Digital Signal Processing

for Communication and Information Systems

DSP-CIS

Chapter-1 : Introduction

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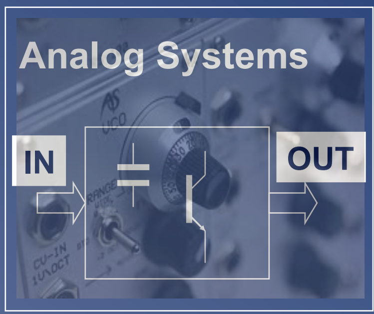
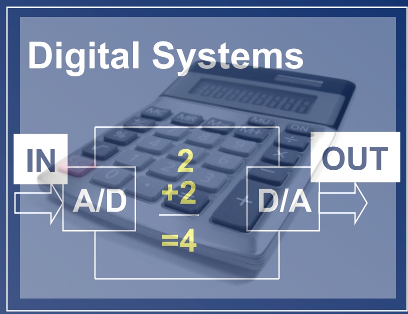
Chapter-1 : Introduction

- **Aims/Scope**
  - Why study DSP ?
  - DSP in applications : Mobile communications example
  - DSP in applications : Hearing aids example
- **Overview**
  - Filter design & implementation
  - Optimal and adaptive filters
  - Filter banks and time-frequency transforms
- Lectures/course material/literature
- Exercise sessions/project
- Exam

Why study DSP ?



vs.



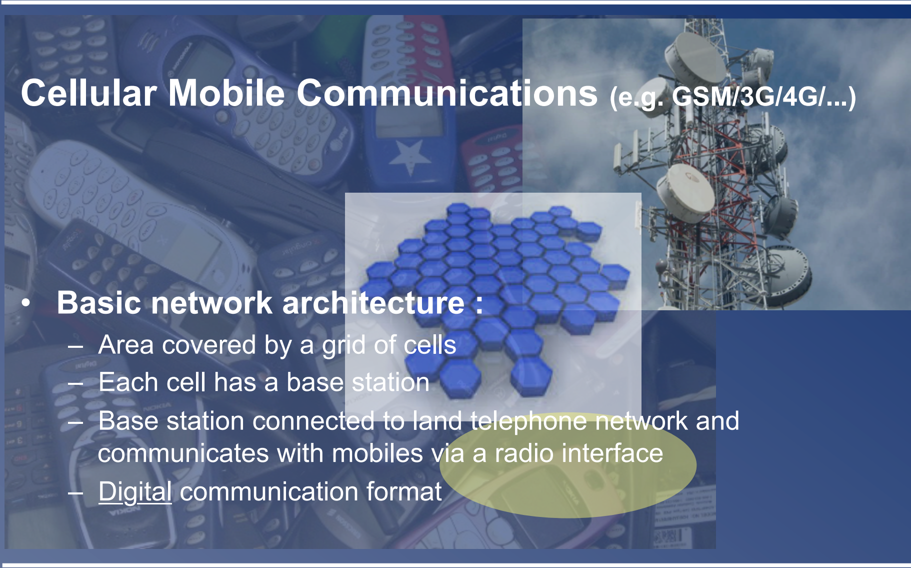
- Can translate (any) analog (e.g. filter) design into digital
- Going `digital' allows to expand functionality/flexibility/…
  (e.g. speech recognition, audio compression…)

Why study DSP ?

- Start with two `DSP in applications' examples:
  - DSP in mobile communications
  - DSP in hearing aids

- Main message:
  Consumer electronics products (and many other systems) have become (embedded) 'supercomputers' (Mops…Gops/sec), packed with mathematics & DSP functionalities…

DSP in applications: Mobile Communications 1/10

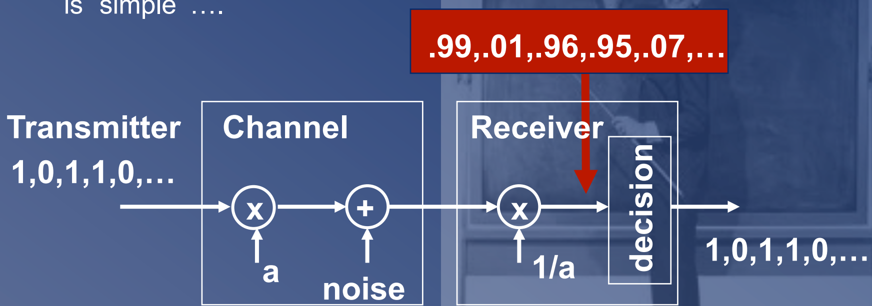


Cellular Mobile Communications (e.g. GSM/3G/4G/...)

