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Multi-zone Audio Delivery in Cars: Fundamental Theory and Recent Advances

Filippo Maria Fazi and
Wilfried Gallian

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Overview of muti-zone audio delivery

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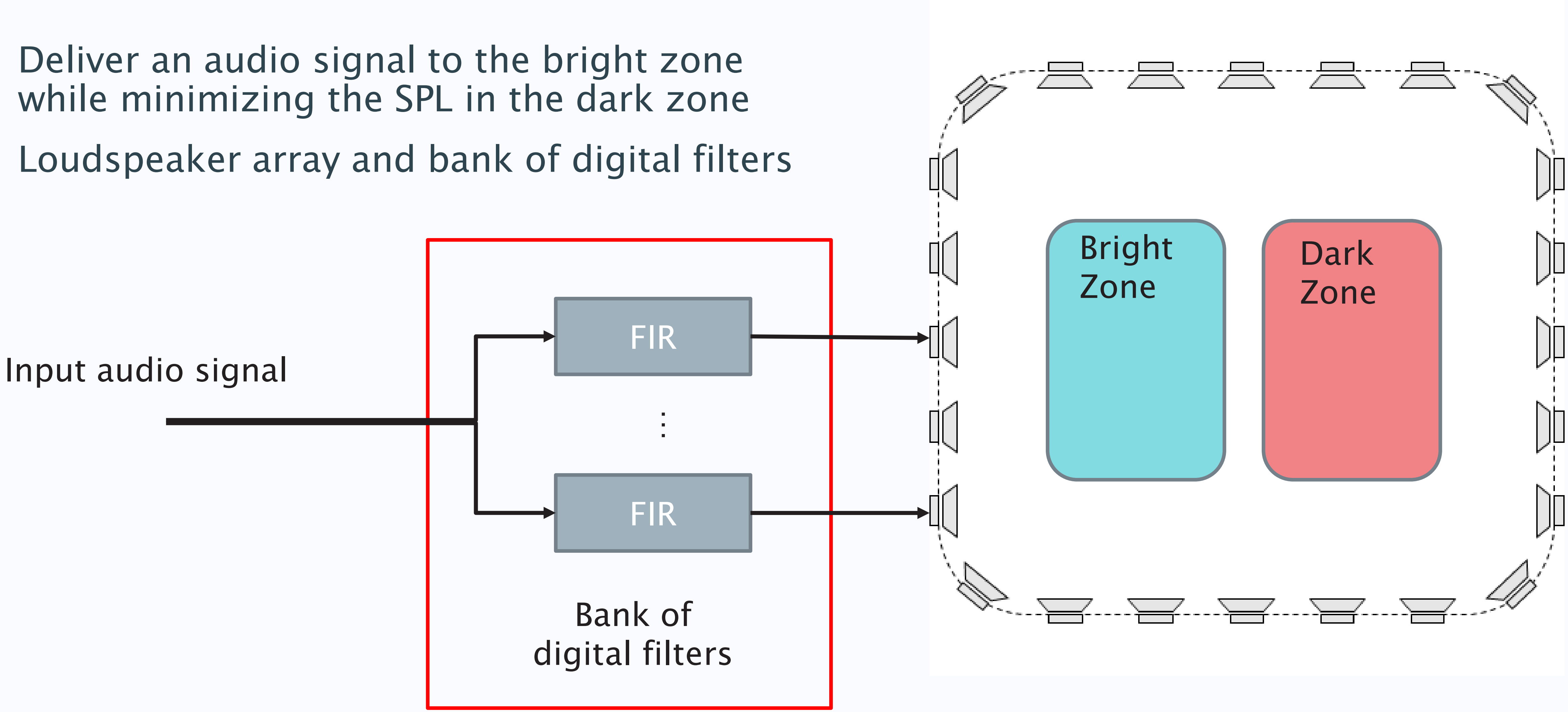
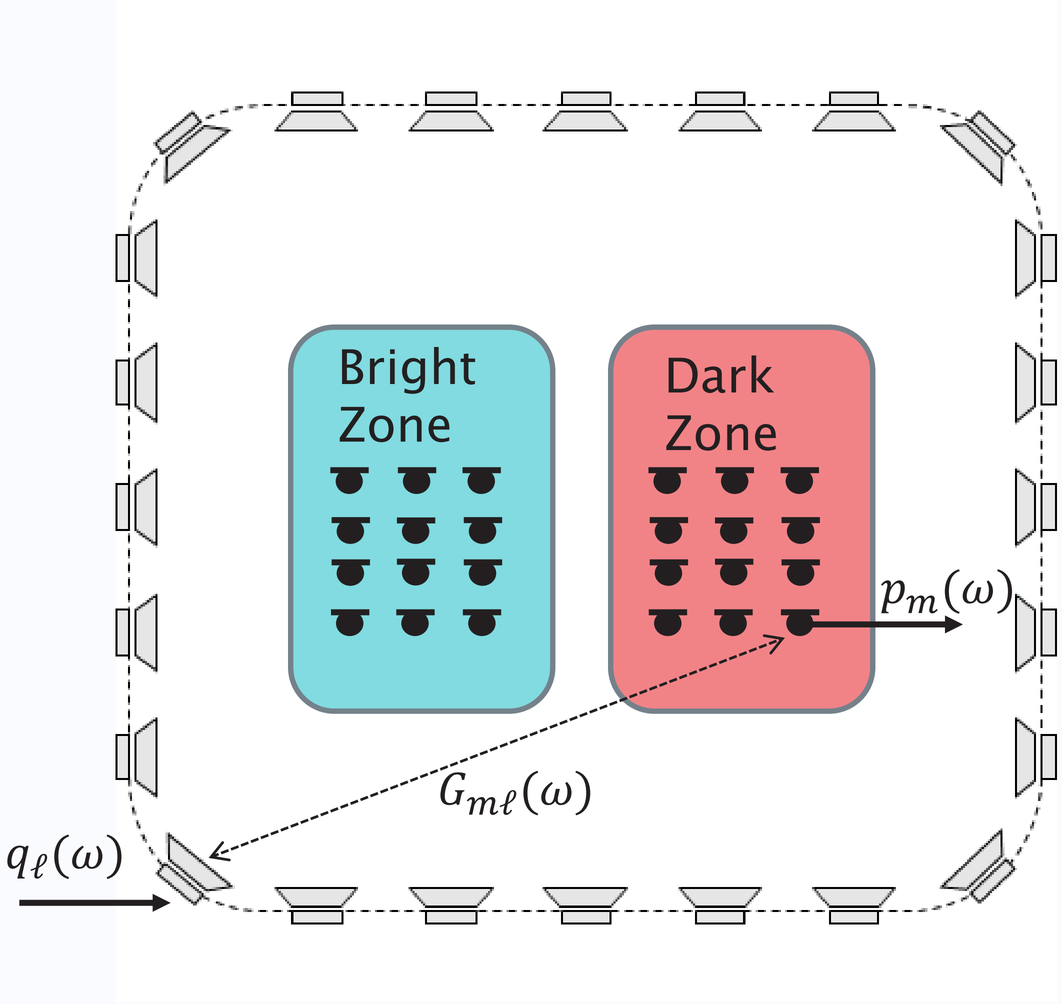
- Deliver an audio signal to the bright zone while minimizing the SPL in the dark zone
- Loudspeaker array and bank of digital filters



Notation

- $q_\ell(\omega)$ driving signal of the ℓ–th loudspeaker
- $p_m(\omega)$ signal of the ℓ–th microphone/control point
- $G_{m\ell}(\omega)$ electroacoustical transfer function between the ℓ–th speaker and the m–th control point

