Speech & Audio Processing / Part-II

Digital Audio Signal Processing
DASP

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Outline

- Aims/Scope
- Contents
- Case Study: Hearing Instruments
- Lectures/Lab Sessions/Exam Website/Questions

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Aims/Scope

Aim is 2-fold..

- Speech & audio per se
  S & A industry in Belgium/Europe/…

  Topics: Noise Reduction / Acoustic Echo & Feedback Cancellation / Active Noise Control / Sound Reproduction / ..etc
- Develop basic signal processing tools/principles which are also used in many other fields

  Spatial filter design (for wireless comms)
  Adaptive filter algorithms, filtered-X LMS (for active vibration control)
  Kalman filters (for automatic control, navigation, ..)
  ..etc

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Contents

- Chapter-1: Introduction
- Chapter-2: Single-Channel Noise Reduction
- Chapter-3: Microphone Array Processing
  – Fixed Beamforming
- Chapter-4: Microphone Array Processing
  – Adaptive Beamforming
  – Multi-Channel Noise Reduction
- Chapter-5: Acoustic Echo & Feedback Cancellation
- Chapter-6: Sound Field Control
- Chapter-7: Sound Field Recording and Reproduction
  (= **Guest Lecture** Dr. Enzo De Sena, Univ.Sussex, UK)
- Chapter-8: Hearing Aid Signal Processing
  (= **Guest Lecture** Dr. Jesper Jensen, Oticon/Demant, DK)

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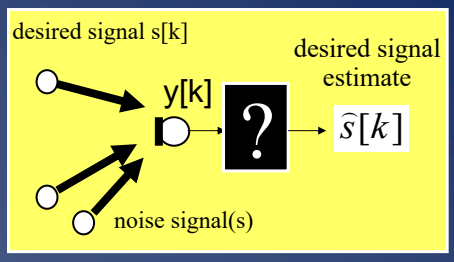
Contents: Chapter-2

Single-Channel Noise Reduction

$$y[k] = s[k] + n[k]$$

desired signal contribution

noise contribution



- Spectral subtraction methods (spectral filtering)
- Iterative methods based on speech modeling (Wiener & Kalman Filters)

Applications: smartphones, conferencing, hearing aids, …

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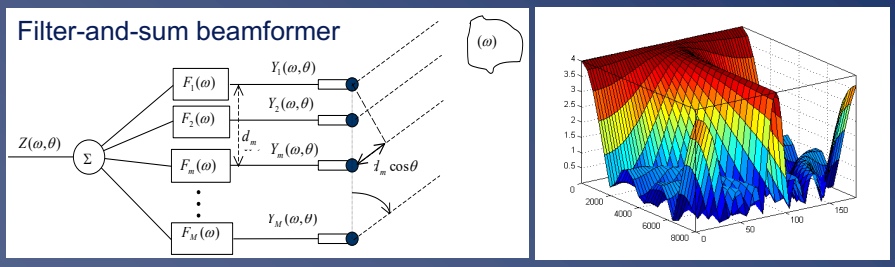
Contents: Chapter-3

Microphone Array Processing

– Fixed Beamforming

Referred to as ‘spatial filtering’ (similar to ‘spectral filtering’)