- **Basic network architecture :**
  - Area covered by a grid of cells
  - Each cell has a base station
  - Base station connected to land telephone network and communicates with mobiles via a radio interface
  - Digital communication format

DSP in applications: Mobile Communications 2/10

- **DSP for Digital Communications (`physical layer') :**
  - A common misunderstanding is that digital communications is `simple' ….

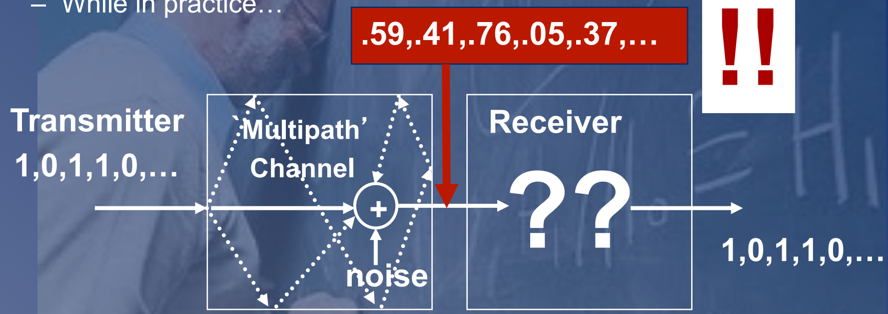


  - While in practice…

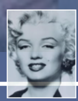
PS: This is a discrete-time system representation, see Chapter-2 for review on signals&systems

DSP in applications: Mobile Communications 3/10

- **DSP for Digital Communications (`physical layer') :**
  - While in practice…



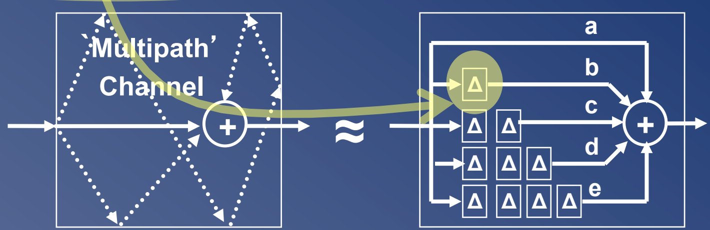
  - This calls for channel model + compensation (equalization)



DSP in applications: Mobile Communications 4/10

- **DSP Challenges: Channel Estimation/Compensation**
  - Multi-path channel can (e.g.) be modeled with short (3…5 taps) FIR filter

$H(z)= a+b.z^{-1}+c.z^{-2}+d.z^{-3}+e.z^{-4}$ (interpretation?)



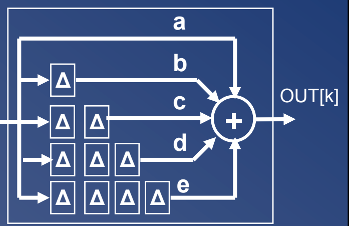
PS: z^{-1} or Δ represents a sampling period delay, see Chapter-2 for review on z-transforms

DSP in applications: Mobile Communications 5/10

- **DSP Challenges: Channel Estimation/Compensation**
  - Multi-path channel can (e.g.) be modeled with short (3…5 taps) FIR filter