$$p_m(\omega) = \sum_{\ell=1}^{L} G_{m\ell}(\omega) q_\ell(\omega)$$



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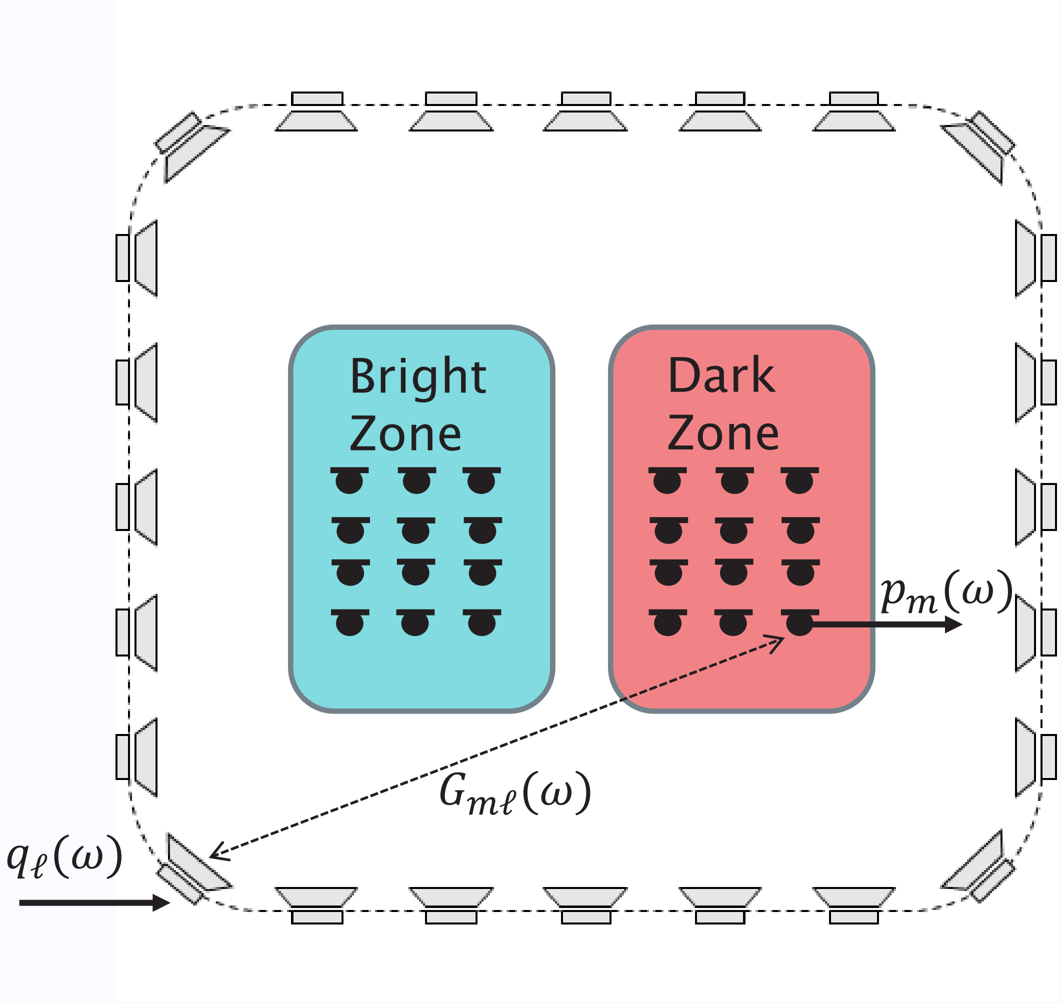
Notation

$$\mathbf{q} = \left[q_1(\omega), q_2(\omega), \ldots q_L(\omega)\right]^T$$

$$\mathbf{p} = \left[p_1(\omega), p_2(\omega), \ldots p_N(\omega)\right]^T$$

$$\mathbf{G} = \begin{bmatrix} G_{1,1}(\omega) & \cdots & G_{1,L}(\omega) \\ \vdots & \ddots & \vdots \\ G_{N,1}(\omega) & \cdots & G_{N,L}(\omega) \end{bmatrix}$$

$$\mathbf{p} = \mathbf{G}\,\mathbf{q}$$



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Pressure matching

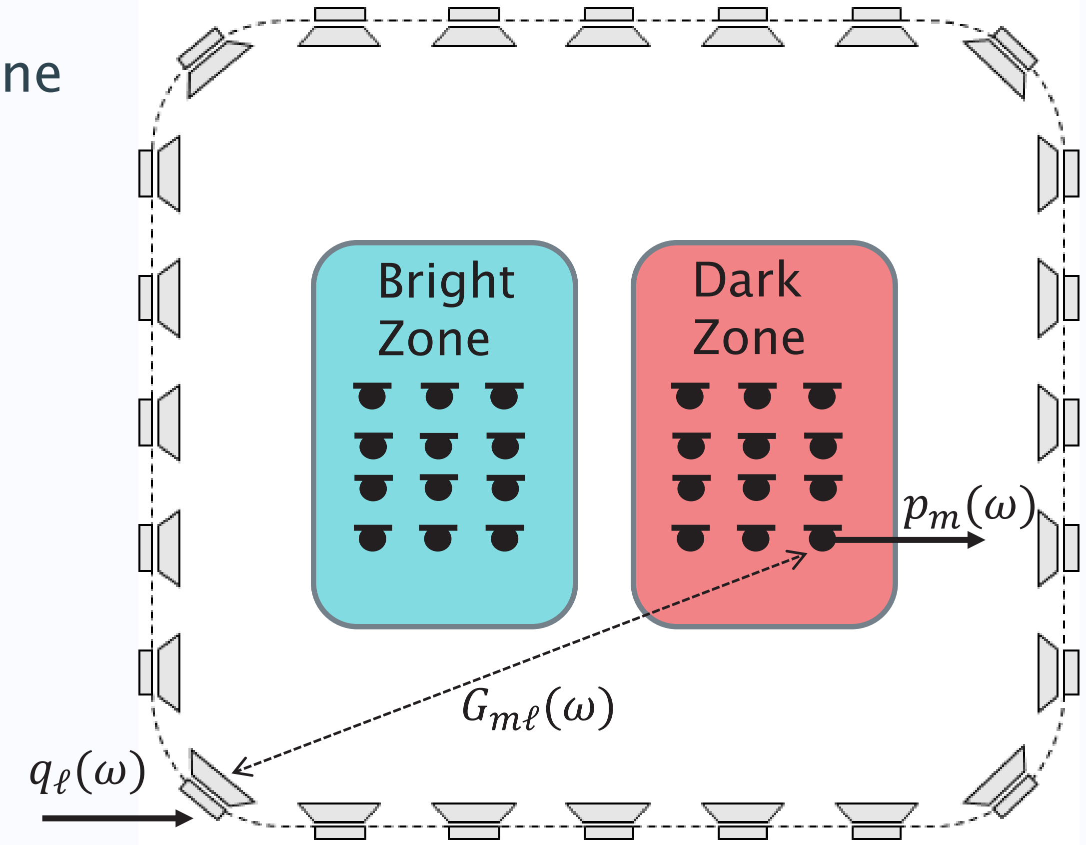
$\mathbf{p}_T$ is the target pressure vector in the bright zone

$$\mathbf{p}_T = \Big[\underbrace{p_1, p_2, \ldots, p_{N_B}}_{\text{Zone 1}}, \underbrace{0, 0, \ldots, 0}_{\text{Zone 2}}\Big]^T$$

$N > L \rightarrow$ overdetermined problem

$$J = \left\| \mathbf{p} - \mathbf{p}_T \right\|^2 = \left\| \mathbf{G}\,\mathbf{q} - \mathbf{p}_T \right\|^2$$

$$\mathbf{q}_{opt} = \mathbf{G}^{\dagger}\mathbf{p}_T = \left(\mathbf{G}^H\mathbf{G}\right)^{-1}\mathbf{G}^H\mathbf{p}_T$$



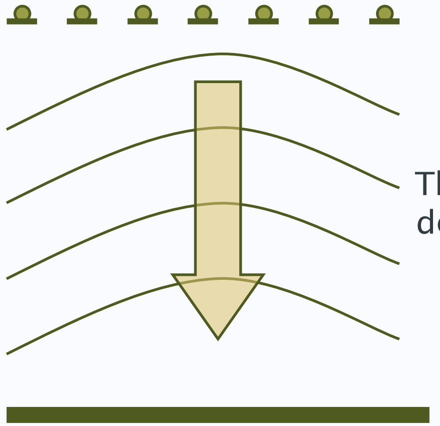
$$\mathbf{p} = \mathbf{G}\,\mathbf{q}$$

Kirkeby and Nelson, 1993. “Reproduction of plane wave sound fields”, JASA

Relation to acoustical holography

ACOUSTICAL HOLOGRAPHY

Measurement of sound field



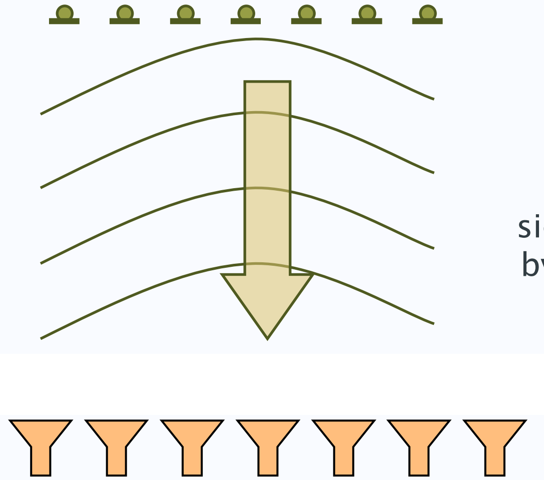
The source strength is determined by solving an inverse problem

Vibrating structure that generates and acoustic field

- The (physical) solution exists

SOUND FIELD CONTROL

Desired sound field



The loudspeaker signals are calculated by solving an inverse problem

Array of loudspekaers

- The solution might not exist!

