}{2} \Rightarrow L(L-1)(M-1) \geq 4$
- Must have multiple frames, multiple sensors, and $M \geq 3$ or $\mathrm{L} \geq 3$.

A Least-Mean-Squares Approach

- Equations may contradict due to assumptions.
- A least-mean-squares (LMS) solution provides a good estimate.
- As L grows:
  - More equations are added.
  - The environment is assumed to be static for longer periods.
- As M grows:
  - More equations are added.
  - More variables are added.

Matrix Formulation

Inputs: M, L,

$X(k, n-l+1)$, $D_m(k, n-l+1)$ $\quad 1 \le l \le L \quad 1 \le m \le M$

Outputs: $\tilde{G}_m(k,n)$ $\quad 1 \le m \le M$

Create list M_{list} of $\binom{M}{2}$ non-repetitive pairs (m_1, m_2)

Create list L_{list} of $\binom{L}{2}$ non-repetitive pairs (l_1, l_2)

$\mathbf{A}(k,n) \leftarrow \mathbf{0}_{\binom{M}{2}\binom{L}{2}\times M}$

for $i = 1, 2, \ldots, \binom{M}{2}$ **do**

$(m_1, m_2) \leftarrow M_{\text{list}}(i)$

for $j = 1, 2, \ldots, \binom{L}{2}$ **do**

$(l_1, l_2) \leftarrow L_{\text{list}}(j)$

$$\mathbf{A}_{\left[(i-1)\binom{L}{2}+j, m_1\right]}(k,n) \leftarrow X(k, n-l_1+1) D_{m_2}(k, n-l_2+1) - X(k, n-l_2+1) D_{m_2}(k, n-l_1+1)$$

$$\mathbf{A}_{\left[(i-1)\binom{L}{2}+j, m_2\right]}(k,n) \leftarrow X(k, n-l_2+1) D_{m_1}(k, n-l_1+1) - X(k, n-l_1+1) D_{m_1}(k, n-l_2+1)$$

$$\mathbf{b}_{\left[(i-1)\binom{L}{2}+j\right]}(k,n) \leftarrow D_{m_1}(k, n-l_1+1) D_{m_2}(k, n-l_2+1) - D_{m_1}(k, n-l_2+1) D_{m_2}(k, n-l_1+1)$$

end for

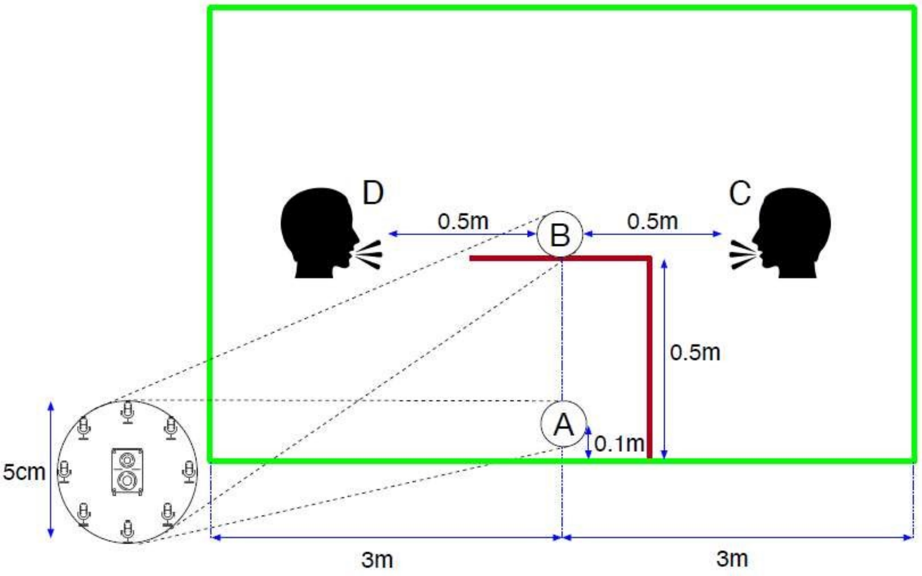
end for

$$\left[\tilde{G}_1(k,n), \tilde{G}_2(k,n), \ldots, \tilde{G}_M(k,n)\right]^T \leftarrow \mathbf{A}^{\dagger}(k,n)\,\mathbf{b}(k,n)$$

$$\tilde{\mathbf{g}}(k,n) = \left[1, \frac{\tilde{G}_2(k)}{\tilde{G}_1(k)}, \ldots, \frac{\tilde{G}_M(k)}{\tilde{G}_1(k)}\right]^T$$

$$\tilde{\mathbf{q}}(k,n) = \left[1, \frac{D_2(k,n) - \tilde{G}_2(k,n) X(k,n)}{D_1(k,n) - \tilde{G}_1(k,n) X(k,n)}, \ldots, \frac{D_M(k,n) - \tilde{G}_M(k,n) X(k,n)}{D_1(k,n) - \tilde{G}_1(k,n) X(k,n)}\right]^T.$$