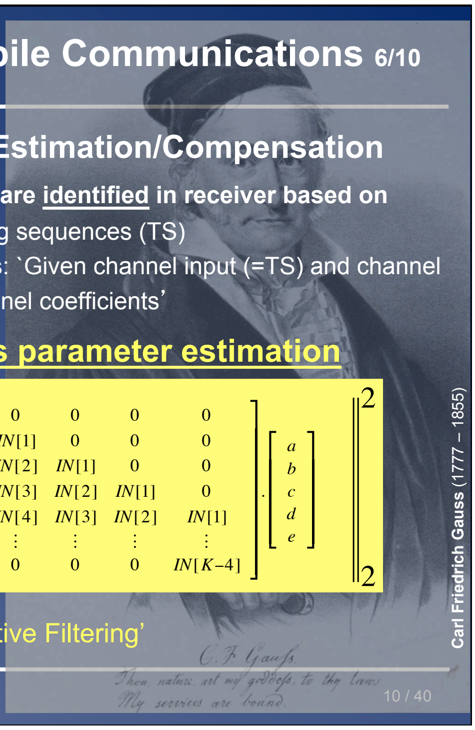
$$H(z)= a+b.z^{-1}+c.z^{-2}+d.z^{-3}+e.z^{-4}$$

$$\begin{bmatrix} OUT[1] \\ OUT[2] \\ OUT[3] \\ OUT[4] \\ OUT[5] \\ \vdots \\ OUT[K] \end{bmatrix} = \begin{bmatrix} IN[1] & 0 & 0 & 0 & 0 \\ IN[2] & IN[1] & 0 & 0 & 0 \\ IN[3] & IN[2] & IN[1] & 0 & 0 \\ IN[4] & IN[3] & IN[2] & IN[1] & 0 \\ IN[5] & IN[4] & IN[3] & IN[2] & IN[1] \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & IN[K-4] \end{bmatrix} . \begin{bmatrix} a \\ b \\ c \\ d \\ e \end{bmatrix}$$



=convolution

DSP in applications: Mobile Communications 6/10



- **DSP Challenges: Channel Estimation/Compensation**

  Channel coefficients (a,b,c,d,e) are identified in receiver based on transmission of pre-defined training sequences (TS)
  Problem to be solved at receiver is: `Given channel input (=TS) and channel output (=observed), compute channel coefficients'

This leads to a least-squares parameter estimation

$$\min_{a,b,c,d,e} \left\| \begin{bmatrix} OUT[1] \\ OUT[2] \\ OUT[3] \\ OUT[4] \\ OUT[5] \\ \vdots \\ OUT[K] \end{bmatrix} - \begin{bmatrix} IN[1] & 0 & 0 & 0 & 0 \\ IN[2] & IN[1] & 0 & 0 & 0 \\ IN[3] & IN[2] & IN[1] & 0 & 0 \\ IN[4] & IN[3] & IN[2] & IN[1] & 0 \\ IN[5] & IN[4] & IN[3] & IN[2] & IN[1] \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & IN[K-4] \end{bmatrix} . \begin{bmatrix} a \\ b \\ c \\ d \\ e \end{bmatrix} \right\|_2^2$$

See PART-III on 'Optimal & Adaptive Filtering'

DSP in applications: Mobile Communications 7/10

- **DSP Challenges: Channel Estimation/Compensation**
  - Channel coefficients (cfr. a,b,c,d,e) are identified in receiver based on transmission of pre-defined training sequences (TS)
  - Channel model is then used to design suitable equalizer (`channel inversion'), or (better) to reconstruct transmitted data bits based on maximum-likelihood sequence estimation (e.g. `Viterbi decoding') (details omitted)
  - Channel is highly time-varying (e.g. terminal speed 120 km/hr !)
    => All this is done at `burst-rate' (e.g. 100's times per sec)

= SPECTACULAR !!

DSP in applications: Mobile Communications 8/10

- **DSP Challenges: Speech Coding**
  - Original PCM-signal has 64kbits/sec =8 ksamples/sec*8bits/sample
  - Aim is to reduce this to <<64kbits/sec, while preserving quality
  - Coding based on speech generation model (vocal tract,…), where model coefficients are identified for each new speech segment (e.g. 20 msec)

DSP in applications: Mobile Communications 9/10

- **DSP Challenges: Speech Coding**
  - Original PCM-signal has 64kbits/sec =8 ksamples/sec*8bits/sample
  - Aim is to reduce this to <<64kbits/sec, while preserving quality
  - Coding based on speech generation model (vocal tract,…), where model coefficients are identified for each new speech segment (e.g. 20 msec)
  - This leads to a least-squares parameter estimation (again), executed +/- 50 times per second.
    Fast algorithm is used, e.g. \`Levinson-Durbin' algorithm
    See PART-III on 'Optimal & Adaptive Filtering'
  - Then transmit model coefficients instead of signal samples (!!!)
  - Synthesize speech segment at receiver (should \`sound like' original speech segment)

= SPECTACULAR !!