Ill-conditioning and Tikhonov Regularization

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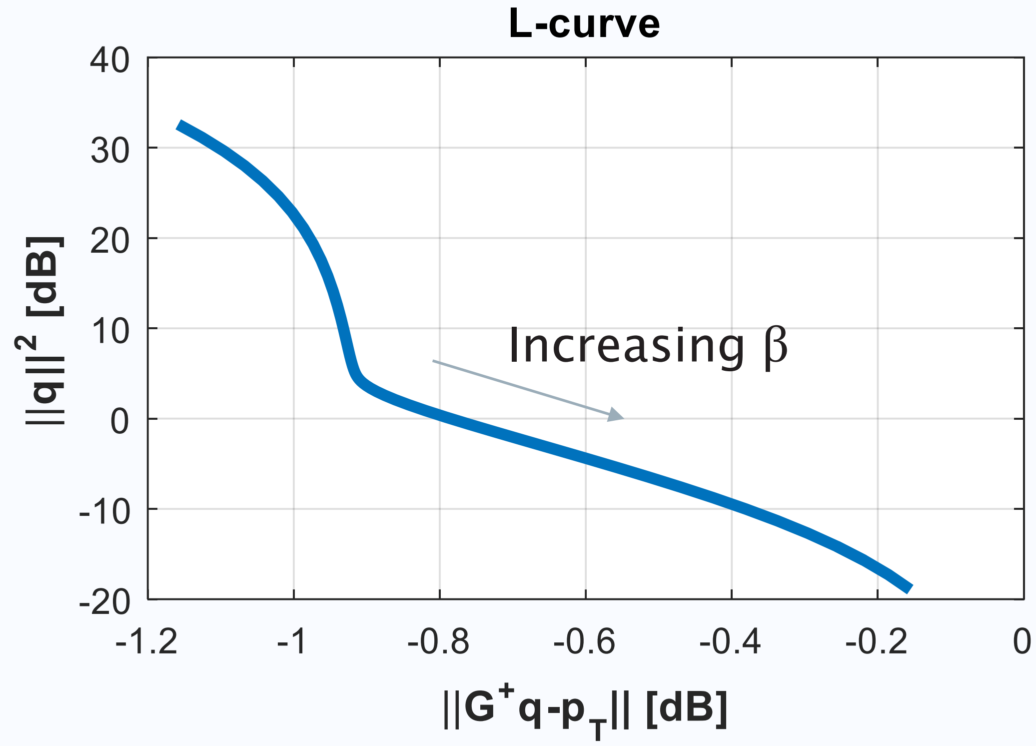
Array effort $E(\omega) \propto \|\mathbf{q}\|^2$

Effort my be very large if **G** is ill-conditioned, leading to unstable solutions.

Cost function with Tikhonov regularization

$$J = \left\|\mathbf{G}\,\mathbf{q} - \mathbf{p}_T\right\|^2 + \beta\left\|\mathbf{q}\right\|^2$$

$$\mathbf{q}_{opt} = (\mathbf{G}^H\mathbf{G} + \beta\mathbf{I})^{-1}\mathbf{G}^H\mathbf{p}_T$$



Reduces of array effort, but increases error

Kirkeby and Nelson, 1993. “Reproduction of plane wave sound fields”, JASA

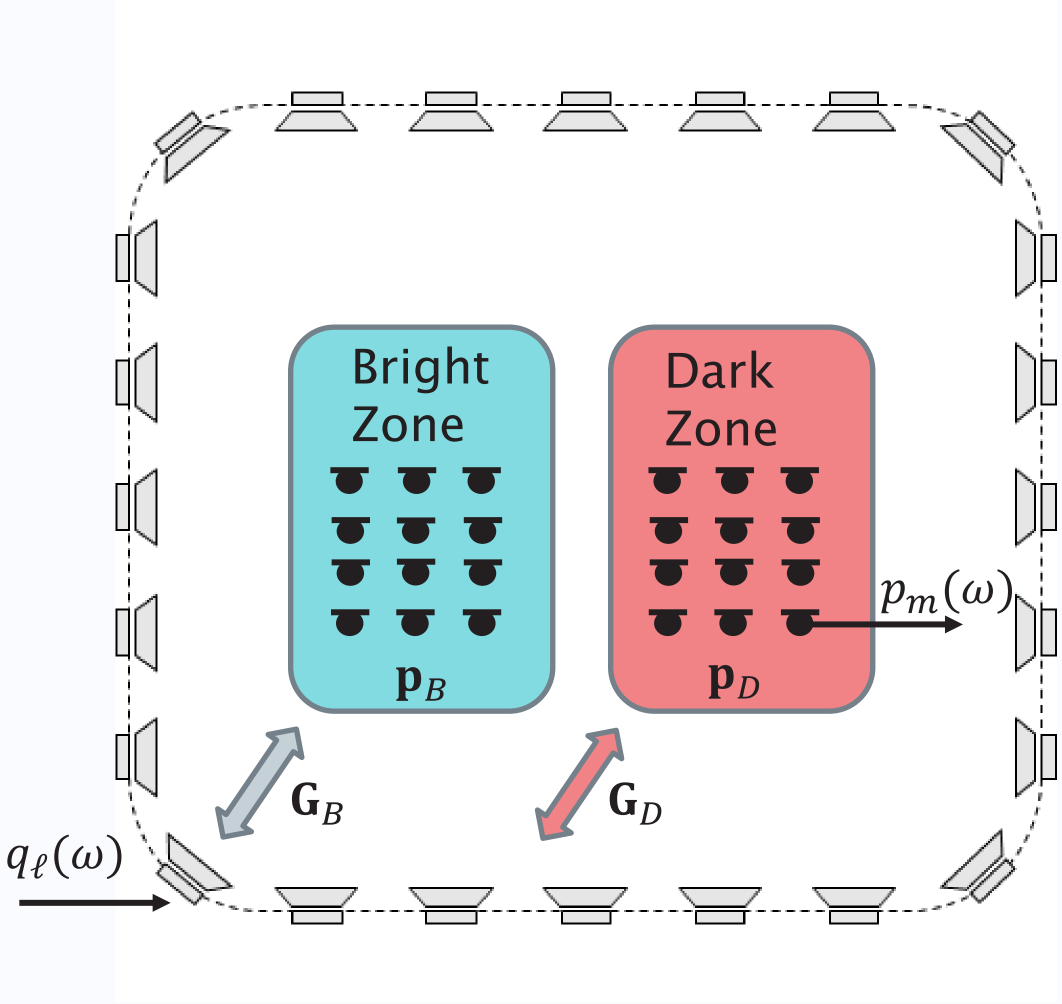
Acoustic contrast

It is the ratio of the average acoustic potential energy in two zones

$$AC = \frac{< E_B >}{< E_D >} \approx \frac{\frac{1}{N_B}\sum_m |p_m^{(\mathrm{B})}|^2}{\frac{1}{N_D}\sum_m |p_m^{(\mathrm{D})}|^2}$$

Target to interferer ratio

It is the ratio of the energy of the desired signal and of the interfering signal i a given zone



$$\mathbf{p}_{B/D} = \mathbf{G}_{B/D}\,\mathbf{q}$$

Acoustic contrast maximisation

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- Direct formulation:

  Maximise $\|\mathbf{p}_B\|^2$

  s.t. $\|\mathbf{p}_D\|^2 = D$ and $\|\mathbf{q}\|^2 \leq E$

- Indirect formulation:

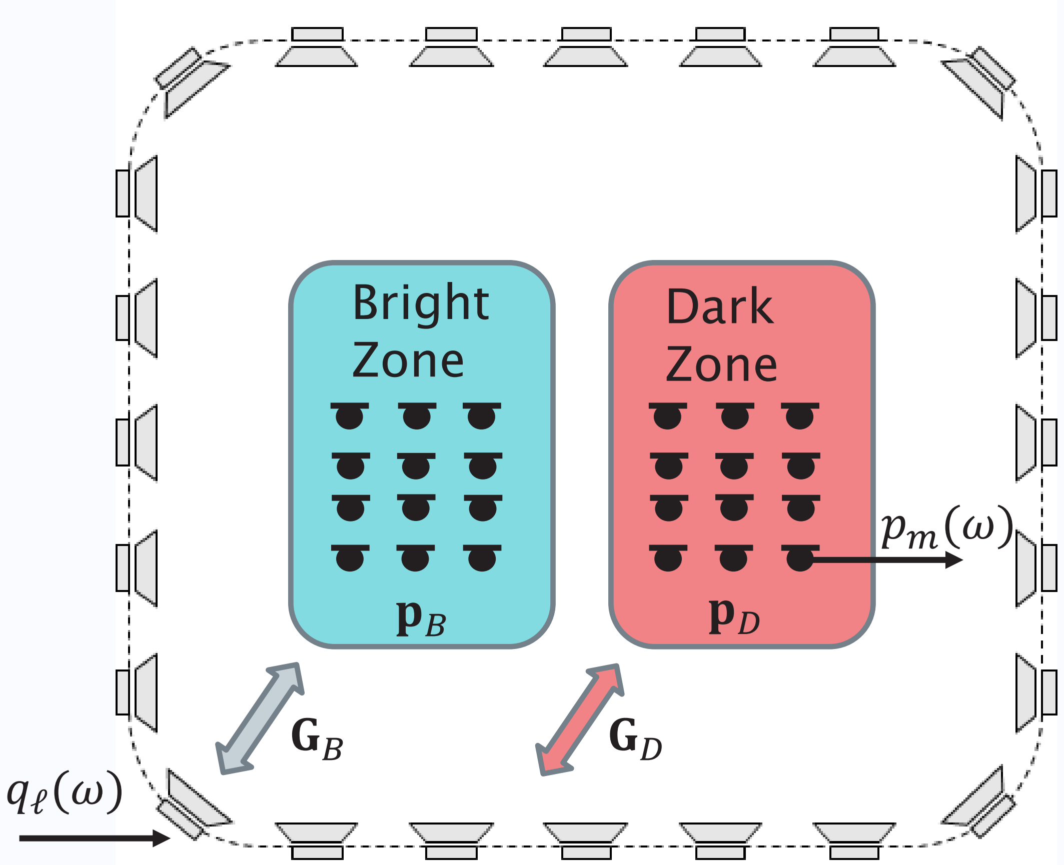
  Minimise $\|\mathbf{p}_D\|^2$

  s.t. $\|\mathbf{p}_B\|^2 = B$ and $\|\mathbf{q}\|^2 \leq E$

- Maximise energy difference

  Maximise $\|\mathbf{p}_B\|^2 - \alpha\|\mathbf{p}_D\|^2$
  s.t. $\|\mathbf{q}\|^2 \leq E$

$$\mathbf{p}_{B/D} = \mathbf{G}_{B/D}\,\mathbf{q}$$



Choi and Kim, 2002. "Generation of an acoustically bright zone with an illuminated region using multiple sources". *JASA*
Elliott, S.J., et al., 2012. "Robustness and regularization of personal audio systems". *TASLP*.
Lee, T., et al, 2018, "A Unified Approach to Generating Sound Zones Using Variable Span Linear Filters", ICASSP.

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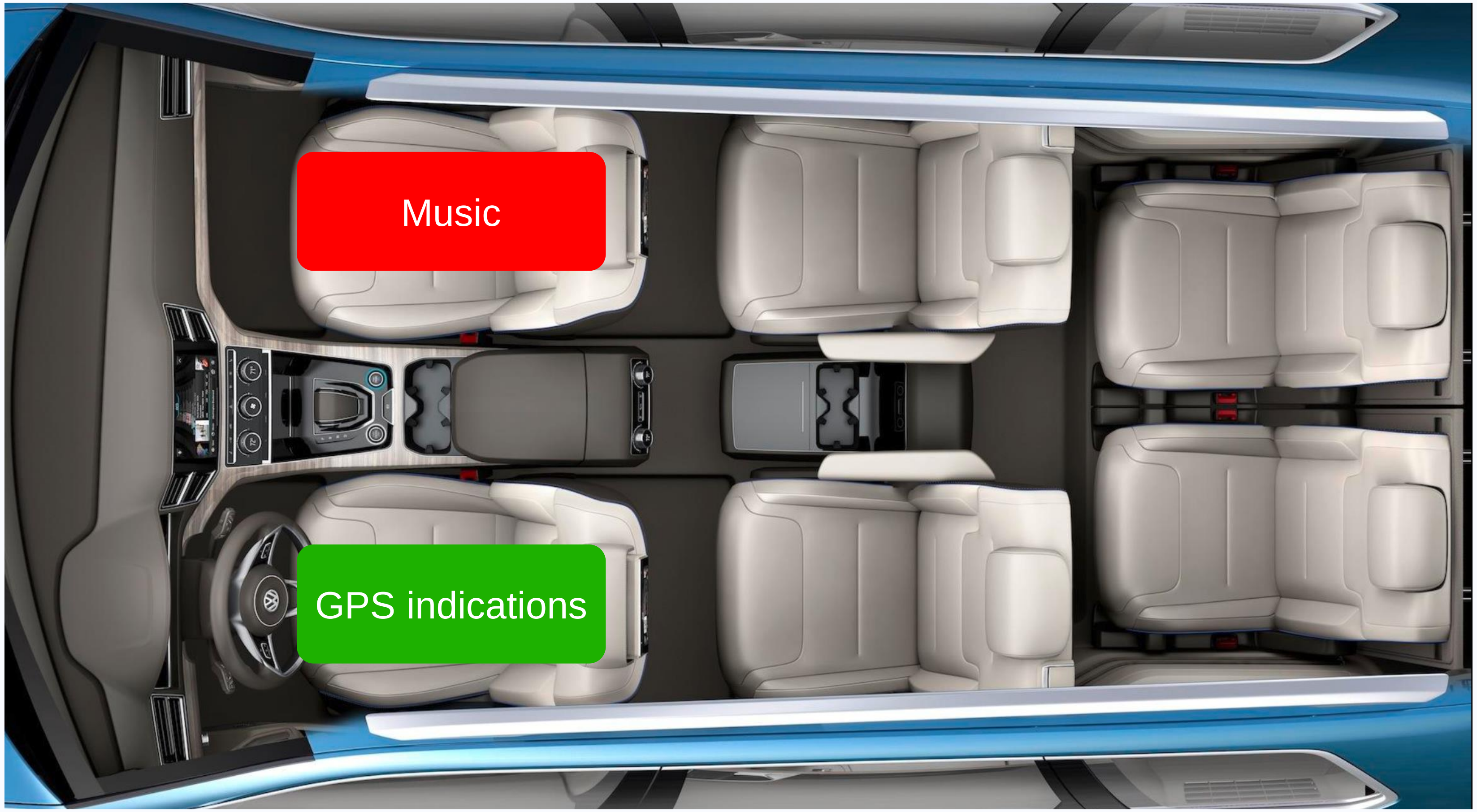
Multi-zone audio delivery in a car



- Acoustically challenging environment
- Time-varying system:
  - Number and position of occupants
  - Temperature and Humidity
  - Windows

M. Olsen and M. B. Møller, 2017, " Sound zones: On the effect of ambient temperature variations in feed-forward systems," *Proc. of the 142nd AES Convention*.

Frequency-dependent trim of measured Impulse Responses

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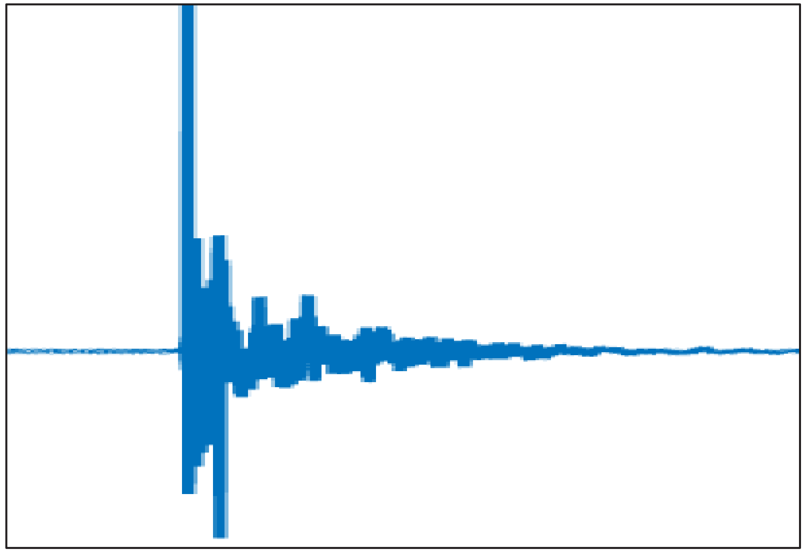
$$J = \left\| \mathbf{G}\,\mathbf{q} - \mathbf{p}_T \right\|^2$$



Loudspeaker Impulse response measured in a car

ASK Automotive Industries Group

UNIVERSITÀ DI PARMA

M. Ebri, N. Strozzi, F.M. Fazi, A. Farina, and L. Cattani, 2020. "Individual Listening Zone with Frequency-Dependent Trim of Measured Impulse Responses," 149 AES Convention, Paper 10409.

