Capteurs acoustiques bioinspirés pour l'étude des milieux marins

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Webinar Biome+, 6th February 2025

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iemn Institut d'Electronique, de Microélectronique et de Nanotechnologie UMR CNRS 8520

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ULP SMART
3D COCHLEA

Ultra low power
SMART 3D Cochlea

Centre de Recherche en Informatique, Signal et Automatique de Lille

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Biodiversity

Biodiversity Loss

Major scientific and Societal challenge

Stimulate research in AI

Requirement of passive acoustic sensors:

- ❑ Detection, Classification, Localization
- ❑ Human / Nature acoustic Event
- ❑ 2 challenges:
  - Biodiversity Monitoring
  - Energetic frugality (carbon footpring as low as possible)

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Biodiversity / Data Deluge

- Biodiversity :
  - Between 1970 and 2018, 69% of wildlife* population declined :
    - Terrestrial environment and/or Marine ecosystems
    - **26%** Marine and/or Terrestrial mammals and **14%** birds are threatened (**)
- Data deluge :
  - Digital data (processing / communication) grows exponentially
  - ICT technologies represent 4% of carbon footprint worlwide (projection is **14%** *** en 2040)

* *Perrine Mouterde, Le Monde, 13 Octobre 2022*

** https://www.ecologie.gouv.fr/biodiversite-presentation-et-informations-cles#scroll-nav__4

*** *L. Belkhir et al, « Assessing global emission footprint : Trends to 2040 & recommendations", Journal of Cleaner Production, 2018*

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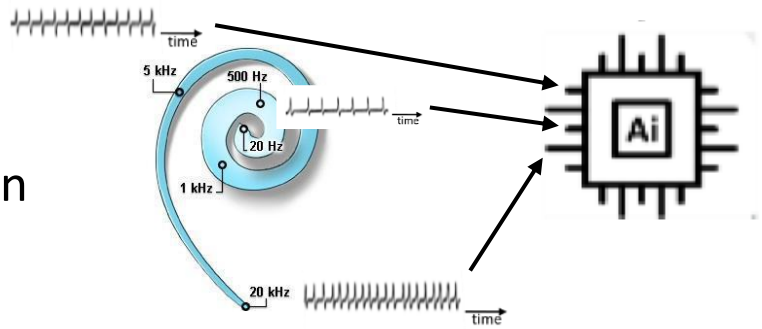
Objective (i)

Development of a quasi-autonomous « embedded » electronic system (maintenance every 3 years)



Artificial Cochlea :

- Analog information pre-processing
- Ultra frugal (power consumption)
- Mature CMOS Technology

« local » information processing:

- Information Processing of « natural data » provided by the cochlea, **locally carried out** (« off the cloud »)

Biodiversity Monitoring:

- Passive Bioacoustic Technology (**non-invasive**, respect wildlife)

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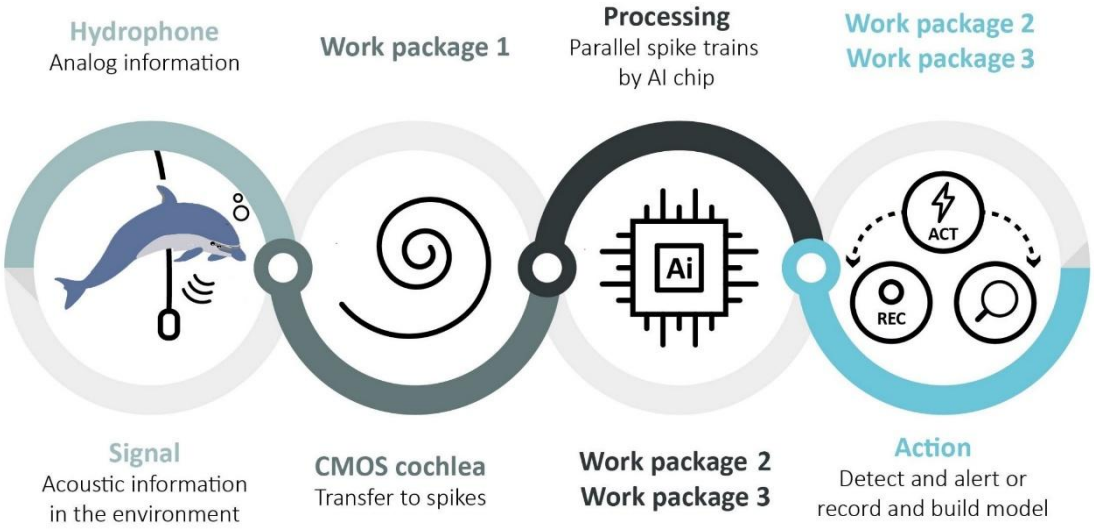
Objectives (ii)



- ❑ Sensor characteristics:
  - Classification/counting of ceteceans (unsupervised learning)
  - Compact design
  - Carbon footprint as low as possible
  - Low cost

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Objectives (iii)

- Design of a monaural / binaural analog artificial Cochlea
  - *Ultra low power (< 30 µWatt), 100 kHz Bandwidth*
  - *Coincidence Detector for sound localization*

- Design of AI chip to carry out biocomputing of « natural data » (generated by the Cochlea)
  - *Software Development based on Spiking Neural Networks trained for Ceteceans classification*

- Detection / Localization of specific acoustic events with main goal to preserve Ceteceans
  - *Add « alert » functionality to detect anthropogenic noise perturbing biodiversity*

Objectives (iv)

LUTTER CONTRE LES POLLUTIONS SONORES SOUS-MARINES

C'est une nouveauté issue de la concertation : la faune marine, et en particulier les cétacés et les phoques, subit de nombreuses conséquences liées à la pollution sonore. Nous engageons une action de réduction de la pollution sonore sous-marine avec les compagnies maritimes et les activités récréatives dans les aires marines protégées.