Applications: smartphones, conferencing, hearing aids, …

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Contents: Chapter-4

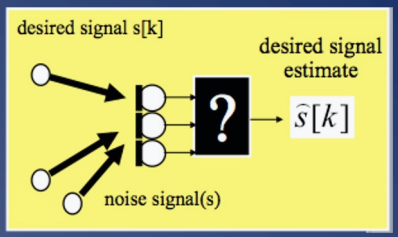
Microphone Array Processing

– Adaptive Beamforming

- Known (fixed) speaker position
- Unknown (time-varying) noise field

– Multi-channel noise reduction

- Wiener filtering approach
  = spectral+spatial filtering



Applications: smartphones, conferencing, hearing aids, …

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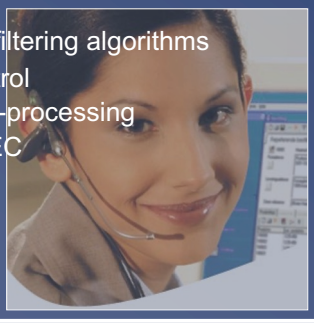
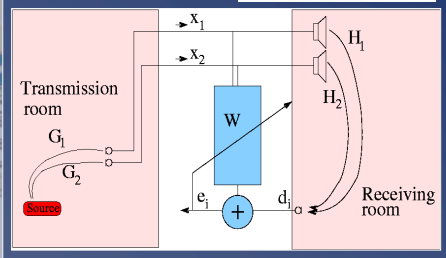
Contents: Chapter-5

Acoustic Echo & Feedback Cancellation

Adaptive filtering problem:
- Non-stationary/wideband/… speech signals
- Non-stationary/long/… acoustic channels

Adaptive filtering algorithms
AEC Control
AEC Post-processing
Stereo AEC





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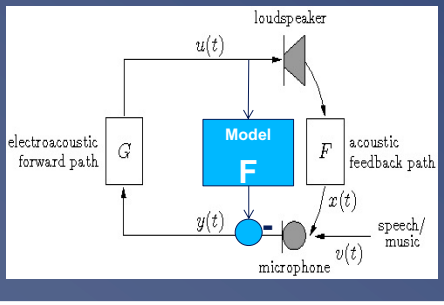
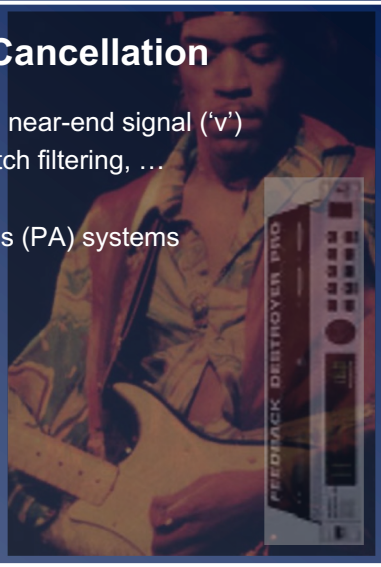
Contents: Chapter-5

Acoustic Echo & Feedback Cancellation

- Correlation between filter input (`u') and near-end signal ('v')
- Fixes : noise injection, pitch shifting, notch filtering, …

Applications: Hearing aids, public address (PA) systems





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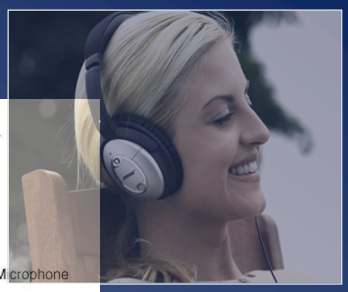
Contents: Chapter-6

Sound Field Control

- **Active Noise Control**



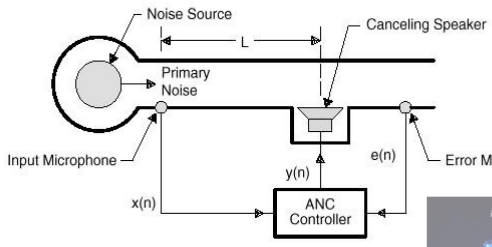
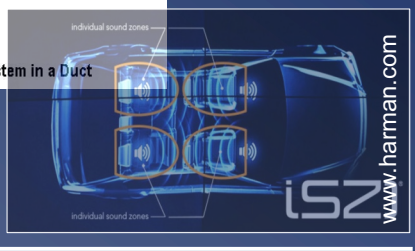


Fig 2. Single-Channel Broadband Feedforward ANC System in a Duct

Solutions based on `filtered-X LMS' algorithm
Applications : Active headsets/ear defenders

- **Sound Zoning**



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Contents: Chapter-7

Sound Field Recording and Reproduction

Guest Lecture: Dr. Enzo De Sena, University of Surrey, UK

Friday Nov. ??, 10.30-12.30
attendance = mandatory!