Simulation Configuration



- Dynamic environment.
- Double-talk.
- Low Signal-to-Echo Ratio in 4 scenarios:
  1. Speakerphone at A, talker at C.
     -17.89 dB.
  2. Speakerphone at A, talker at D.
     -18.7 dB.
  3. Speakerphone at B, talker at C.
     -15.27 dB.
  4. Speakerphone at B, talker at D.
     -16.89 dB.

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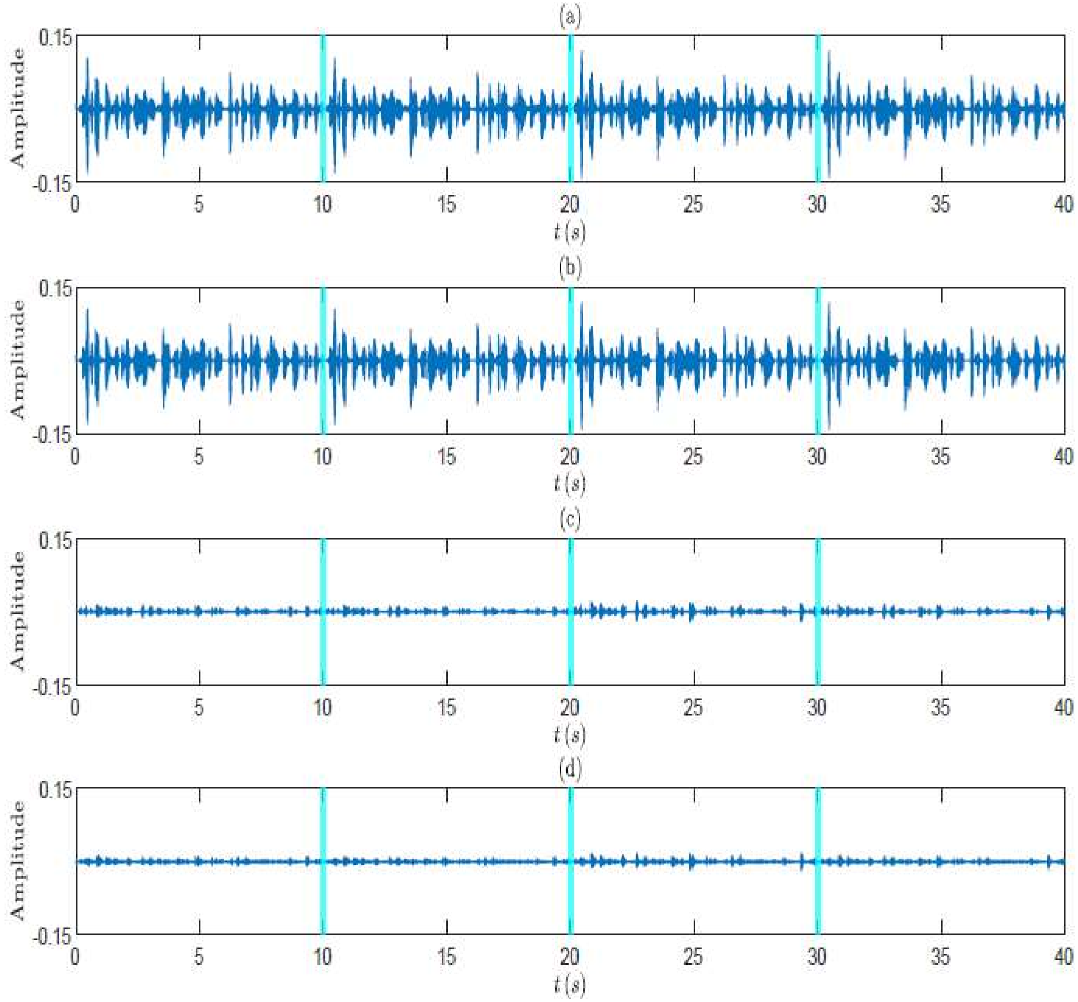
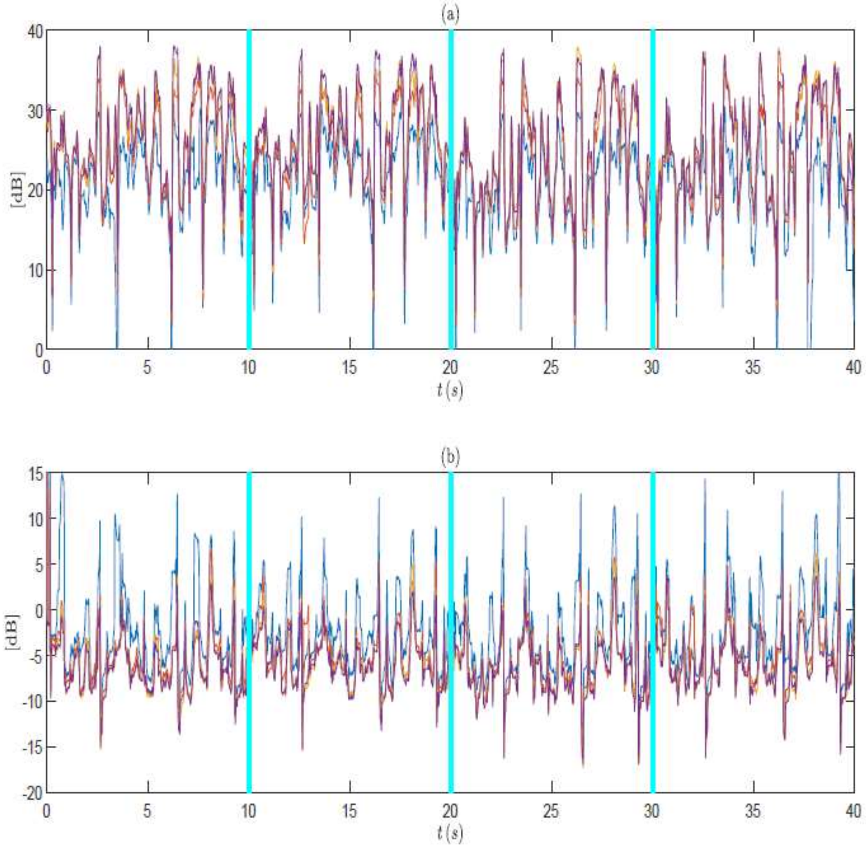
Results - Echo Cancellation