Biological Cochlea

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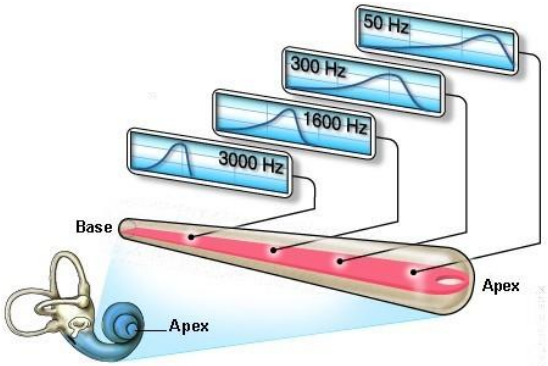
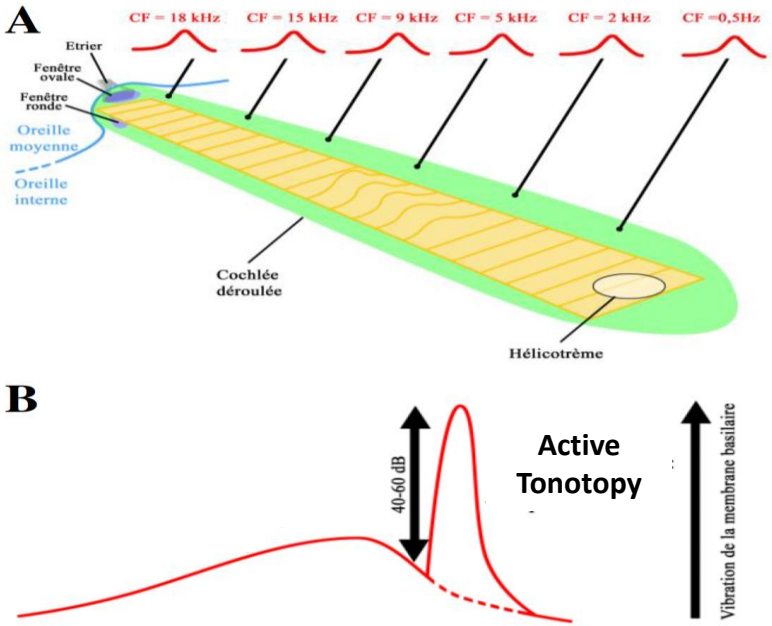
G. V. Békésy ~ 1960*



Passive Tonotopy

Johnstone et Boyle ~ 1970



* https://www.cochlea.eu/cochlee/fonctionnement

Artificial Cochlea : the Pioneers (i)

IEEE TRANSACTIONS ON ACOUSTICS, SPEECH, AND SIGNAL PROCESSING, VOL. 36, NO. 7, JULY 1988

An Analog Electronic Cochlea

RICHARD F. LYON, MEMBER, IEEE, AND CARVER MEAD

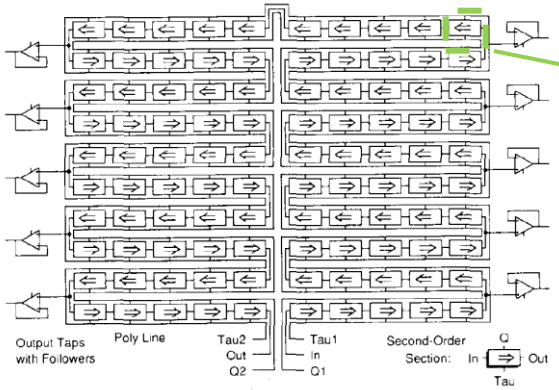


Fig. 8. Floorplan of 100-stage cochlea chip, in serpentine arrangement. The wires that are shown connecting the TAU and Q control terminals of the filter stages are built using a resistive polysilicon line, to act as a voltage divider that adjusts the bias currents in the cascade as an exponential function of distance from the input.

Basic Unit :
2nd order Filter

$$H(s) = \frac{1}{\tau^2 s^2 + \frac{1}{Q}\tau s + 1}$$

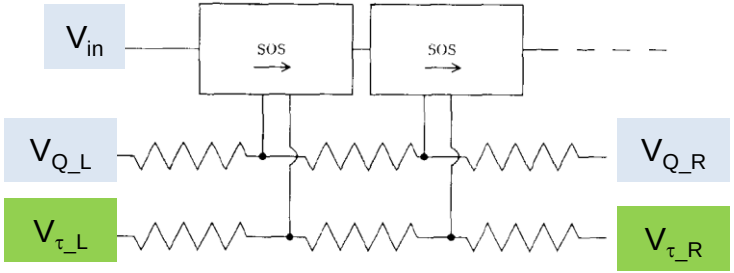


Fig. 3. Silicon cochlea, consisting of a serial cascade of second-order sections and tilted bias lines.

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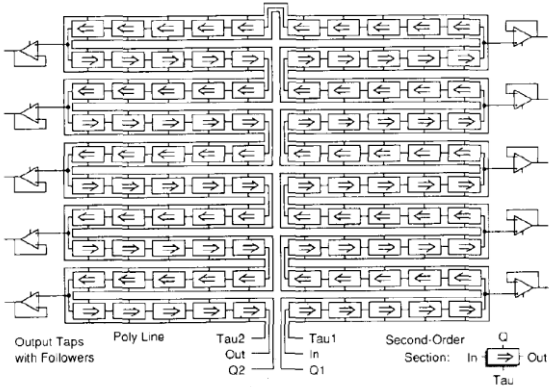
Artificial Cochlea : the Pioneers (ii)

IEEE TRANSACTIONS ON ACOUSTICS, SPEECH, AND SIGNAL PROCESSING, VOL. 36, NO. 7, JULY 1988

An Analog Electronic Cochlea

RICHARD F. LYON, MEMBER, IEEE, AND CARVER MEAD



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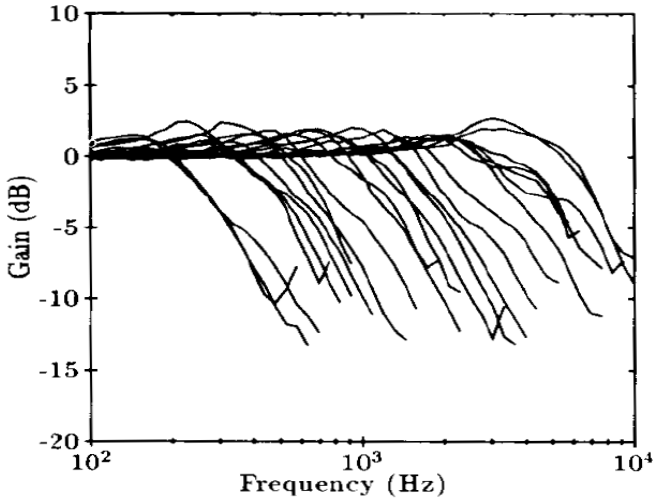