DSP in applications: Mobile Communications 10/10

- **DSP Challenges: Multiple Access Schemes**

  Accommodate multiple users by time & frequency \`multiplexing'
  - FDMA: frequency division multiple access
  - OFDMA: orthogonal frequency division multiple access
  - TDMA: time division multiple access
  - CDMA: code division multiple access

  See PART-IV on 'Filter Banks & Time-Frequency Transforms'

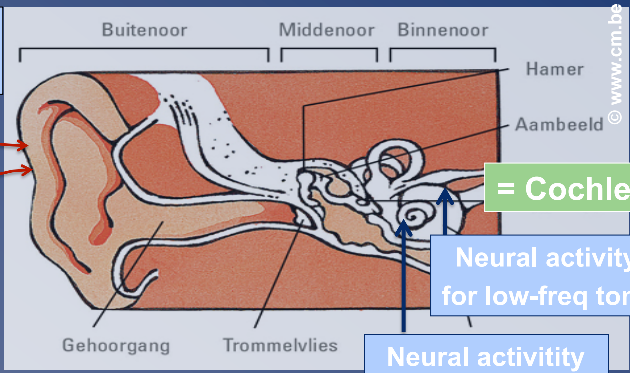
- **Etc..**

= BOX FULL OF DSP/MATHEMATICS !!
(for only €25)

DSP in applications: Hearing Aids 1/10

Hearing

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



DSP in applications: Hearing Aids 2/10

Hearing loss types

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

One in six adults (Europe) suffers from hearing loss

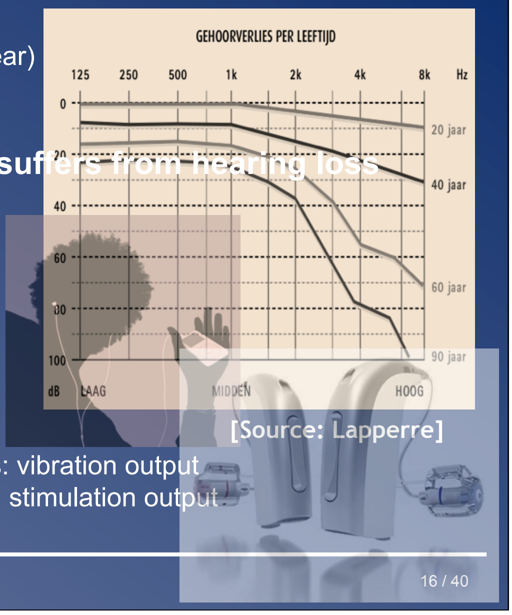
…and still increasing

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]

DSP in applications: Hearing Aids 3/10

➔Hearing Aids (HAs)

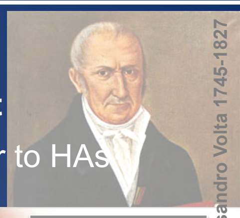
- Audio input/audio output (`microphone-processing-loudspeaker')
- 'Amplifier', but so much more than an amplifier!!
- History:
  - Horns/trumpets/…
  - `Desktop' HAs (1900)
  - Wearable HAs (1930)
  - Digital HAs (1980)
- State-of-the-art:
  - MHz's clock speed
  - Millions of arithmetic operations/sec,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

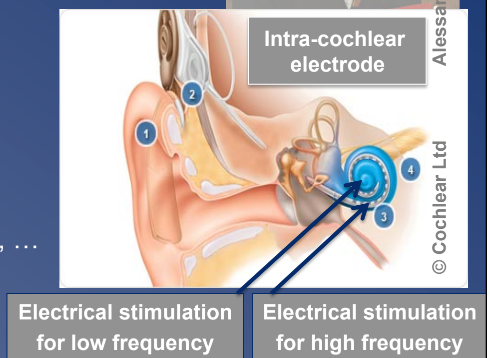
= BOX FULL OF DSP/MATHEMATICS !!