a. The total received signal in the reference microphone $d_1(t)$
b. The echo component signal in the reference microphone $y_1(t)$
c. The desired component signal in the reference microphone $u_1(t)$
d. The beamformer output signal $\hat{u}(t)$.

- Good echo cancellation despite significant acoustic coupling.





Results - Performance as Function of Microphones

a. ERLE.

b. DI.

- Blue - $M = 2$, Red - $M = 3$, Yellow - $M = 4$, Purple - $M = 5$. $\mathrm{L} = 4$.
- Significant change only between $M = 2$ and $M = 3$.
- Performance limit. Increasing M also increases number of variables in estimation process.

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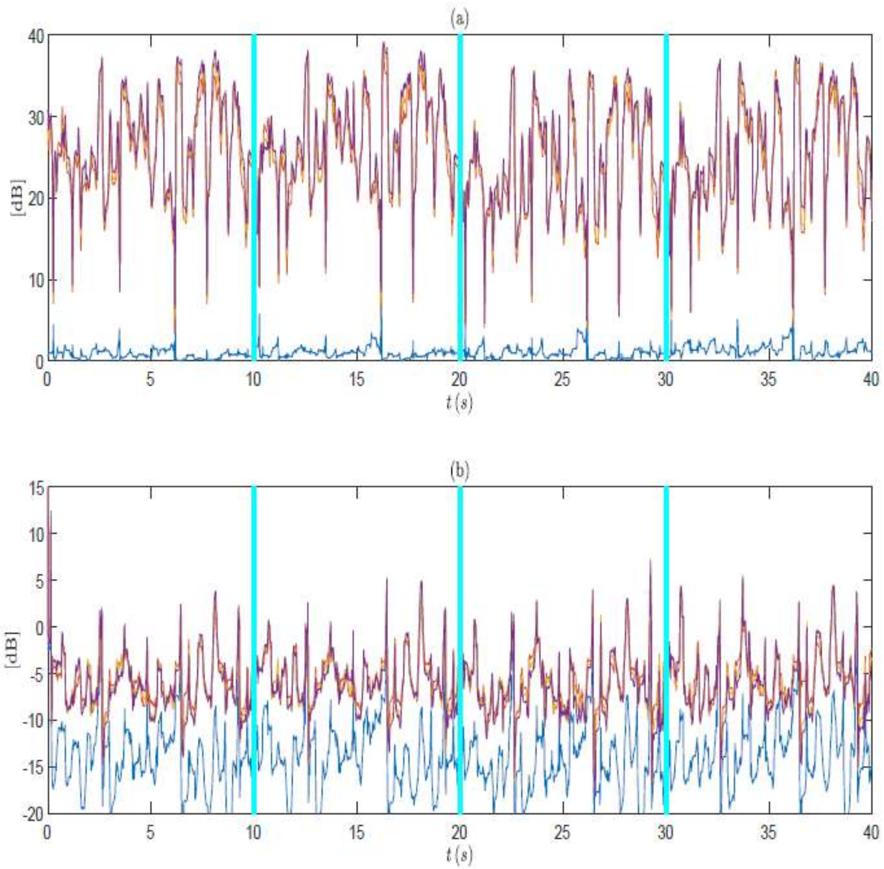


Results - Performance as Function of Frames

a. ERLE.
b. DI.

- Blue - $L = 2$. Red - $L = 3$.
  Yellow - $L = 4$. Purple - $L = 5$. $M = 4$.
- $L = 2$ are insufficient for the proposed approach.
- Performance limit. Increasing L also relies more strongly on a longer period where the environment is static.

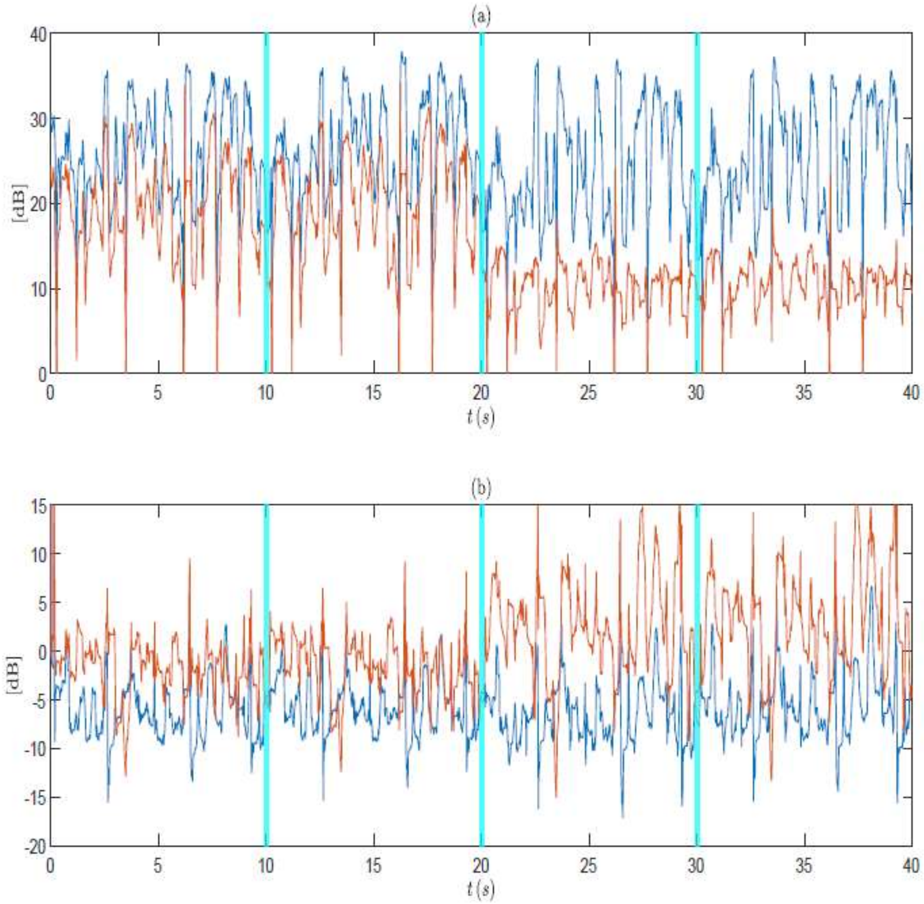
Results - Method Comparison (*)

a. ERLE.

b. DI.