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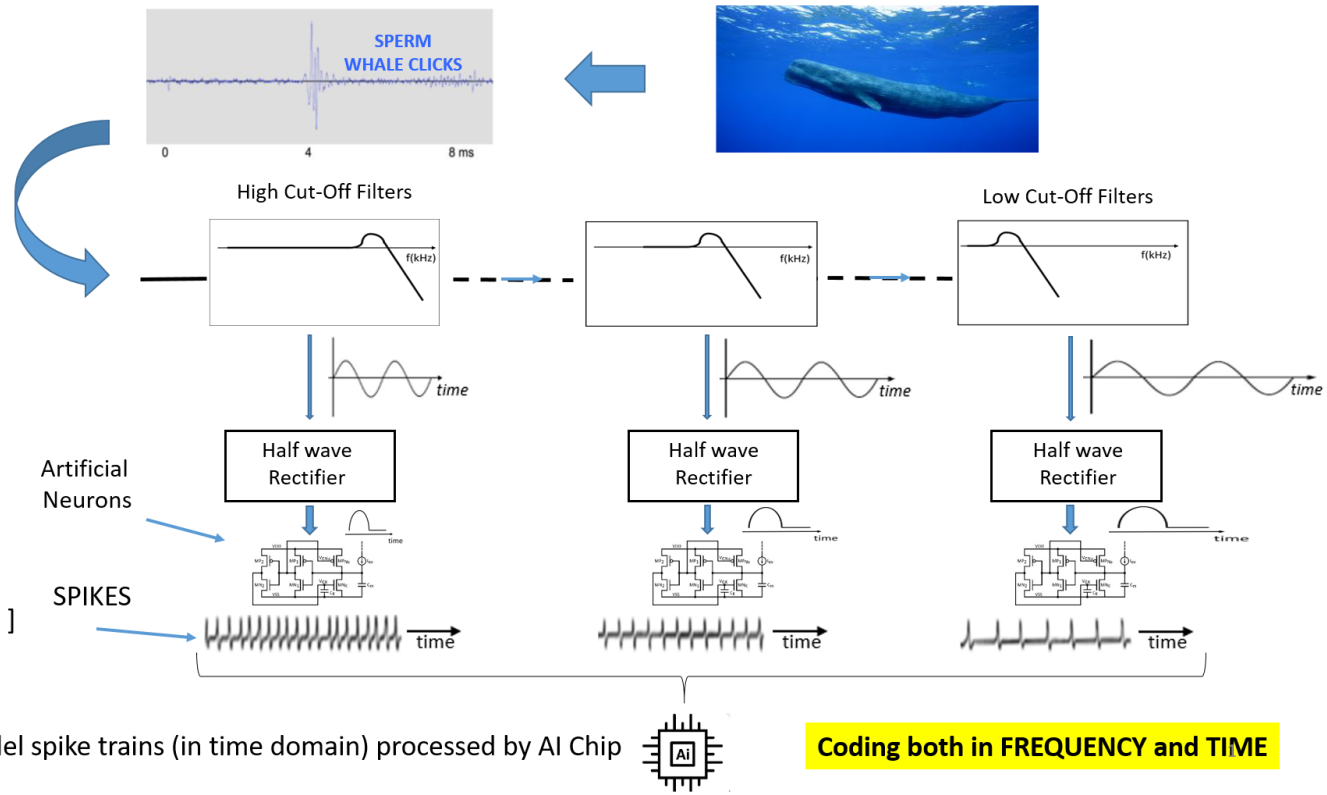
Artificial Cochlea

From acoustic signal sensing to spike encoding



Coding both in FREQUENCY and TIME

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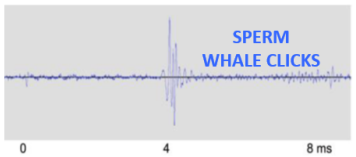
Artificial Cochlea

Cascade of Filters



High Cut-Off Filters

Low Cut-Off Filters

f(kHz)

time

Half wave Rectifier

Artificial Neurons

8 Channels :
[1 kHz – 64 kHz]

SPIKES

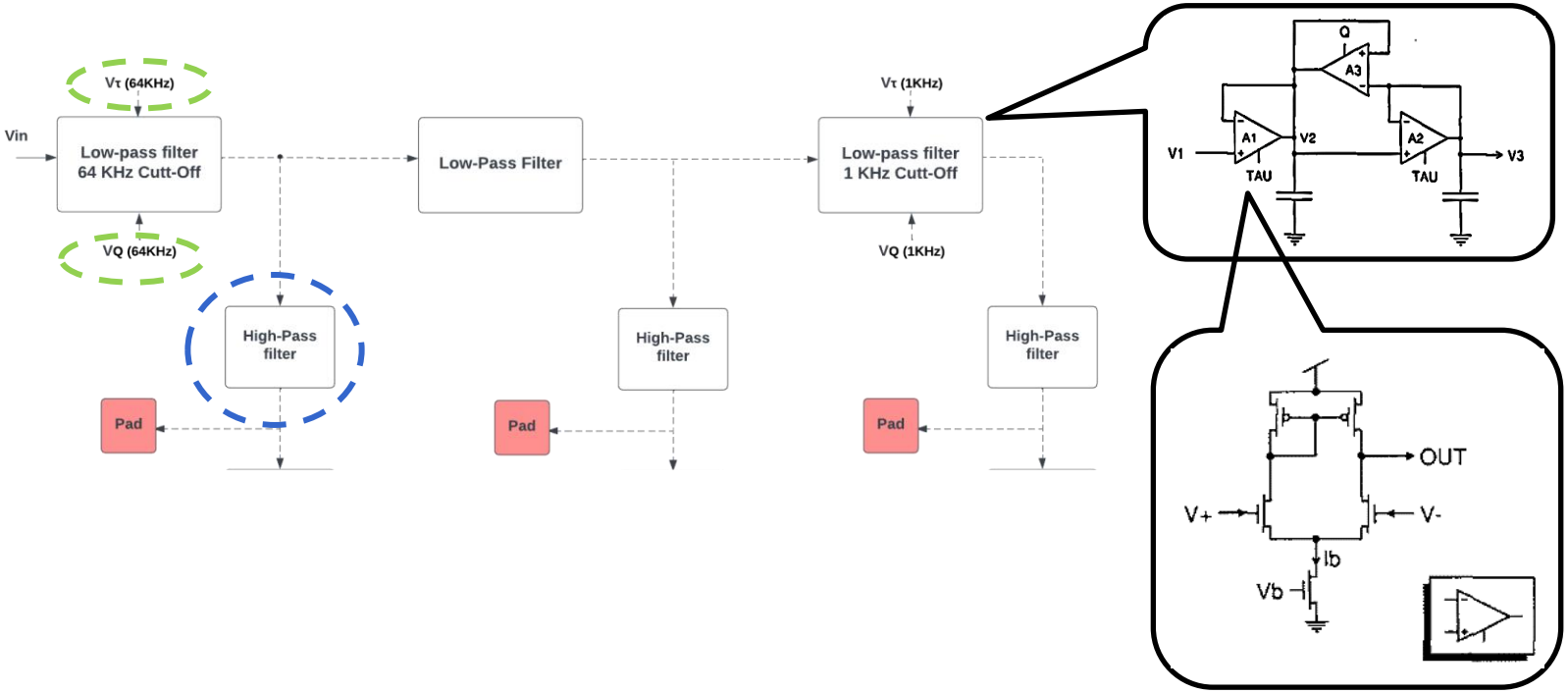
Parallel spike trains (in time domain) processed by AI Chip

Coding both in FREQUENCY and TIME

ULP SMART
3D COCHLEA

Artificial Cochlea

Cascade of Filters



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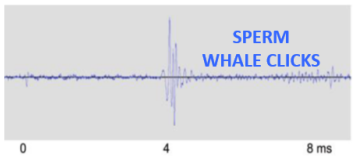
3D COCHLEA

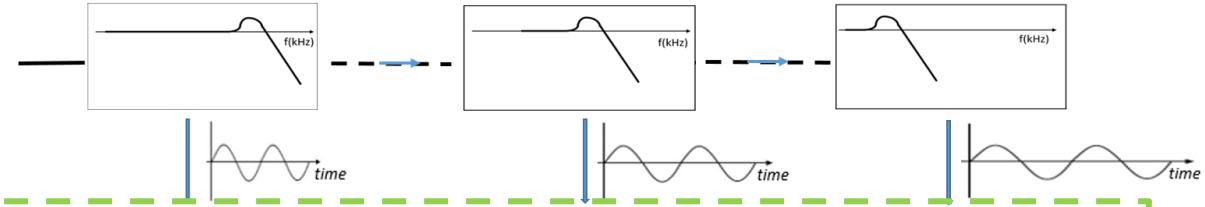
Artificial Cochlea

Conversion to spikes ?