DSP in applications: Hearing Aids 4/10

➔Cochlear Implants (CIs)

- **Audio input/electrode stimulation output**
- Stimulation strategy + preprocessing similar to HAs
- **History:**
  - Volta's experiment…
  - First implants (1960)
  - Commercial CIs (1970-1980)
  - Digital CIs (1980)
- **State-of-the-art:**
  - MHz's clock speed, Mops/sec, …
  - Multiple microphones





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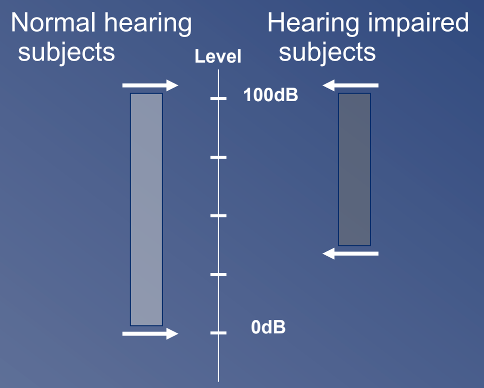
DSP in applications: Hearing Aids 5/10

DSP Challenges: Dynamic range compression

Dynamic range & audibility

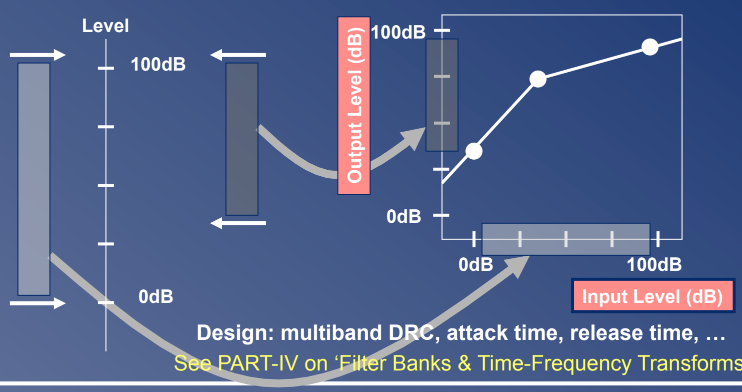


DSP in applications: Hearing Aids 5/10

DSP Challenges: Dynamic range compression

Dynamic range & audibility

need `signal dependent amplification'

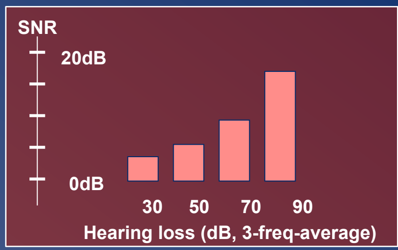


Design: multiband DRC, attack time, release time, …

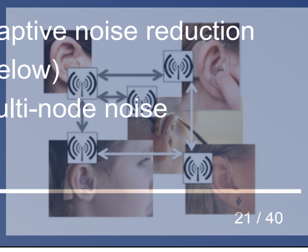
See PART-IV on 'Filter Banks & Time-Frequency Transforms'

DSP in applications: Hearing Aids 6/10

- However: Audibility does not imply intelligibility
- Hearing impaired subjects need 5..10dB larger signal-to-noise ratio (SNR) for speech understanding in noisy environments



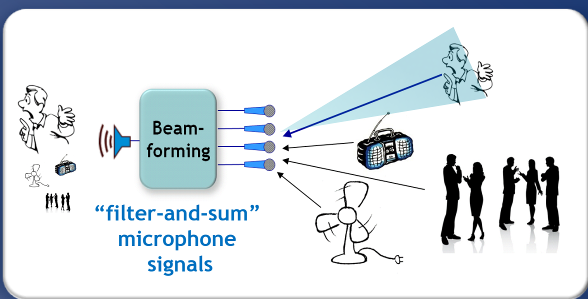
- Need for **noise reduction** (=speech enhancement) algorithms:
  - State-of-the-art: monaural 2-microphone adaptive noise reduction
  - Near future: binaural noise reduction (see below)
  - Not-so-near future: cooperative HAs with multi-node noise reduction