- The NLMS filter in (*) was trained in a period like the first segment, but with no near-end speech.
- Blue – proposed. Red – competing.

- Improvement in both ERLE and DI.
- Significant improvement after the speakerphone moves due to changing reflections. The NLMS filter is irrelevant once the reflections have changed.



(*) H. Huang, C. Hofmann, W. Kellermann, J. Chen, and J. Benesty, "Multiframe echo suppression based on orthogonal signal decompositions," in *Proc. Speech Communication; ITG Symposium*, pp. 287–291, 2016.

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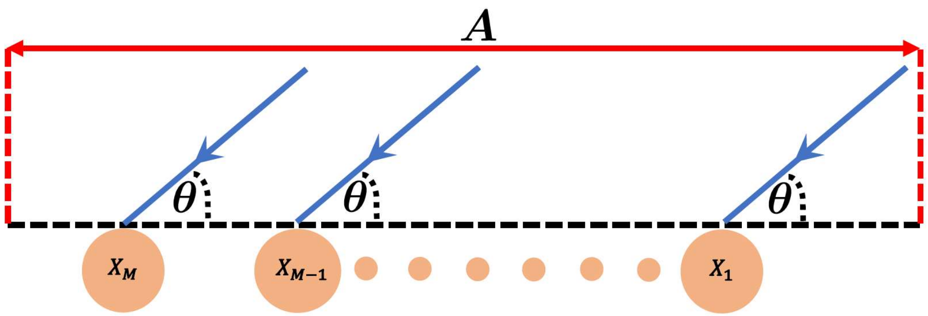
Array Geometry Optimization for Region-of-Interest Broadband Beamforming

A Variable Geometry

- M omnidirectional microphones are placed nonuniformly across a linear aperture A in placements x_m, $m = 1, 2, \dots, M$.



- The steering vector is

$$\mathbf{d}(\mathbf{x}, \omega, \theta) = \left[e^{-\jmath \frac{\omega}{c} x_1 \cos\theta}, e^{-\jmath \frac{\omega}{c} x_2 \cos\theta}, \dots, e^{-\jmath \frac{\omega}{c} x_M \cos\theta}\right]^T$$

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Coefficients Dependent on Geometry

- For different geometries, the coefficients are designed differently. For a geometry x and look direction θ, we define the coefficients vector as

$$\mathbf{h}(\mathbf{x},\omega,\theta) \triangleq [H_1(\mathbf{x},\omega,\theta), H_2(\mathbf{x},\omega,\theta), \ldots, H_M(\mathbf{x},\omega,\theta)]^T$$

- With geometry x, the beampattern directed toward $\tilde{\theta}$ has a response at angle θ of

$$\mathcal{B}\left[\mathbf{h}\left(\mathbf{x},\omega,\tilde{\theta}\right),\theta\right] = \mathbf{d}^H(\mathbf{x},\omega,\theta)\,\mathbf{h}\left(\mathbf{x},\omega,\tilde{\theta}\right)$$

Problem Formulation

- Our objective is to find the optimal array geometry x, that maximizes the worst-case directivity index, in an ROI Θ. Each beamformer, directed toward θ, must admit to the distortionless constraint, have sufficient WNG, and maintain minimal distances.

$$
\begin{aligned}
\mathbf{x}^* = \arg\max_{\mathbf{x}} \quad & \min_{\theta\in\Theta} \mathcal{DI}_{[\omega_L,\omega_H]}\left[\mathbf{h}\left(\mathbf{x},\omega,\theta\right)\right] \\
\text{s.t.} \quad & \mathcal{B}\left[\mathbf{h}\left(\mathbf{x},\omega,\theta\right),\theta\right] = 1 && \forall\theta\in\Theta, \forall\omega\in\Omega \\
& \mathcal{W}\left[\mathbf{h}\left(\mathbf{x},\omega,\theta\right)\right] \geq \delta && \forall\theta\in\Theta, \forall\omega\in\Omega \\
& |x_i - x_j| \geq d_c && \forall i,j\in[1,M], i\neq j \\
& 0 \leq x_m \leq A && \forall m\in[1,M]
\end{aligned}
$$