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Contents: Chapter-8

Hearing Aid Signal Processing

Guest Lecture: Dr. Jesper Jensen, Oticon/Demant, DK

Friday Nov ??, 10.30-12.30
attendance = mandatory!

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Outline

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Case Study: Hearing Instruments 1/15

DASP Challenges in hearing instruments (next slides)

- Dynamic range compression
- Noise reduction (=chapter 2-3-4, chapter 7)
- Dereverberation
- Acoustic feedback cancellation (=chapter 5)
- Active noise control (=chapter 6)
- Etc.

Technology Challenges in hearing instruments

- Small form factor (cfr. user acceptance)
- Low power: 1…5mW (cfr. battery lifetime ≈ 1 week)
- Low processing delay: 10msec (cfr. synchronization with lip reading)

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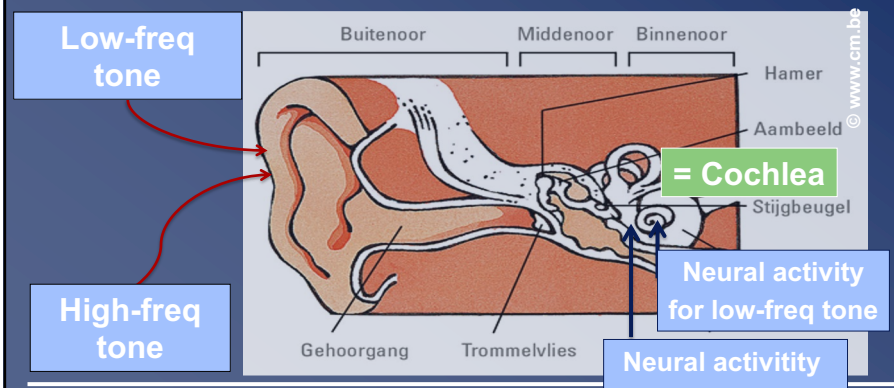
Case Study: Hearing Instruments 2/15

Hearing

- Outer ear/middle ear/inner ear
- Tonotopy of inner ear: spatial arrangement of where sounds of different frequency are processed



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Case Study: Hearing Instruments 3/15

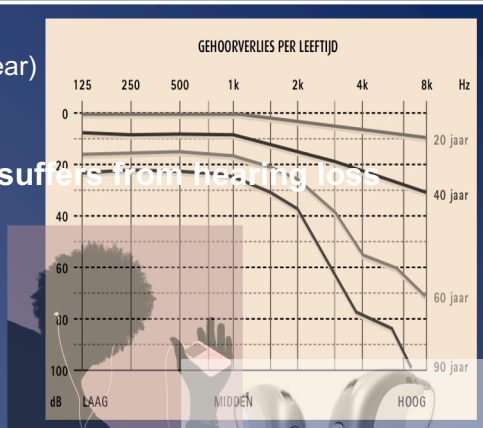
Hearing loss types
- Conductive (~outer/middle ear)
- Sensorineural (~inner ear)
- Mixed

One in six adults (Europe) suffers from hearing loss

…and still increasing

Typical causes
- Aging
- Exposure to loud sounds
- …

Hearing Instruments
- Hearing aids: audio output
- Bone anchored hearing aids: vibration output
- Cochlear implants: electrical stimulation output
- …



[Source: Lapperre]

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Case Study: Hearing Instruments 4/15

Hearing Aids (HAs)
- Audio input/audio output (`microphone-processing-loudspeaker')
- 'Amplifier', but so much more than an amplifier!!
- History:
  - Horns/trumpets/…
  - `Desktop' HAs (1900)
  - Wearable HAs (1930)
  - Digital HAs (1980)
- State-of-the-art:
  - MHz's clock speed
  - Millions of arithmetic operations/sec, …
  - Multiple microphones