High Cut-Off Filters

Low Cut-Off Filters

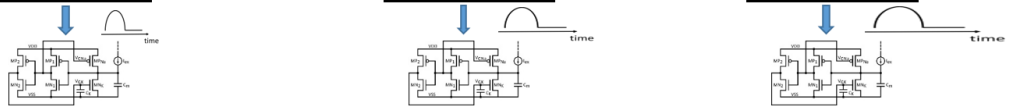


Artificial Neurons

Half wave Rectifier

Half wave Rectifier

Half wave Rectifier



8 Channels :
[1 kHz – 64 kHz]

SPIKES

Parallel spike trains (in time domain) processed by AI Chip

Coding both in FREQUENCY and TIME

Artificial Cochlea

Artificial Neuron*

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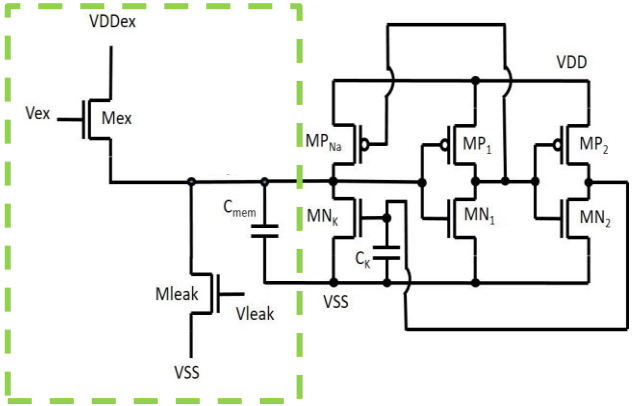
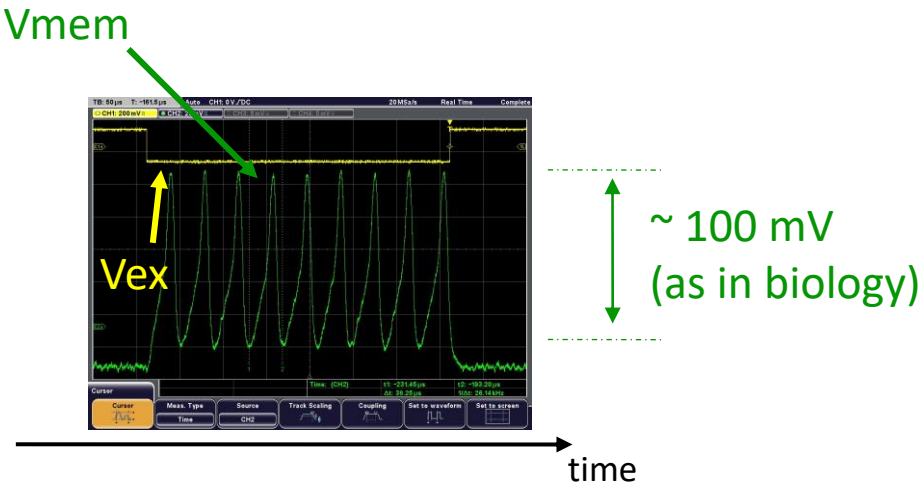
3D COCHLEA

Silicon transistor circuit





Power Consumption < 100 pW

Ilias Sourikopoulos et al,
Frontiers in Neuroscience 2017

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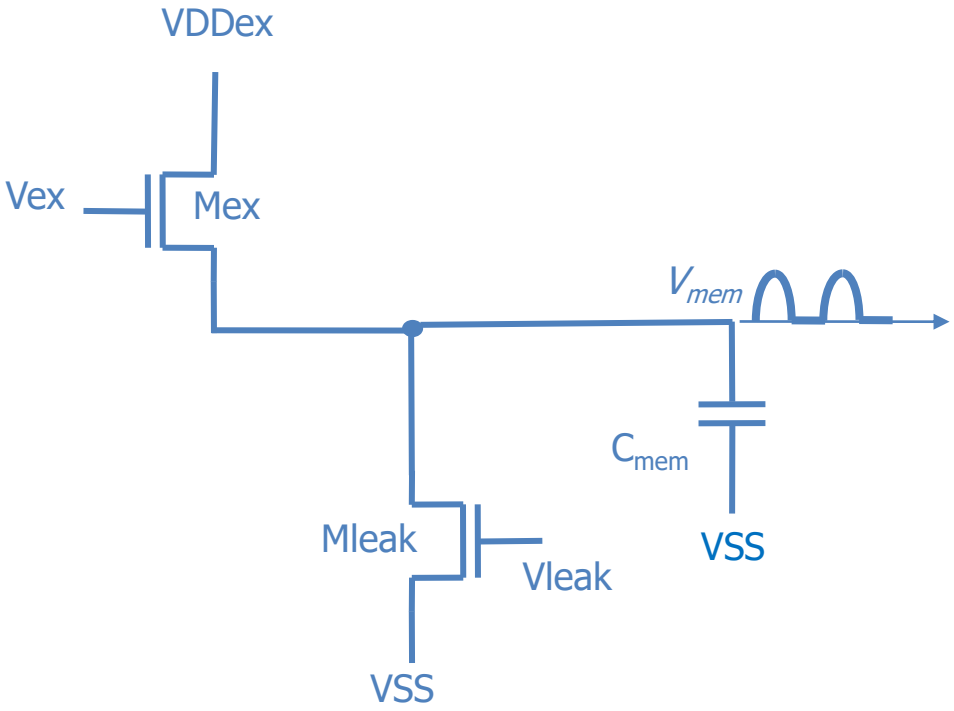
Artificial Cochlea

Half Wave Rectifier ?