- Not convex. Cannot be solved by convex optimization algorithms. 👎

Formalizing a Solvable Problem - Constraints

- Consider N candidate microphone locations, Q frequencies, and P look directions.
- To guarantee number of microphones:

$$\mathcal{C}_1\left[\mathbf{s}\right]:\mathbf{s}^H\mathbf{i}_N=M$$

- To guarantee minimal spacing:

$$\mathcal{C}_2\left[\mathbf{s}\right]:\mathbf{s}^H U\leq\mathbf{i}_G^T$$

$$\mathbf{s}=[1,0,1,0,1]^{\mathrm{T}}$$

- To guarantee the distortionless constraint:

$$\mathcal{C}_3\left[\mathbf{h}_{\text{tot}}\left(\omega,\theta\right)\right]:\mathbf{d}_{\text{tot}}^H\left(\omega_q,\theta_p\right)\mathbf{h}_{\text{tot}}\left(\omega_q,\theta_p\right)=1 \qquad \forall p\in\left[1,P\right],\quad\forall q\in\left[1,Q\right]$$

- To guarantee the desired WNG:

$$\mathcal{C}_4\left[\mathbf{h}_{\text{tot}}\left(\omega,\theta\right)\right]:\mathbf{h}_{\text{tot}}^H\left(\omega_q,\theta_p\right)\mathbf{h}_{\text{tot}}\left(\omega_q,\theta_p\right)\leq\frac{1}{\delta}$$
$$\forall p\in\left[1,P\right],\quad\forall q\in\left[1,Q\right]$$

- To guarantee beamformer use of selected placements:

$$\mathcal{C}_5\left[\mathbf{s},\mathbf{h}_{\text{tot}}\left(\omega,\theta\right)\right]:\left|H_{\text{tot},i}\left(\omega_q,\theta_p\right)\right|^2\leq\frac{S_i}{\delta}$$
$$\forall i\in\left[1,N\right],\quad\forall p\in\left[1,P\right],\quad\forall q\in\left[1,Q\right]$$

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Formalizing a Solvable Problem - Target

- When the distortionless constraint is met, the directivity index is determined only by the denominator. Therefore, to maximize the worst-case directivity index we should minimize:

$$R\left[\mathbf{h}_{\text{tot}}(\omega,\theta)\right] = \max_{p\in[1,P]} \sum_{q=1}^{Q} \mathbf{h}_{\text{tot}}^{H}(\omega_q,\theta_p)\,\boldsymbol{\Gamma}_{\text{tot}}(\omega_q)\,\mathbf{h}_{\text{tot}}(\omega_q,\theta_p)$$

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Optimal Array Design

- The optimal design is found by solving a mixed-integer convex optimization problem.
- The non-zero elements of the optimal binary vector $\boldsymbol{s}^*$ yield the optimal microphone locations $\boldsymbol{x}^*$. The non-zero elements of the optimal coefficients $\boldsymbol{h}^*_{tot}(\omega,\theta)$ yield the optimal coefficients $\boldsymbol{h}^*(\boldsymbol{x}^*,\omega,\theta)$.

$$\begin{aligned} \min_{\mathbf{s},\mathbf{h}_{\mathrm{tot}}(\omega,\theta)} \quad & R\left[\mathbf{h}_{\mathrm{tot}}(\omega,\theta)\right] \\ \text{s.t.} \quad & \mathcal{C}_1[\mathbf{s}], \mathcal{C}_2[\mathbf{s}], \mathcal{C}_3[\mathbf{h}_{\mathrm{tot}}(\omega,\theta)], \\ & \mathcal{C}_4[\mathbf{h}_{\mathrm{tot}}(\omega,\theta)], \mathcal{C}_5[\mathbf{s}, \mathbf{h}_{\mathrm{tot}}(\omega,\theta)] \end{aligned}$$

Coefficient Post-Processing

- Since the worst-case look direction is considered, beamformers directed toward other directions may not yield the best possible directivity. To circumvent this, we introduce a post-processing scheme.
- To maximize directivity while maintaining sufficient WNG, the coefficients are found by the robust superdirective beamformer:

$$\mathbf{h}_\epsilon\left(\mathbf{x}^*,\omega,\theta\right)=\frac{\mathbf{\Gamma}_\epsilon^{-1}\left(\mathbf{x}^*,\omega\right)\mathbf{d}\left(\mathbf{x}^*,\omega,\theta\right)}{\mathbf{d}^H\left(\mathbf{x}^*,\omega,\theta\right)\mathbf{\Gamma}_\epsilon^{-1}\left(\mathbf{x}^*,\omega\right)\mathbf{d}\left(\mathbf{x}^*,\omega,\theta\right)}$$