DSP in applications: Hearing Aids 7/10

DSP Challenges: Noise reduction

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

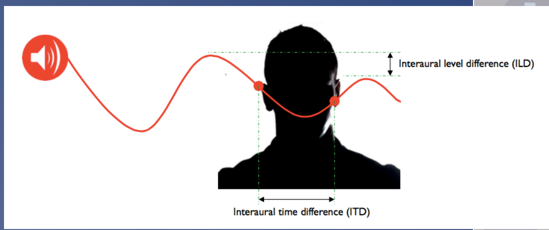


See PART-II on 'Filter Design & Implementation'

DSP in applications: Hearing Aids 8/10

Binaural hearing based on binaural auditory cues

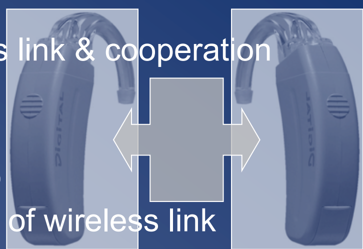
- **ITD (interaural time difference)**
- **ILD (interaural level difference)**



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

DSP in applications: Hearing Aids 9/10

DSP Challenges: Binaural hearing aids



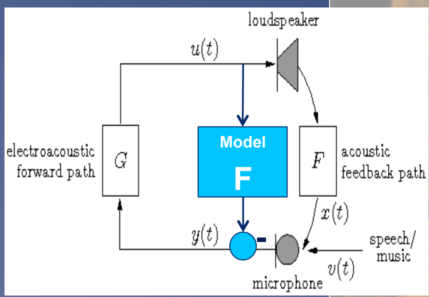
- Two hearing aids (L&R) with wireless link & cooperation
- Opportunities:
  - More signals (e.g. 2*2 microphones)
  - Better sensor spacing (17cm i.o. 1cm)
- Constraints: power/bandwith/delay of wireless link
- Challenges:
  - Improved localization through 'localization cue' preservation
  - Improved noise reduction + benefit from 'binaural unmasking'
  - **Signal selection/filtering**, **audio coding**, **synchronisation**, …

= SPECTACULAR !!

DSP in applications: Hearing Aids 10/10

DSP Challenges: 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

See PART-III on 'Optimal & Adaptive Filtering'

= SPECTACULAR !!

DSP in applications : Other…

- **Digital Communications**

  Wireline (xDSL,Powerline), Wireless (GSM, 3G, 4G, Wi-Fi, WiMax CDMA, MIMO-transmission,..)
- **Speech**

  Speech coding (GSM, DECT, ..), Speech synthesis (text-to-speech), Speech recognition
- **Audio Signal Processing**

  Audio Coding (MP3, AAC, ..), Audio synthesis
  Editing, Automatic transcription, Dolby/Surround, 3D-audio,..
- **Image/Video**
- …

Aims/Scope

- **<u>Basic</u> signal processing theory/principles**

  Filter design, filter banks, optimal filters & adaptive filters

  …as well as…

- **Recent/<u>advanced</u> topics**

  Robust filter realization, perfect reconstruction filter banks, fast adaptive algorithms, ...

- **Often ` bird's-eye view '**

  Skip many mathematical details (if possible… ☺)
  Selection of topics (non-exhaustive)

- Prerequisites: Signals & Systems (sampling, transforms,..)

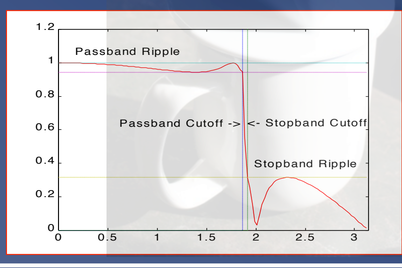
Overview

- <u>Part I</u> : Introduction

  Chapter-1: Introduction
  Chapter-2: Signals and Systems Review
  Chapter-3: Acoustic Modem Project