Sinusoïdal Signal (from a Cochlea channel)



V_{mem} turns to be a half wave signal

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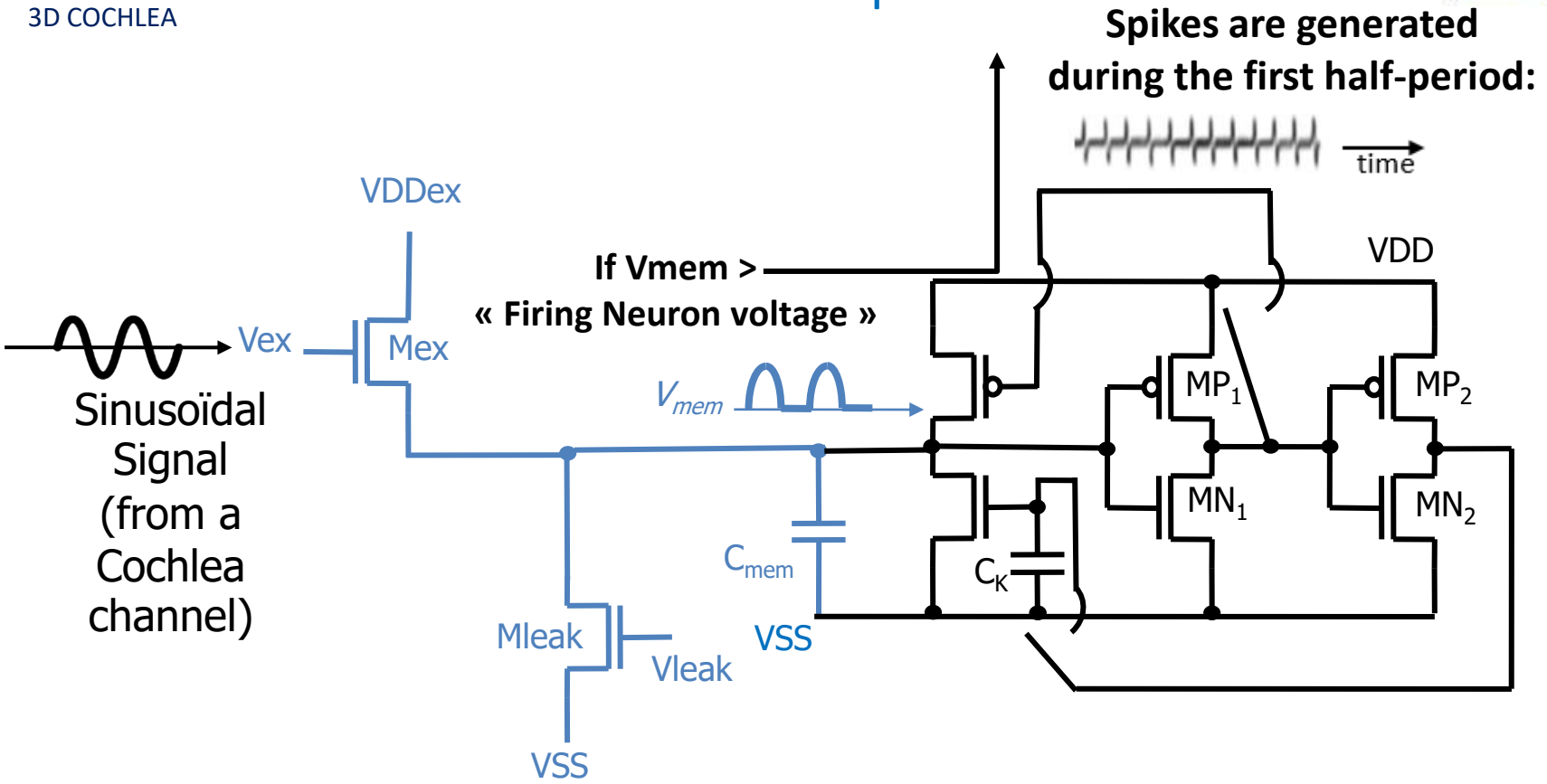
Artificial Cochlea

Conversion to spikes ?



Implementation in CMOS TSMC 65nm Technology

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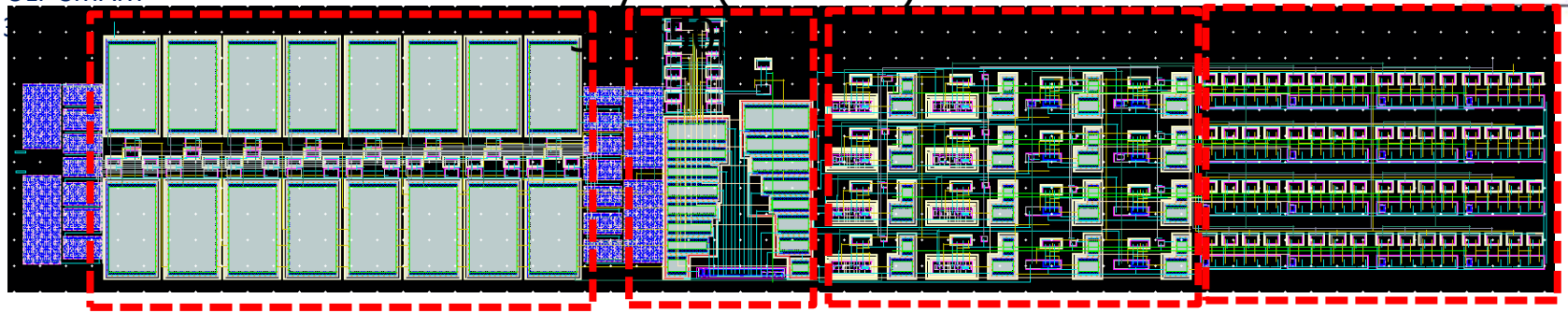
Layout (Cadence)



Low-Pass filters

High-Pass filters

HWR / Output Neurons

Buffers

CMOS Microchip 1500*250µm²

8 Output Channels

Simulated results

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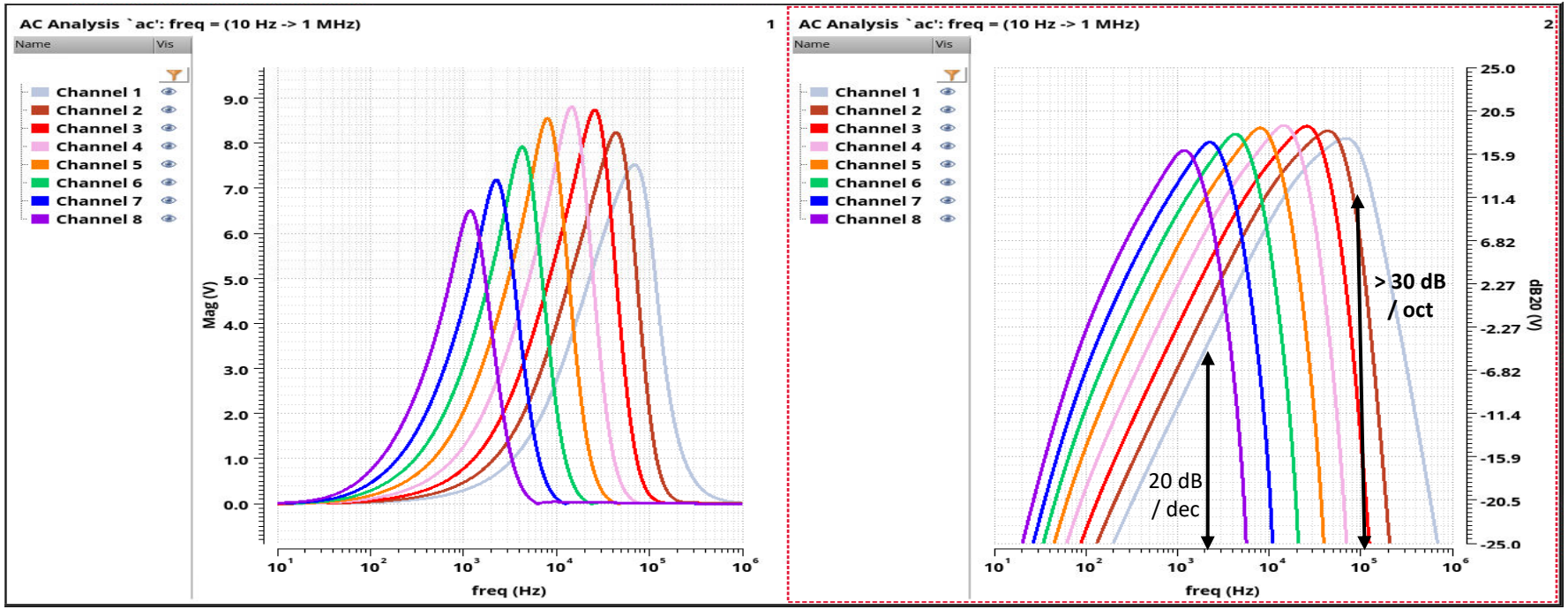
Artificial Cochlea