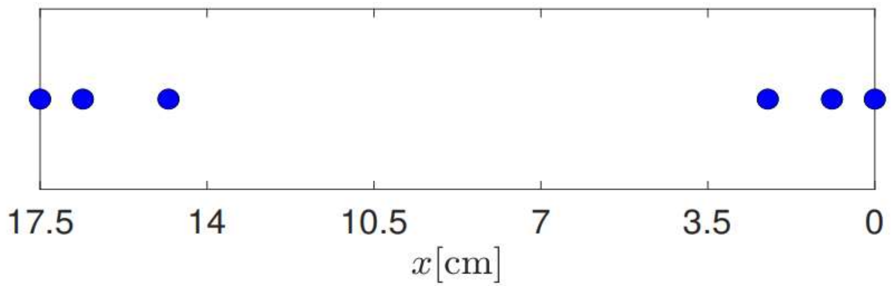
- For every frequency and look direction, ϵ is found by a bisection search:

$$0\leq\epsilon\leq\frac{\lambda_1-\sqrt{M/\delta}\lambda_M}{\sqrt{M/\delta}-1}$$

where $\mathbf{\Gamma}\left(\mathbf{x}^*,\omega\right)=\mathbf{Q}\left(\mathbf{x}^*,\omega\right)\mathbf{\Lambda}\left(\mathbf{x}^*,\omega\right)\mathbf{Q}^T\left(\mathbf{x}^*,\omega\right)$ is the eigenvalue decomposition such that that $\mathbf{\Lambda}=\operatorname{diag}\left[\lambda_1,\lambda_2,...,\lambda_M\right]$, $\lambda_1\geq\lambda_2\geq...\geq\lambda_M$.

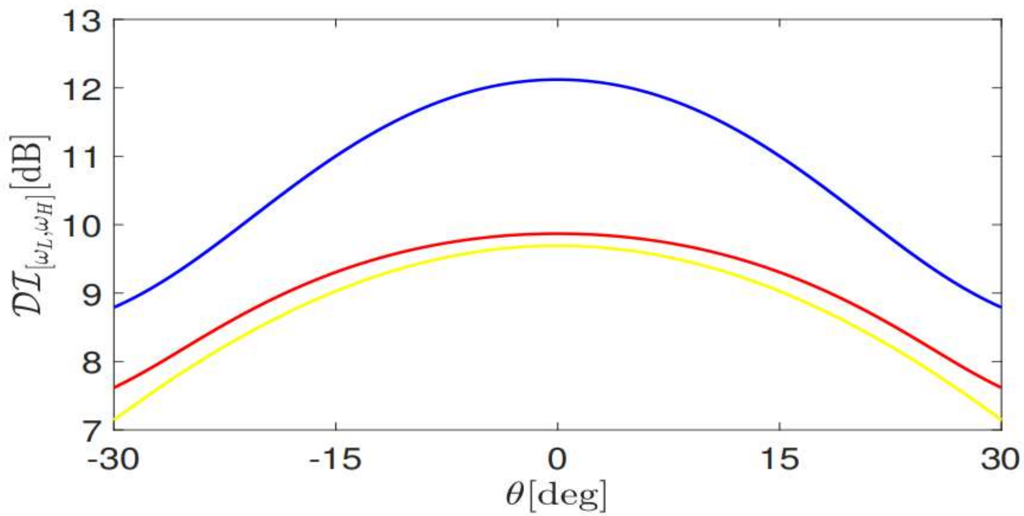
Results - Geometry

- $M = 6$ microphones, aperture length $A = 17.5[cm]$, minimal distance $d_c = 0.5[cm]$. Frequencies from $f_L = 2[kHz]$ to $f_H = 6[kHz]$, look directions up to $\theta_H = 30°$. Minimum WNG is $\delta = -10[dB]$. $N = 40$, $Q = 15$, $P = 15$.



- Some sensors close together yield high directivity, like DMAs.
- Some sensors further apart, due to WNG constraint.