Frequency-dependent IR trimming

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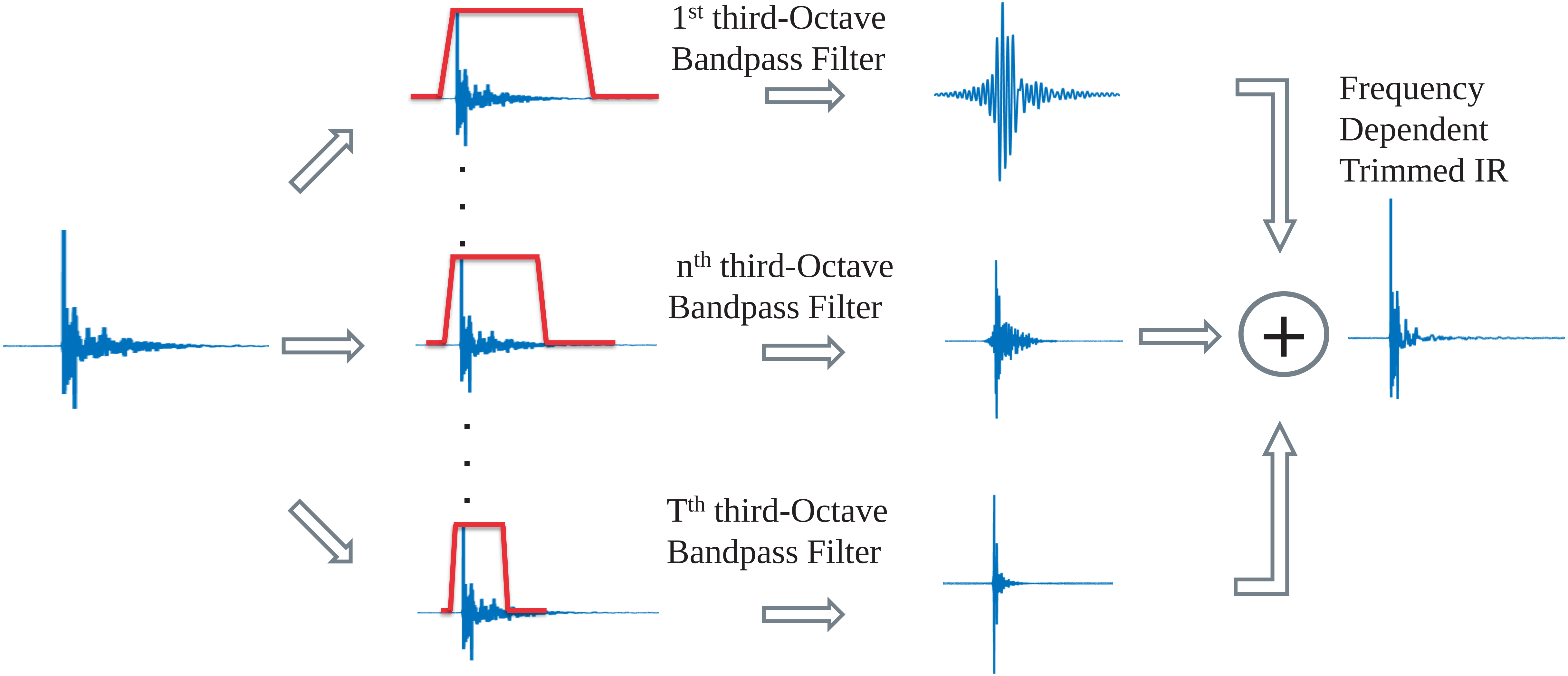

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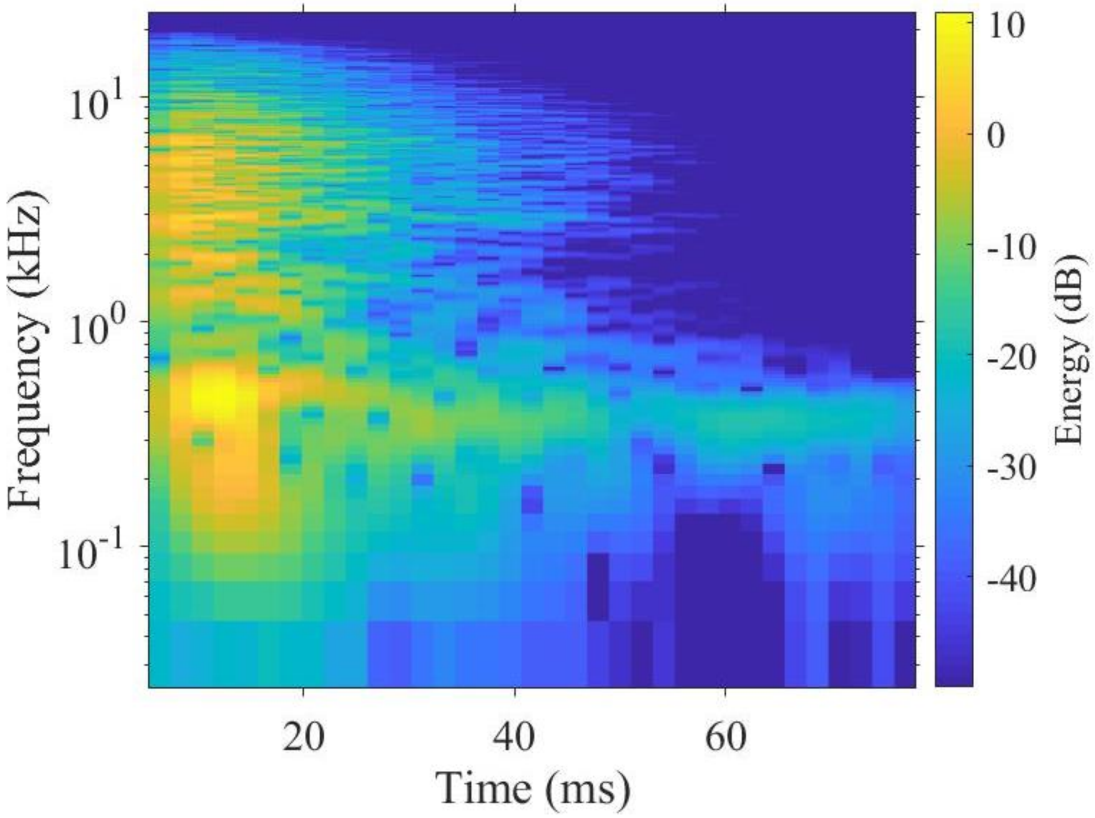
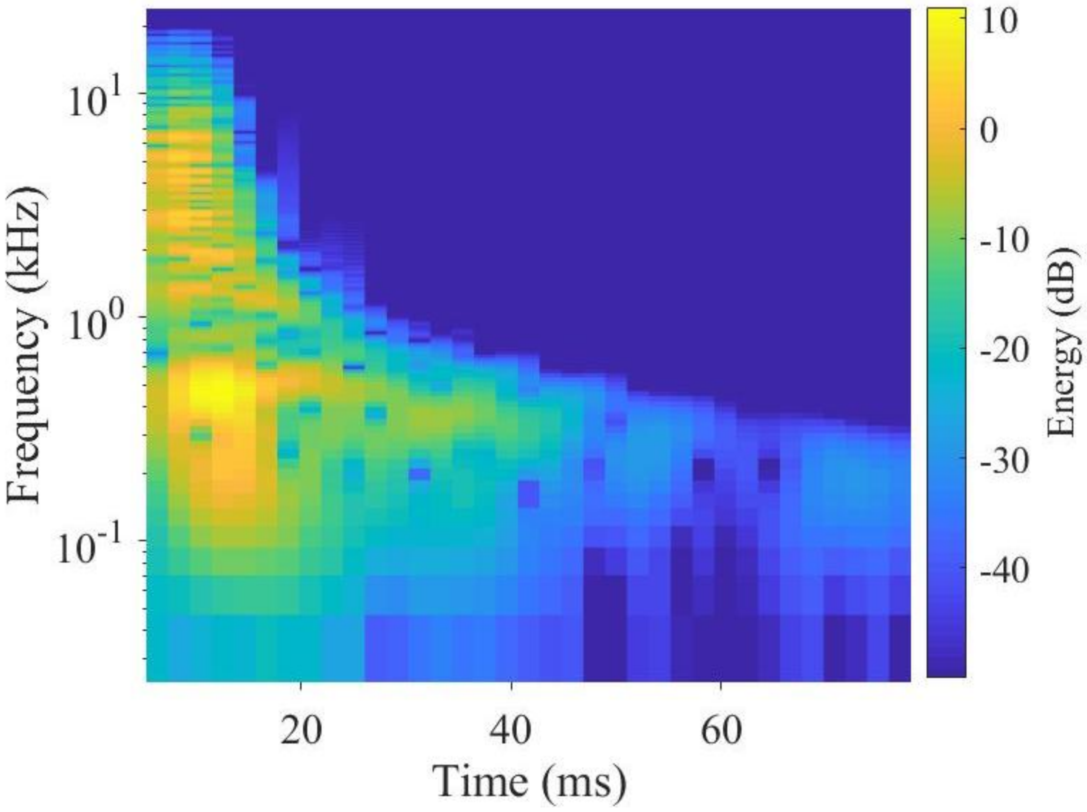
Frequency-dependent IR trimming