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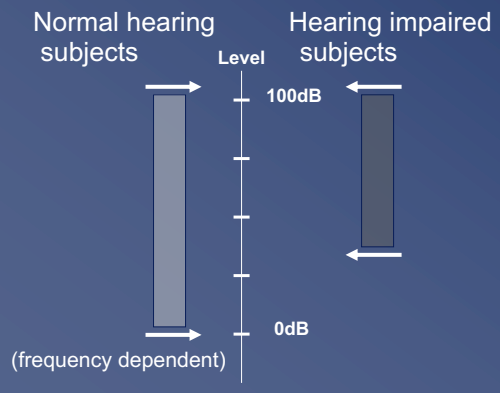
Case Study: Hearing Instruments 5/15

- **DASP Challenges: Dynamic range compression**

Dynamic range & audibility



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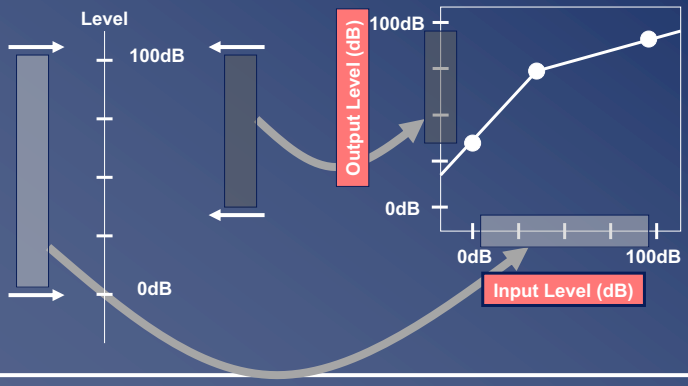
Case Study: Hearing Instruments 5/15

- **DASP Challenges: Dynamic range compression**

Dynamic range & audibility

Hence need (frequency &) signal amplitude dependent amplification



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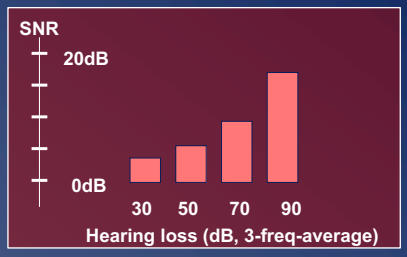
Case Study: Hearing Instruments 6/15

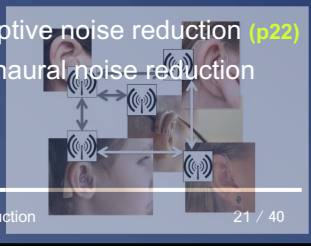
However: Audibility does not imply intelligibility

Hearing impaired subjects need 5..10dB larger signal-to-noise ratio (SNR) for speech understanding in noisy environments



Need for **noise reduction** (=speech enhancement) algorithms:

- State-of-the-art: monaural 2-microphone adaptive noise reduction (p22)
- Near future: external microphone nodes & binaural noise reduction (with wireless links) (p23-23)
- Not-so-near future: cooperative HAs (p25)



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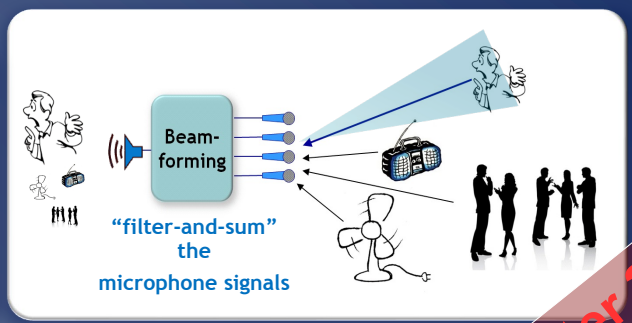
Case Study: Hearing Instruments 7/15

- **DASP Challenges: Noise reduction & beamforming**

Multimicrophone 'beamforming', typically with 2 microphones
e.g. 'directional' front microphone and 'omnidirectional' back microphone