Results – Directivity Index



- Blue – proposed. Red – ULA. Yellow – dense geometry.
- Better directivity in the worst-case direction. 👍
- Better directivity in **all** ROI directions. 👍

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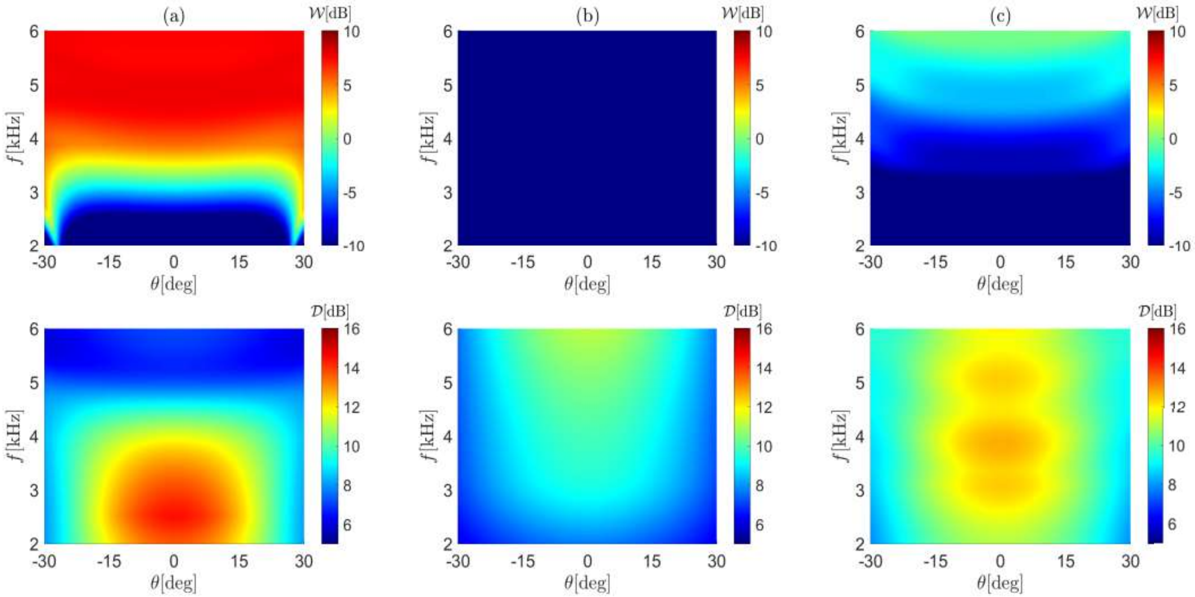
Results – WNG and Directivity Factor

- (a) ULA – Excellent WNG, but spatial aliasing damages DF at higher frequencies.
- (b) Dense geometry – Barely sufficient WNG, cannot produce high directivity due to WNG constraint.
- (c) Proposed – Good WNG, good broadband directivity. 👍

WNG:

DF:



Conclusions

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Research Contributions

- A novel beamforming-based multichannel AEC method was proposed.
  - Capable of operating in dynamic environments.
  - Does not require double-talk detection.
  - Robust to extremely low SER.
  - Achieves higher ERLE and lower DI compared to an existing method.
- The array geometry for broadband ROI was optimized.
  - A convex framework was used, enabling the convergence to the global optimum.
  - A broadband frequency range was considered.
  - Sensors were placed close closer / further apart , to achieve compromise between directivity and noise robustness.

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Future Research

- Modelling nonlinear loudspeaker distortion and background noise. The LMS approach works well only if those components are relatively small.
- Developing more accurate inter-frame and inter-sensor relations. For example, instead of the MTF approximation (*) using the Cross-Multiplicative Transfer Function (CMTF) approximation (**).
- Exploring other array types. The search is limited to non-uniform linear arrays. This will enable more complex ROIs too.
- Geometry optimization by other approaches, such as learning-based methods or deep neural networks (DNNs). Our framework runtime grows considerably with more optimization variables.

(*)Y. Avargel and I. Cohen, “On multiplicative transfer function approximation in the short-time fourier transform domain,” *IEEE Signal Processing Letters*, vol. 14, pp. 337–340, 2007.

(**) Y. Avargel and I. Cohen, “Adaptive system identification in the short-time fourier transform domain using cross-multiplicative transfer function approximation,” *IEEE Transactions on Audio, Speech, and Language Processing*, vol. 16, pp. 162– 173, 2008.

Questions?

Thank you!

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