Spectrogram of original IR



Spectrogram of trimmed IR

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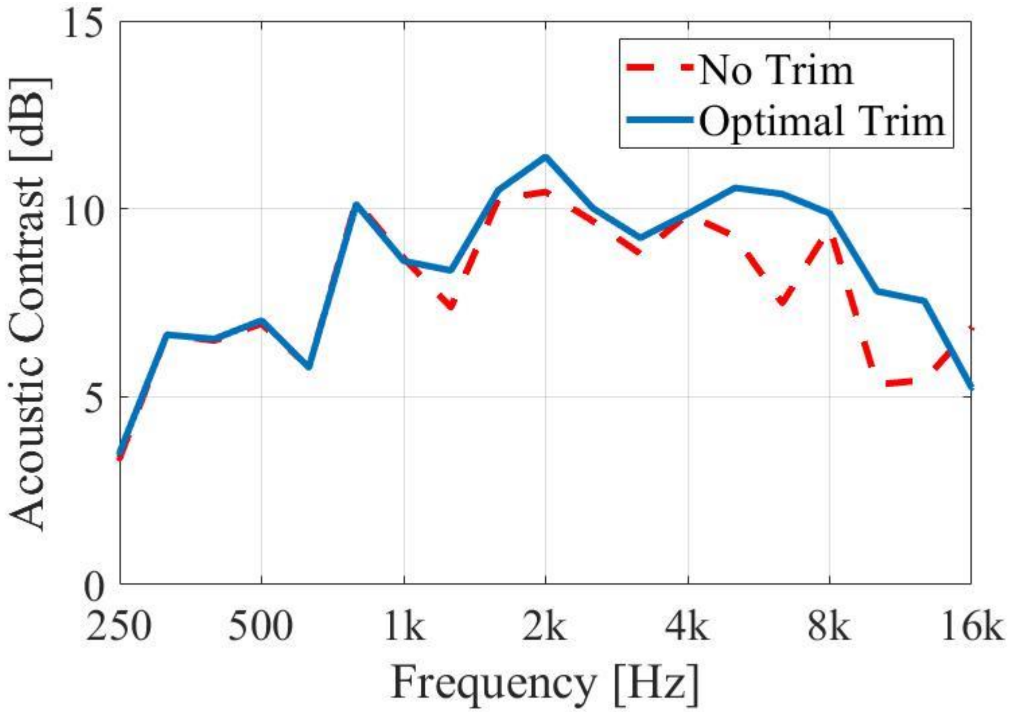
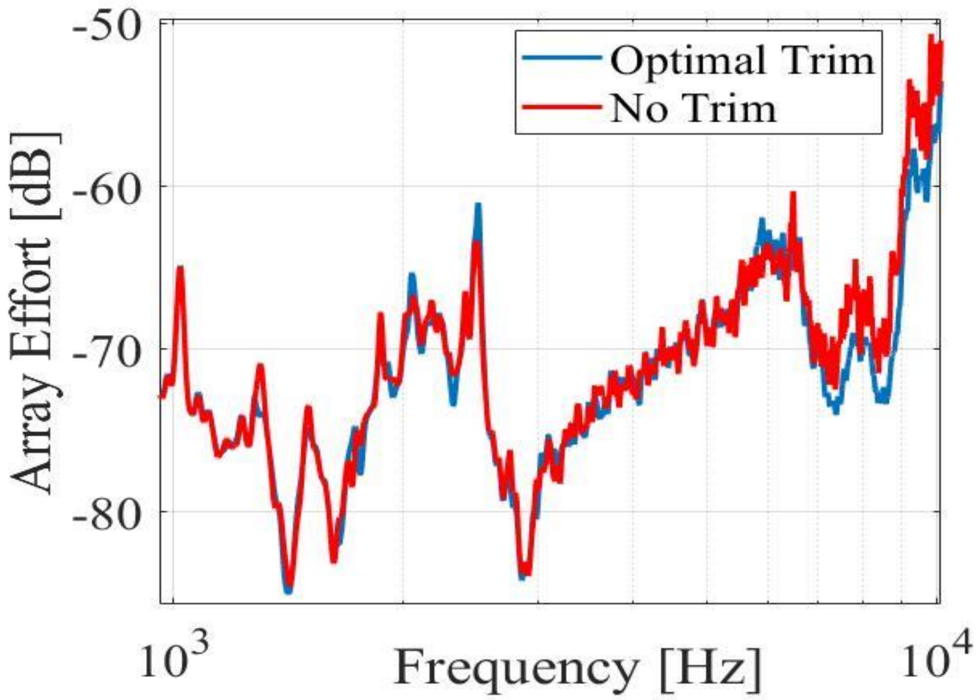
Frequency-dependent IR trimming



Acoustic contrast



Array effort

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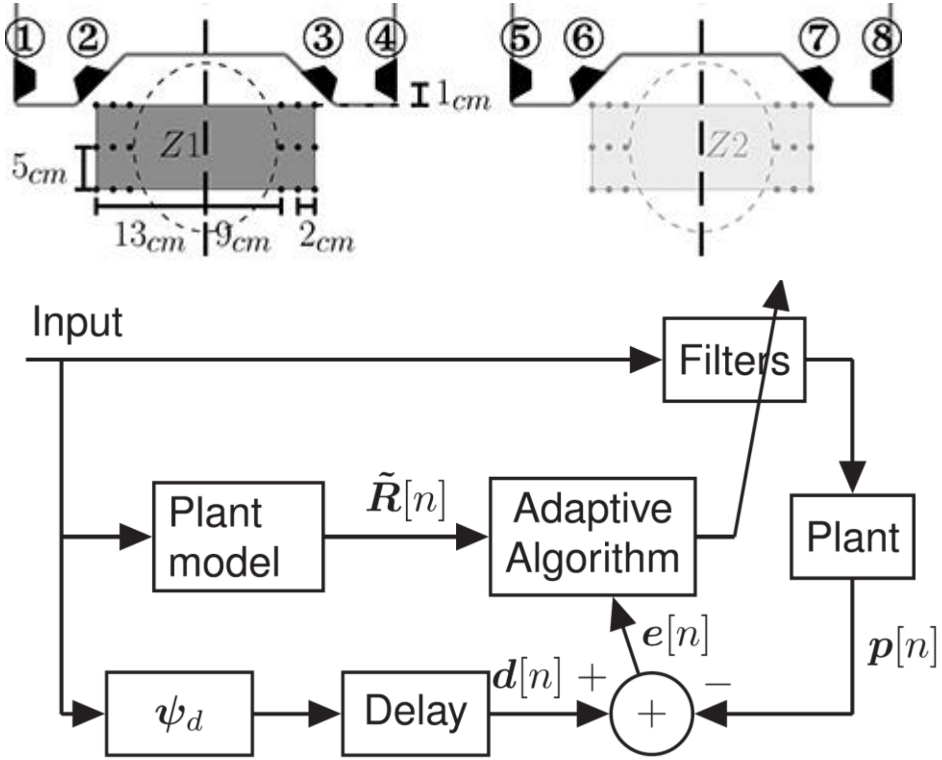
Adaptive multi-zone with FxLMS



L. Vindrola, M. Melon and J.-C. Chamard, "Use of the filtered-x least-mean-squares algorithm to adapt personal sound zones in a car cabin," The Journal of the Acoustical Society of America, vol. 150, no. 1779, 2021.