PS: related/specific challenge = wind noise

Chapter 3-4

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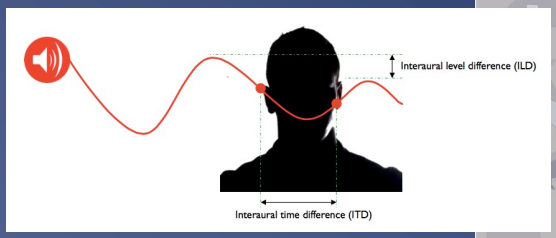
Case Study: Hearing Instruments 8/15

Binaural hearing based on binaural auditory cues

- **ITD (interaural time difference)**
- **ILD (interaural level difference)**



- Binaural cues (ITD: f < 1500Hz, ILD: f > 2000Hz) used for
  - Sound localization
  - Noise reduction
    =`Binaural unmasking' ('cocktail party' effect) : 0-5dB

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Case Study: Hearing Instruments 9/15

Binaural hearing aids

- Two hearing aids (L&R) with wireless link & cooperation
- Opportunities:
  - More signals (e.g. 2*2 microphones)
  - Better sensor spacing (17cm i.o. 1cm)
- Constraints: power/bandwith/delay of wireless link
  - ..10kBit/s: coordinate program settings, parameters,…
  - ..300kBits/s: exchange 1 or more (compressed) audio signals
- Challenges:
  - Improved localization through (speech) cue preservation
  - Improved noise reduction through (speech+noise) cue preservation (=benefit from binaural unmasking)
  - Signal selection/filtering, audio coding, synchronisation, …

Chapter 7

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Case Study: Hearing Instruments 10/15

Future: Multi-node noise reduction
in sensor networks/Internet-of-Things

Chapter 7

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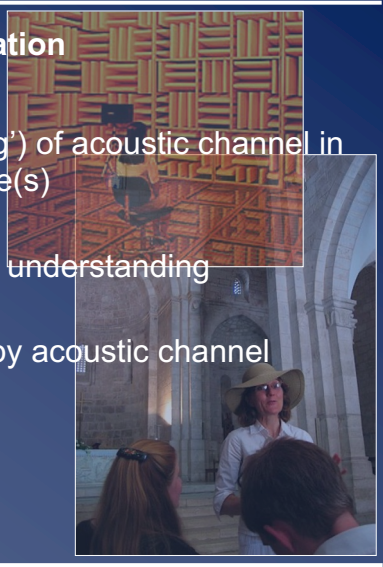
Case Study: Hearing Instruments 11/15

- **DASP Challenges: Dereverberation**

Reverb = filtering effect ('echo-ing') of acoustic channel in between speaker and microphone(s)

Reverb has an impact on speech understanding

Dereverberation = undo filtering by acoustic channel (e.g. 'inverse filtering')



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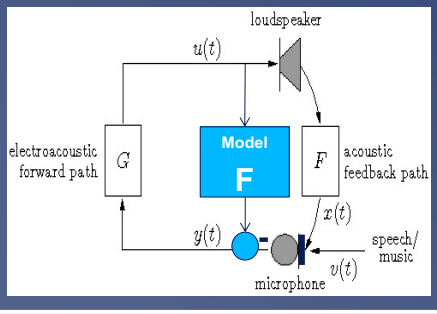
Case Study: Hearing Instruments 12/15

- **DASP Challenges: Acoustic feedback cancellation**

  Problem statement: Loudspeaker signal is fed back into microphone, then amplified and played back again

  Closed loop system may become unstable (=howling)

  Similar to feedback problem in public address systems (for the musicians amongst you)



Similar to echo cancellation in GSM handsets, Skype,…

but more difficult due to signal correlation

Chapter 5

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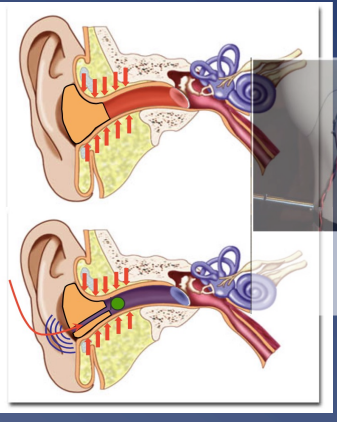
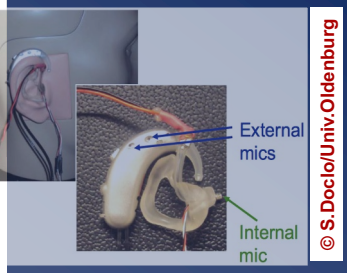
Case Study: Hearing Instruments 13/15