- <u>Part II</u> : Filter Design & Implementation

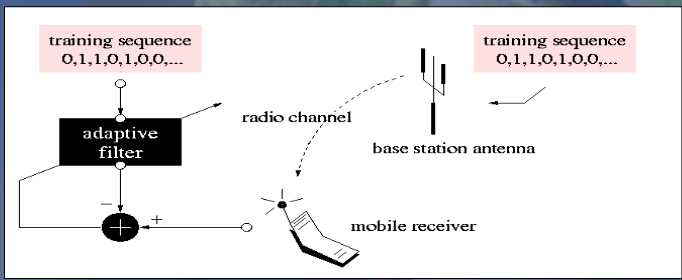
  Chapter-3: Filter Design
  Chapter-4: Filter Realization
  Chapter-5: Filter Implementation



Overview

- Part III : Optimal & Adaptive Filtering

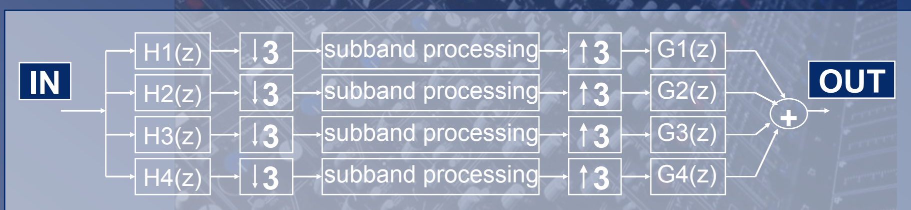
  Chapter-7: Wiener Filters & the LMS Algorithm
  Chapter-8: Recursive Least Squares Algorithms
  Chapter-9: Fast Recursive Least Squares Algorithms
  Chapter-10: Kalman Filters



Overview

- Part IV : Filter Banks & Time-Frequency Transforms

  Chapter-11: Filter Bank Preliminaries/Applications
  Chapter-12: Filter Bank Design
  Chapter-13: Frequency Domain Filtering
  Chapter-14: Time-Frequency Analysis & Scaling



- Part V : Outro

  Chapter-15: DSL Technologies (Nokia Guest Lecture)

Lectures

Lectures: 15 * 2 hrs

PS: Time budget = (15*2hrs)*4 = 120 hrs

Course Material:

- Part I-V: Slides (use version 2019-2020 !!)

  Download from DSP-CIS webpage

  Master copy available @ ESAT B00.10 (Ida Tassens)

- Part III: `Introduction to Adaptive Signal Processing ‘

  (Marc Moonen & Ian.K. Proudler)

  = optional reading

  Download from DSP-CIS webpage (if needed)

Lectures

Lectures: 15 * 2 hrs

PS: Time budget = (15*2hrs)*4 = 120 hrs

‘Web Lectures’ 

- Slides with audio
- Date/Time: See schedule (!)
- Place: Your place instead of lecture room
- Support: See page 40

Literature / Campus Library Arenberg

- **A. Oppenheim & R. Schafer (*)** — Part-I
  `Digital Signal Processing' (Prentice Hall 1977) — Part-II
- **L. Jackson**
  `Digital Filters and Signal Processing' (Kluwer 1986)
- **Simon Haykin** — Part-III
  `Adaptive Filter Theory' (Pearson Education 2014)
- **P.P. Vaidyanathan**
  `Multirate Systems and Filter Banks' (Dorling Kindersley 1993)
- **M. Bellanger** — Part-IV
  `Digital Processing of Signals' (Kluwer 1986)
- **etc...**

(*) MOOC www.edx.org/course/discrete-time-signal-processing-mitx-6-341x-1

Literature / DSP-CIS Library

- **Collection of books is available to support course material**
- **List/reservation via DSP-CIS webpage**
- Contact: amin.hassani@esat.kuleuven.be

Exercise Sessions: Acoustic Modem Project

– Digital communication over an acoustic channel (from loudspeaker to microphone)
– FFT/IFFT-based modulation format : OFDM (as in ADSL/VDSL, WiFi, DAB, DVB,…)
– Channel estimation, equalization, etc…

Exercise Sessions: Acoustic Modem Project

PS: groups of 2

- Runs over 8 weeks
- Each week
  – 1 PC/Matlab session (supervised, 2.5hrs)
  – 2 'Homework' sessions (unsupervised, 2*2.5hrs)