Cascade of Filters:

Frequency Channels (kHz) : 0.5-1-2-4-8-16-32-64



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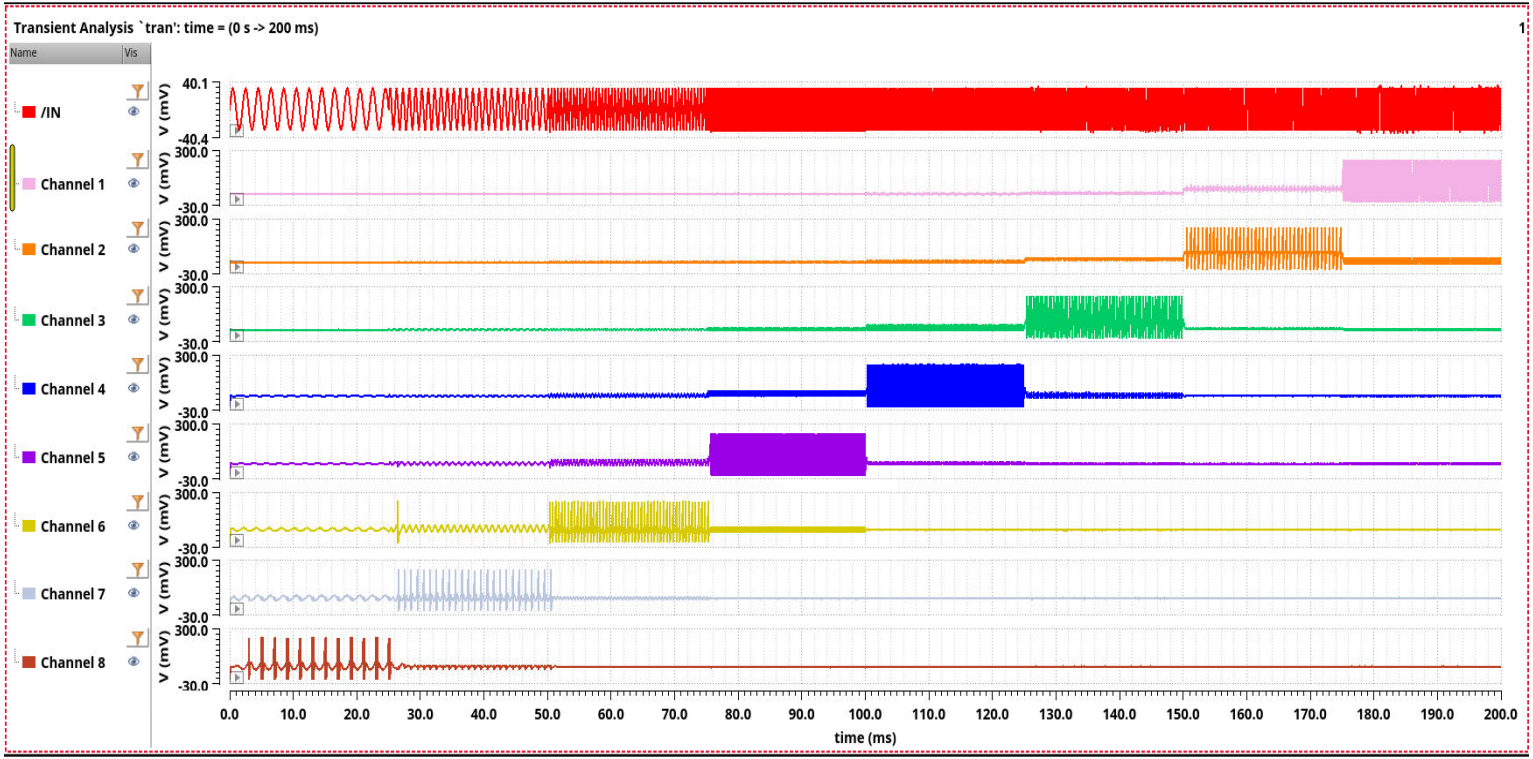
Artificial Cochlea

Conversion to spikes



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Acoustic (natural) Signal of Sperm Whale

Sperm Whale clicks : Discovery of Sound in the Sea
https://dosits.org/galleries/audio-gallery/marine-mammals/toothed-whales/sperm-whale