Adaptive multi zone with multi-sensor array

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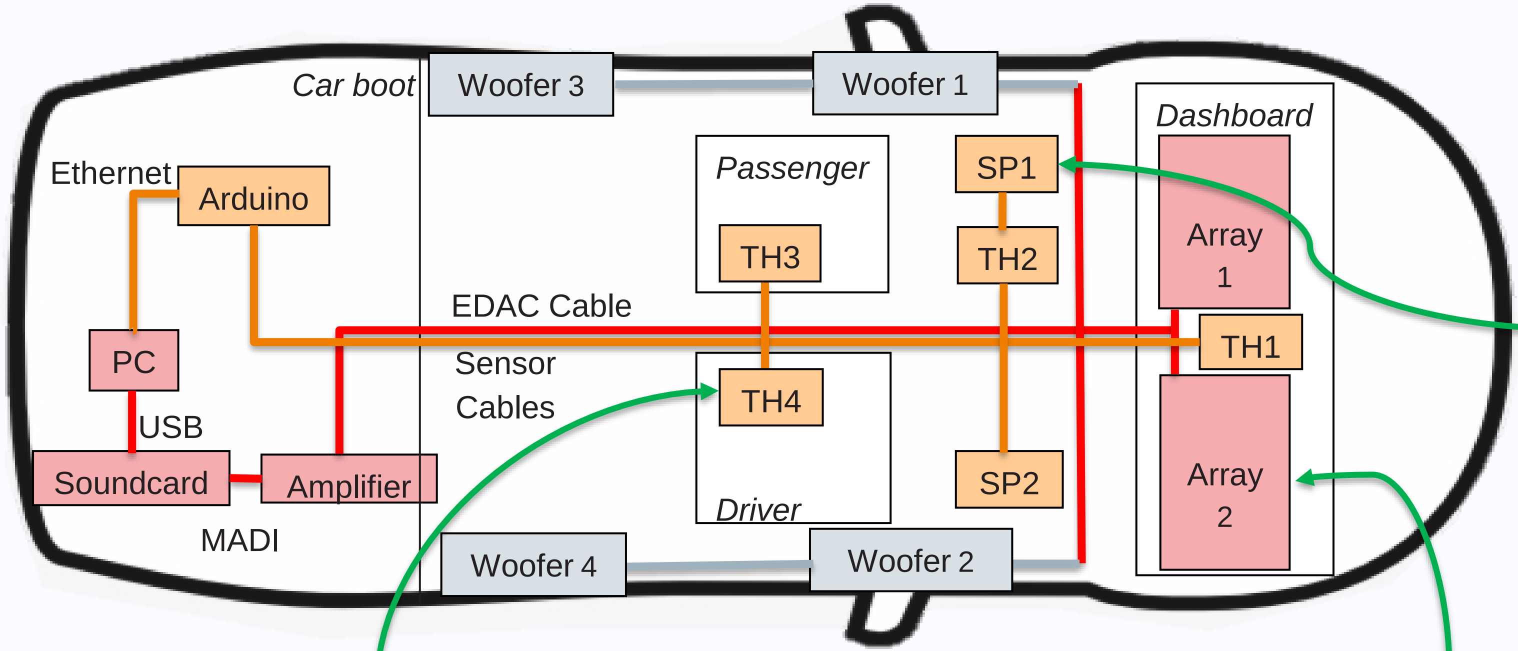
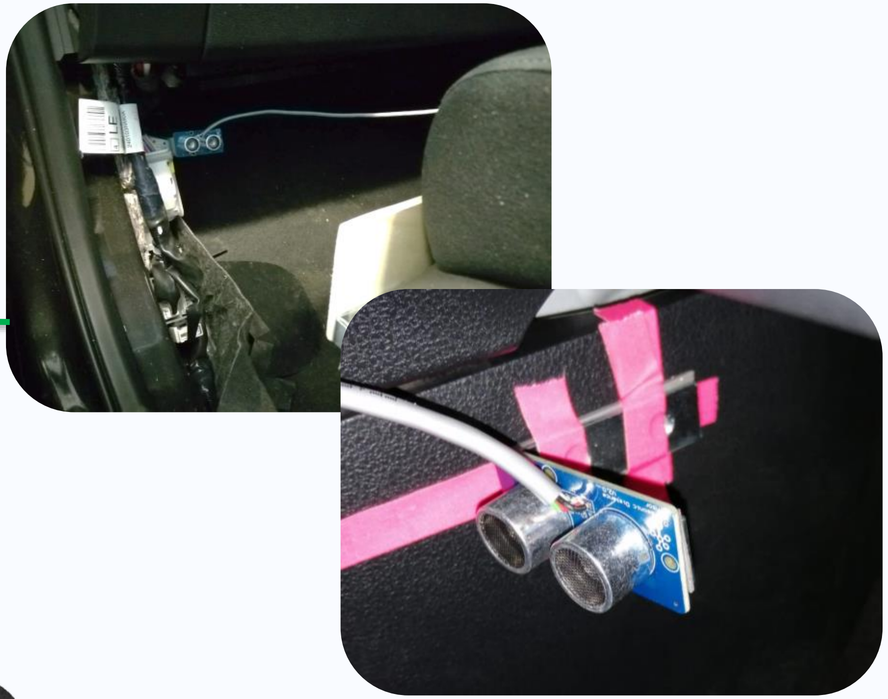
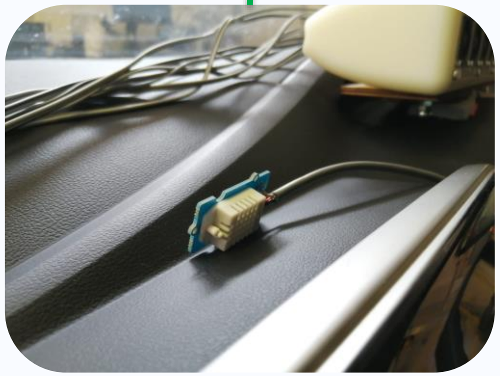




Ultrasonic distance sensor



Temperature/humidity sensor

Dashboard loudspeaker arrays

In collaboration with

ASK Automotive Industries Group

Adaptive multi zone with multi-sensor array

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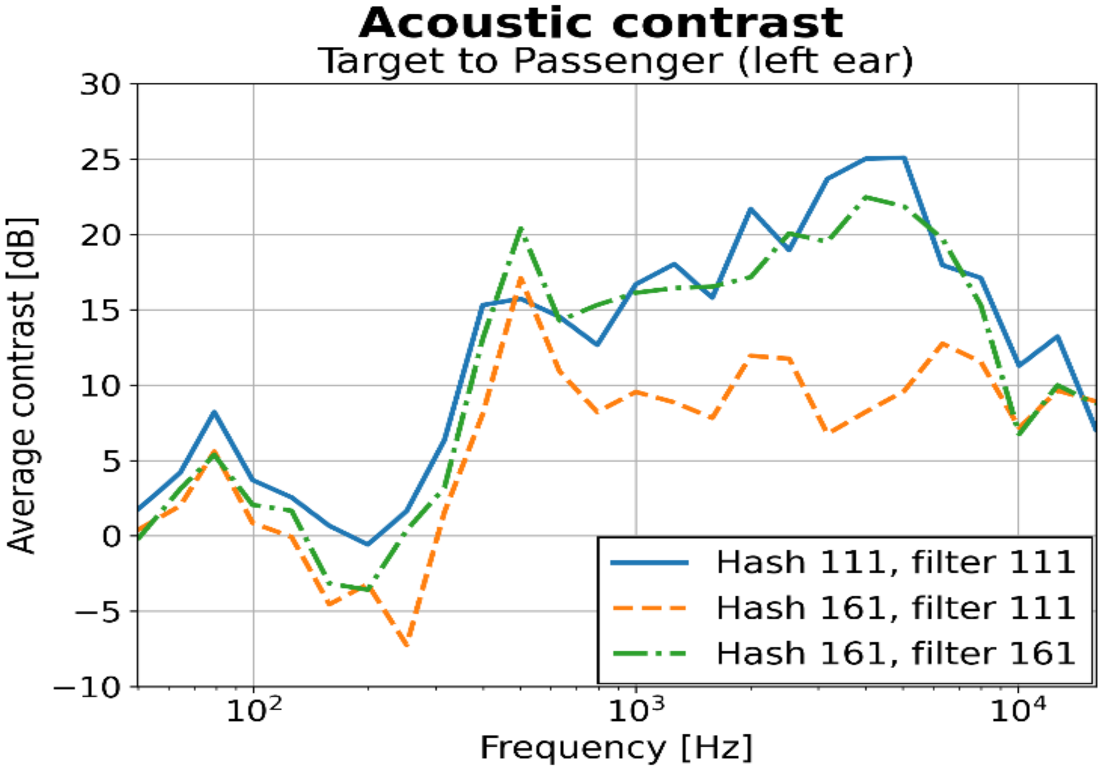
Acoustic contrast before and after passenger movement. Passenger in bright zone.



Blue – initial measurement

Orange – change in environment

Green – adaptive filter

C. Flint, Z. Francis-Cox, D. Gonsalves, M. Mehhovits, L. Turoff, W. Gallian, F.M. Fazi, 2021, "Advanced car audio system", Group Design Report, University of Southampton.

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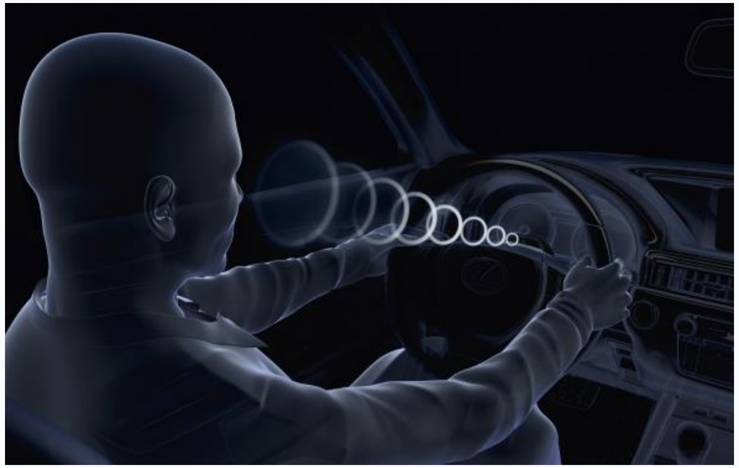
Head tracking and computer vision

Lexus



Bosch

Continental

Nissan

Active Control with Head Tracking

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Elliott, S.J., Jung, W. & Cheer, J., 2018, "Head tracking extends local active control of broadband sound to higher frequencies". *Sci Rep* **8**, 5403.