PS: Time budget = 8*(2.5hrs+5hrs) = 60 hrs

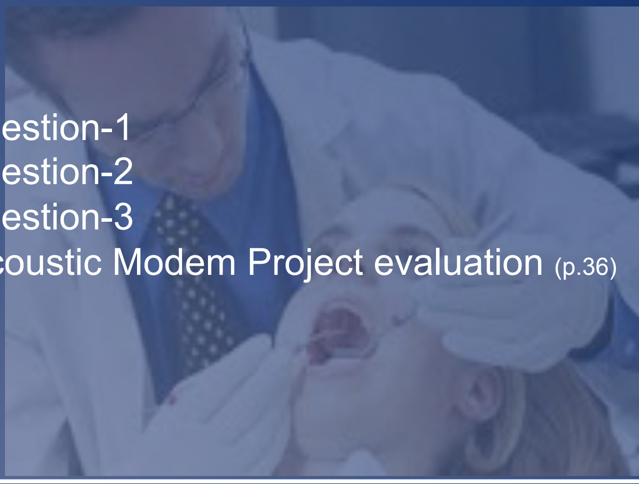
- 'Deliverables' after week 2, 4, 6, 8
- Grading: based on deliverables, evaluated during sessions
  main part=80%, optional part=20%
- TAs: amin.hassani@kuleuven.be (English+Persian)
  mohit.sharma@kuleuven.be (English+Hindi)
  robbe.vanrompaey@kuleuven.be (Dutch+English+French)
  jeroen.verdyck@kuleuven.be (Dutch+English+French)

Exam

- **Oral exam, with preparation time**
- **Open book**
- **Grading :**

  5 pts for question-1
  5 pts for question-2
  5 pts for question-3
  +5 pts for Acoustic Modem Project evaluation (p.36)

  ——
  = 20 pts

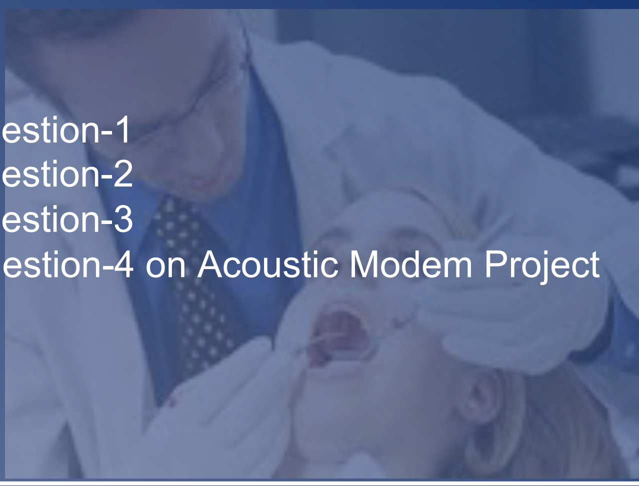


September Retake Exam

- **Oral exam, with preparation time**
- **Open book**
- **Grading :**

  5 pts for question-1
  5 pts for question-2
  5 pts for question-3
  +5 pts for question-4 on Acoustic Modem Project

  ——
  = 20 pts



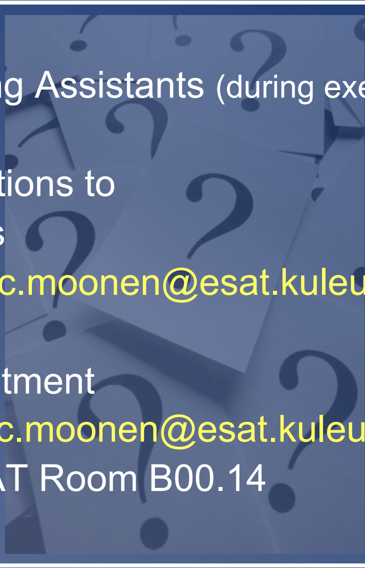
Website

1) **TOLEDO**

2) **homes.esat.kuleuven.be/~dspuser/DSP-CIS**

- Contact: robbe.vanrompaey@kuleuven.be
- Slides
- Project info/schedule
- DSP-CIS Library
- FAQs (send questions to
  robbe.vanrompaey@kuleuven.be
  or marc.moonen@kuleuven.be)

Questions?



1) Ask Teaching Assistants (during exercises sessions)

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

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