- **DASP Challenges: Active noise control (ANC)**

- **Closed-fitting:**
  - Increase in low-frequency sound pressure when ear canal is blocked from the acoustical environment
  - Own voice is being perceived as hollow (occlusion effect)

- **Open-fitting (venting):**
  - Reduces occlusion effect
  - However, undesired perceptual effects (direct + delayed sound)
  - Increased risk of feedback
  - Ambient noise leakage





ANC to counteract noise leakage & occlusion effect, exploiting additional 'internal' reference microphone

Chapter 6

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Case Study: Hearing Instruments 14/15

- **DASP Challenges: Occlusion Effect Reduction**

OCCLUSION EFFECT REDUCTION USING A VIBRATION SENSOR

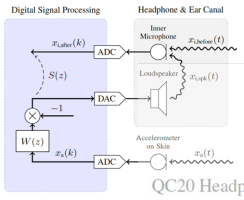
Christoph Weyer and Peter Jax

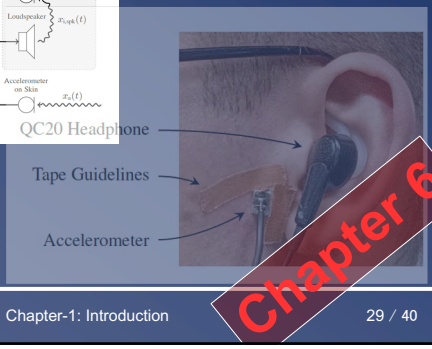
Institute of Communication Systems
RWTH Aachen University
E-Mail: {weyer,jax}@iks.rwth-aachen.de

ABSTRACT

As in-ear headphones are worn for increasing periods of time, the occlusion effect (OE) becomes a growing problem for their users. Today, in-ear headphones are often equipped with active noise cancellation (ANC) systems. Previous research has shown that it is possible to use ANC systems to reduce the OE. In this publication, we present a novel feedforward OE reduction system based on a head-mounted accelerometer. The accelerometer acts as a vibration sensor, which enables us to directly capture and subsequently cancel low frequency body-conducted speech components contributing to the OE. We demonstrate that the system is capable of reducing the OE in simulations, as well as using measurements with a real-time implementation.

***Index Terms*—** Hearables, occlusion effect reduction, active noise cancellation, feedforward filter design, body-conducted speech





Chapter 6

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Case Study: Hearing Instruments 15/15

- **DASP Challenges:** …piecing things together

Signal Processing in High-End Hearing Aids: State of the Art, Challenges, and Future Trends

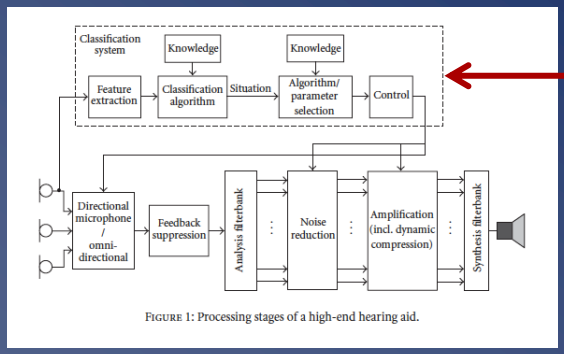

FIGURE 1: Processing stages of a high-end hearing aid.

Auditory scene analysis for optimal parametrization and control of DSP algorithms (e.g. machine learning based classification: quiet/speech in noise/speech in loud noise/speech in car/music/…)

- **Future:** GPS for localization, head-trackers, eye-trackers, EEG-sensors for auditory attention detection, etc.