3D audio with listener tracking

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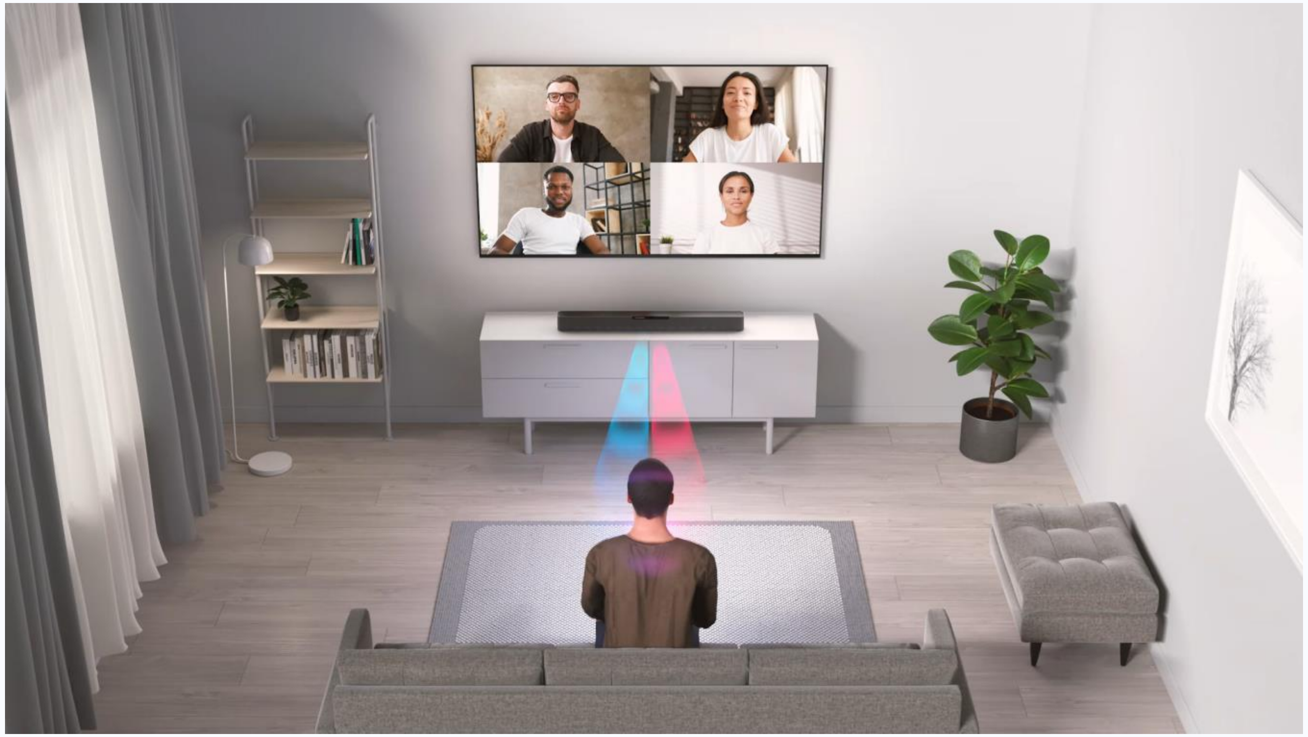

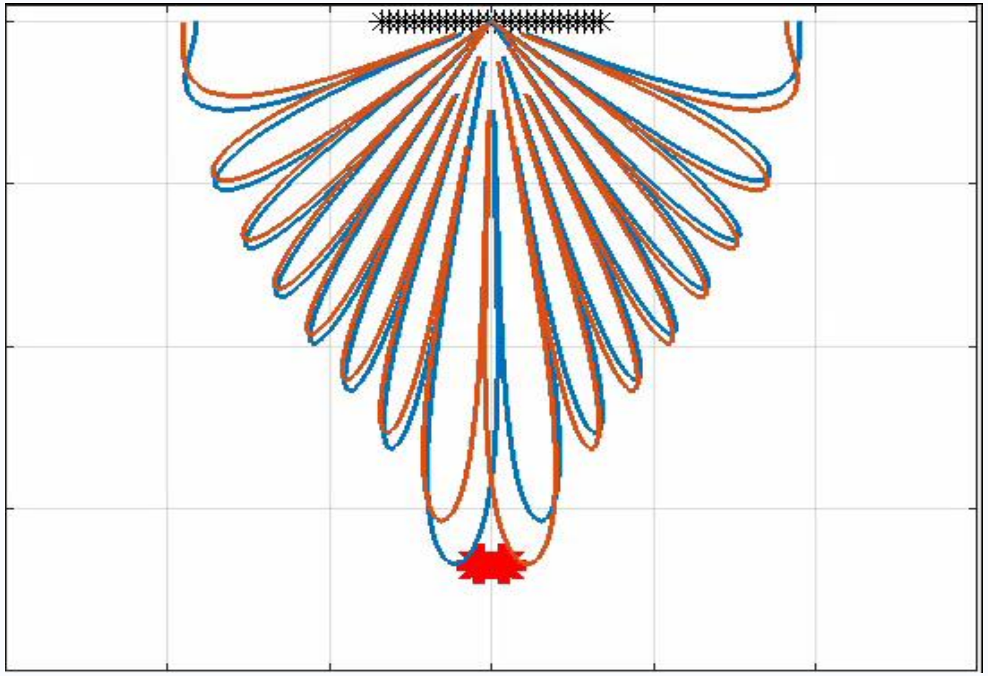

AUDIOSCENIC

The listener is tracked with a camera and new loudspeaker filters are created in real-time to adapt to the user's position. This is crucial for the quality of spatial audio reproduction

Adaptive multi-zone and 3D audio with listener tracking

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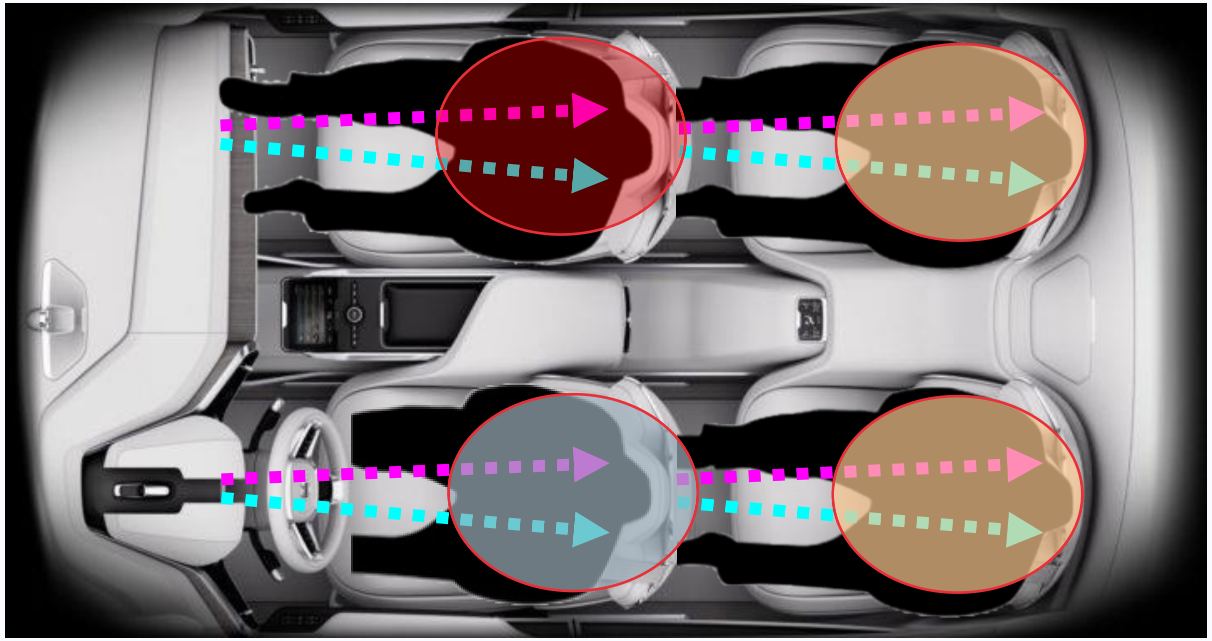
- Position of car occupants is tracked with one or more cameras
- Personalised 3D audio signals are independently delivered to each occupant
- The algorithm adapts in real-time depending on the number and position of listeners



AUDIOSCENIC

Conclusions

- Theoretical review of establish techniques for multi-zone audio delivery
- Novel solutions for multi-zone audio in cars:
  - Trimming of measured impulse responses
  - Adaptative system based on FxLMS
  - Adaptative system based on multi-sensor array
  - Adaptative system based on listener tracking
- Many open challenges (e.g. psychoacoustics adaptation)
- New technologies have recently been developed – stay tuned!