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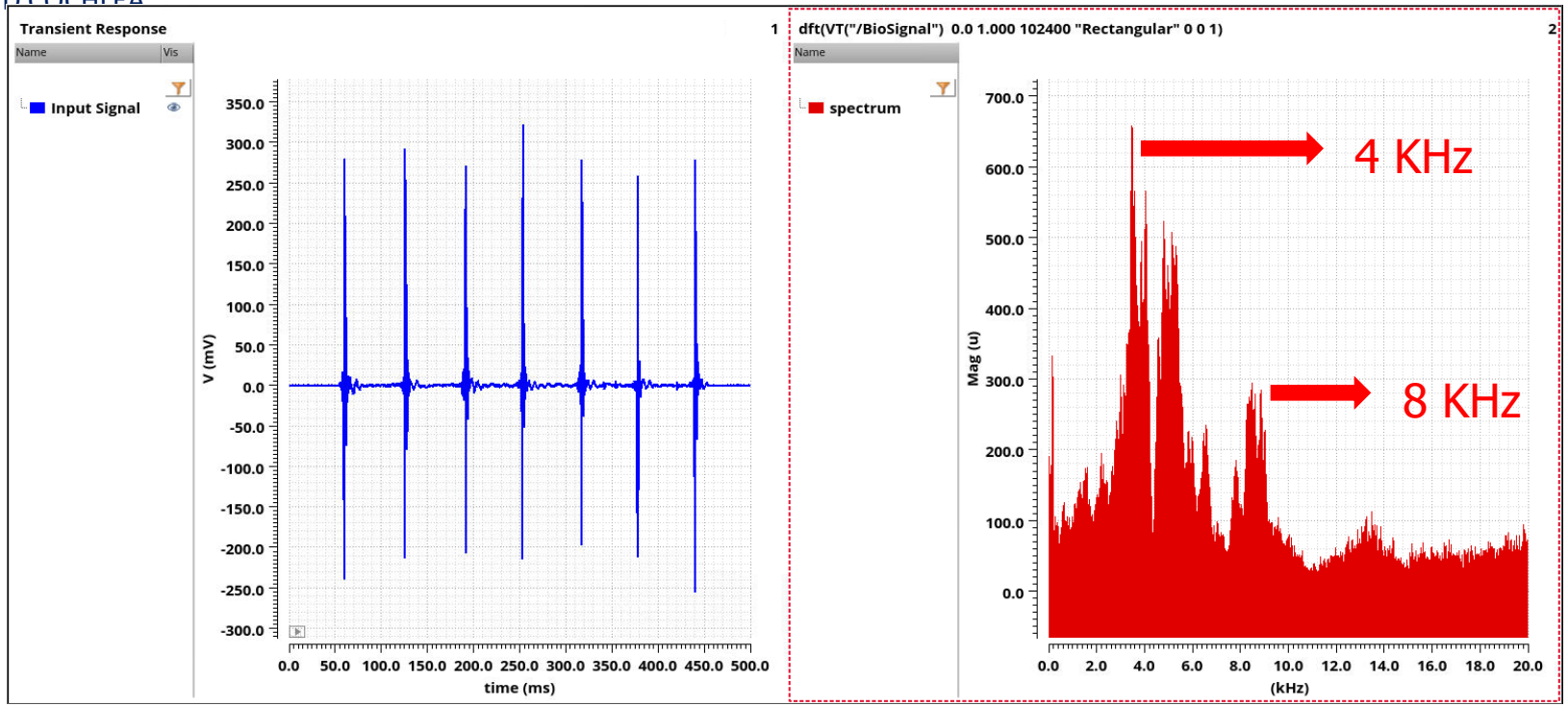
Sperm Whale clicks



Sperm whale clicks : spectrum

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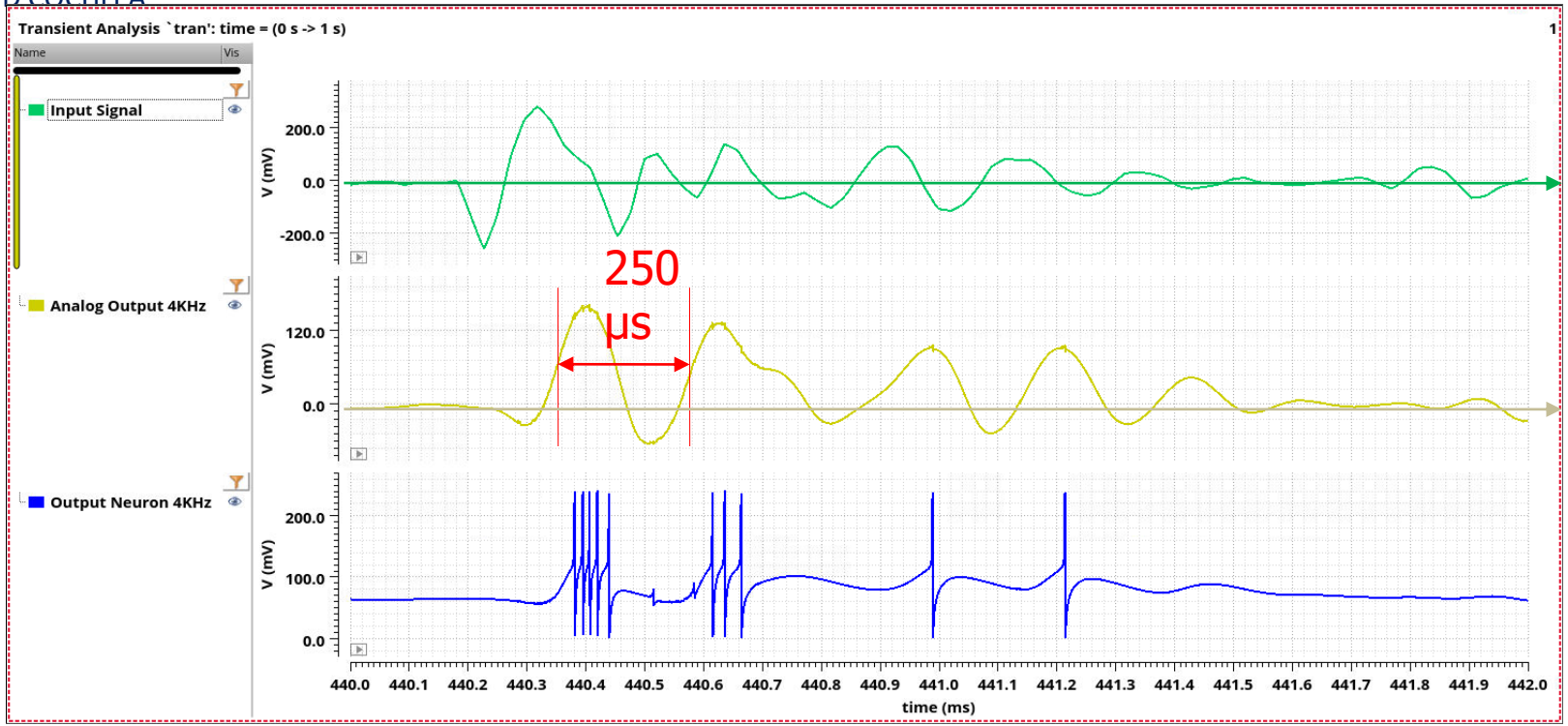
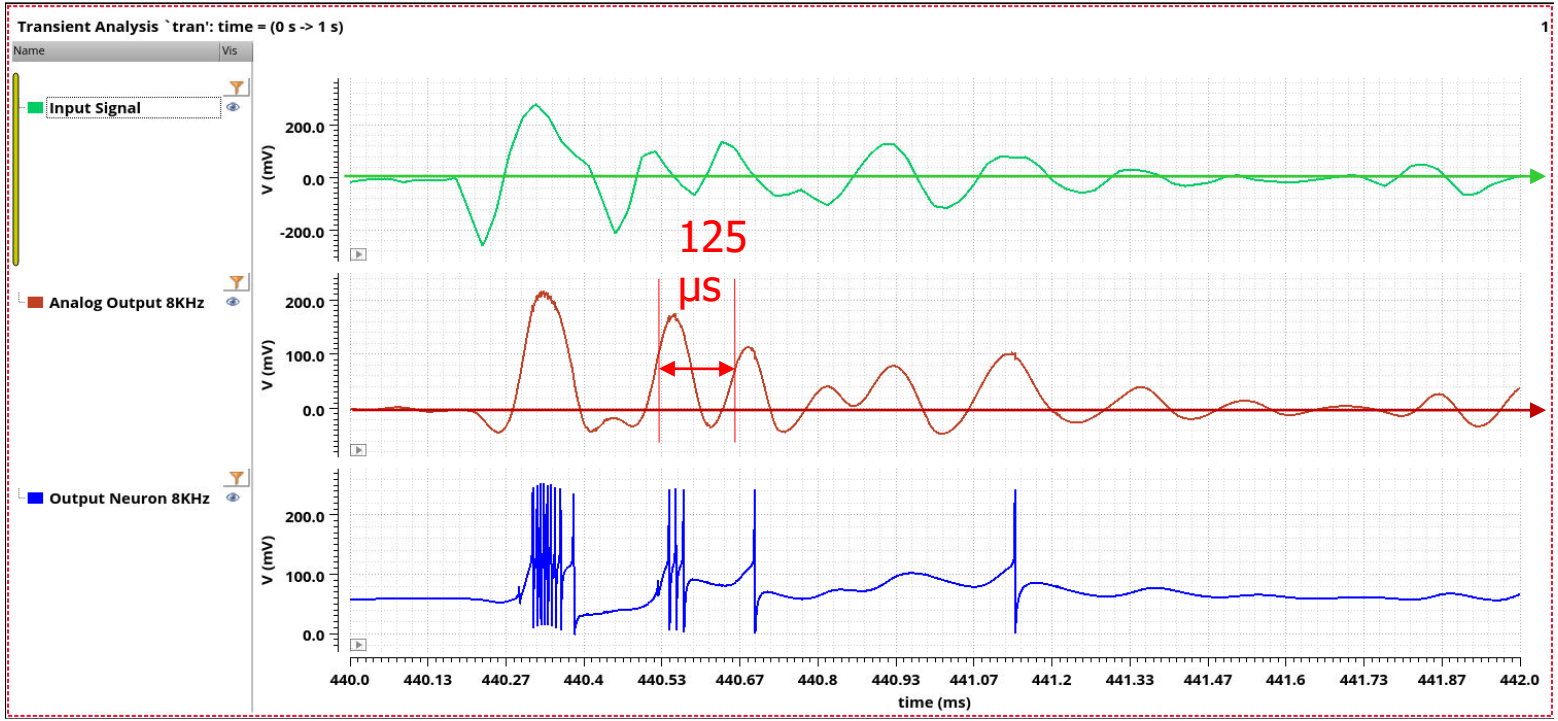
Response of the Cochlea to Sperm Whale Clicks (simulation in CADENCE)