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Lectures

Lectures: 8 Lectures

Course Material: Slides

- Use version 2023-2024 !
- Download (pdf/ppt) from TOLEDO or DASP webpage homes.esat.kuleuven.be/~dspuser/dasp/
- Master copy can be made available if needed
- **Optional**: Slides **2020-2021** with audio

Course Prerequisite: DSP-CIS H05F3A/H05F1A

filter design, filter banks, optimal & adaptive filters
https://homes.esat.kuleuven.be/~dspuser/DSP-CIS/2022-2023/

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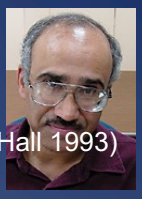
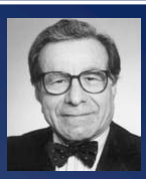
Literature

Literature (General DSP)





- **Simon Haykin**
  `*Adaptive Filter Theory*' (Prentice Hall 1996)
- **P.P. Vaidyanathan**
  `*Multirate Systems and Filter Banks*' (Prentice Hall 1993)

Literature (Speech/Audio/Acoustics)

- **S.L. Gay & J. Benesty**
  `*Acoustic Signal Processing for Telecommunication*' (Kluwer 2000)
- **M. Kahrs & K. Brandenburg (Eds)**
  `*Applications of Digital Signal Processing to Audio and Acoustics*' (Kluwer1998)
- **B. Gold & N. Morgan**
  `*Speech and Audio Signal Processing*' (Wiley 2000)

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Lab Sessions/Project

Acoustic sound field synthesis/Binaural audio

Virtual sound source

Loudspeaker array to produce sound field such that virtual sound source is perceived as coming from virtual sound source location

- Pre-filter design
- Frequency domain realization (OLA/WOLA)
- Noise reduction
- Active noise control …all in a simulated set-up

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Lab Sessions/Project

- Runs over 4 weeks (non-consecutive)
- Each week
  - 1 PC/Matlab session (supervised, 2.5hrs)
  - 2 'Homework' sesions (unsupervised, 2*2.5hrs)

PS: groups of 2

- 'Deliverables' after week 2 & 4
- Grading: based on deliverables, evaluated during sessions


- TAs: jesper.brunnstroem@kuleuven.be (English+Swedish)
  julian.schott@kuleuven.be (English+German+Dutch)

..be there !

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Time Budget

	Lecture (hrs)	Self Study (hrs)
Chapter-1	2	2 (≠ exam material)
Chapter-2	2	6
Chapter-3	2	6
Chapter-4	2	6
Chapter-5	2	6
Chapter-6	2	6
Chapter-7 (guest lecture)	2 (attendance=mandatory)	6
Chapter-8 (guest lecture)	2 (attendance=mandatory)	6
TOTAL = 60 hrs		

	Lab Session (hrs)	Homework (hrs)
Session-1	2.5	5
Session-2	2.5	5
Session-3	2.5	5
Session-4	2.5	5
TOTAL = 30 hrs		

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Exam

- ~~Oral~~ **Written exam**
- **Open book** (only printed material, no electronic devices !!)
- **Grading:**

  *6*2.5 for questions 1-to-6*

  + 5 for project

  = 20

- Exam feedback: send request to marc.moonen@kuleuven.be

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Retake Exam

- ~~Oral~~ **Written exam**
- **Open book** (only printed material, no electronic devices !!)
- **Grading**

  *6*2.5 for questions 1-to-6*

  + 5 for for question-7 *(related to project work)*

  = 20

- Exam feedback: send request to marc.moonen@kuleuven.be

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Website

Course info & material in…

1) TOLEDO

1) http://homes.esat.kuleuven.be/~dspuser/dasp/

- Slides
- Schedule
- Contact: julian.schott@kuleuven.be

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Questions?

1) Toledo

2) Ask Teaching Assistants (during lab sessions)

3) E-mail questions to
TA's
or marc.moonen@esat.kuleuven.be

3) Make appointment
marc.moonen@esat.kuleuven.be
ESAT Room B00.14

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