Transient response of the cochlea to a single Sperm Whale click (4KHz Channel)

ULP SMART
3D COCHLEA

Response of the Cochlea to Sperm Whale Clicks (simulation in CADENCE)



Transient response of the cochlea to a single Sperm Whale click (8KHz Channel)

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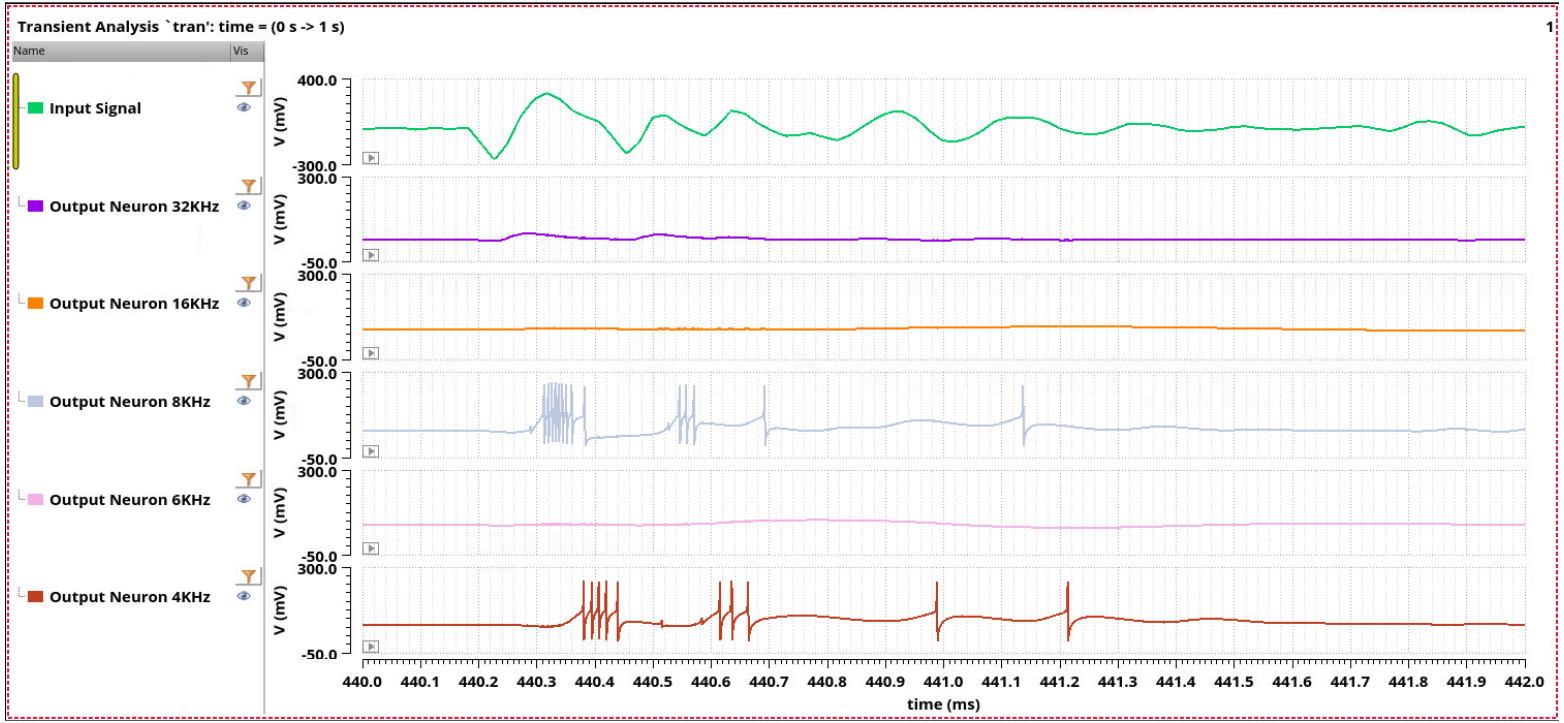
3D COCHLEA

Response of the Cochlea to Sperm Whale Clicks (simulation in CADENCE)



Transient response of the cochlea to a single Sperm Whale click (All Channels)

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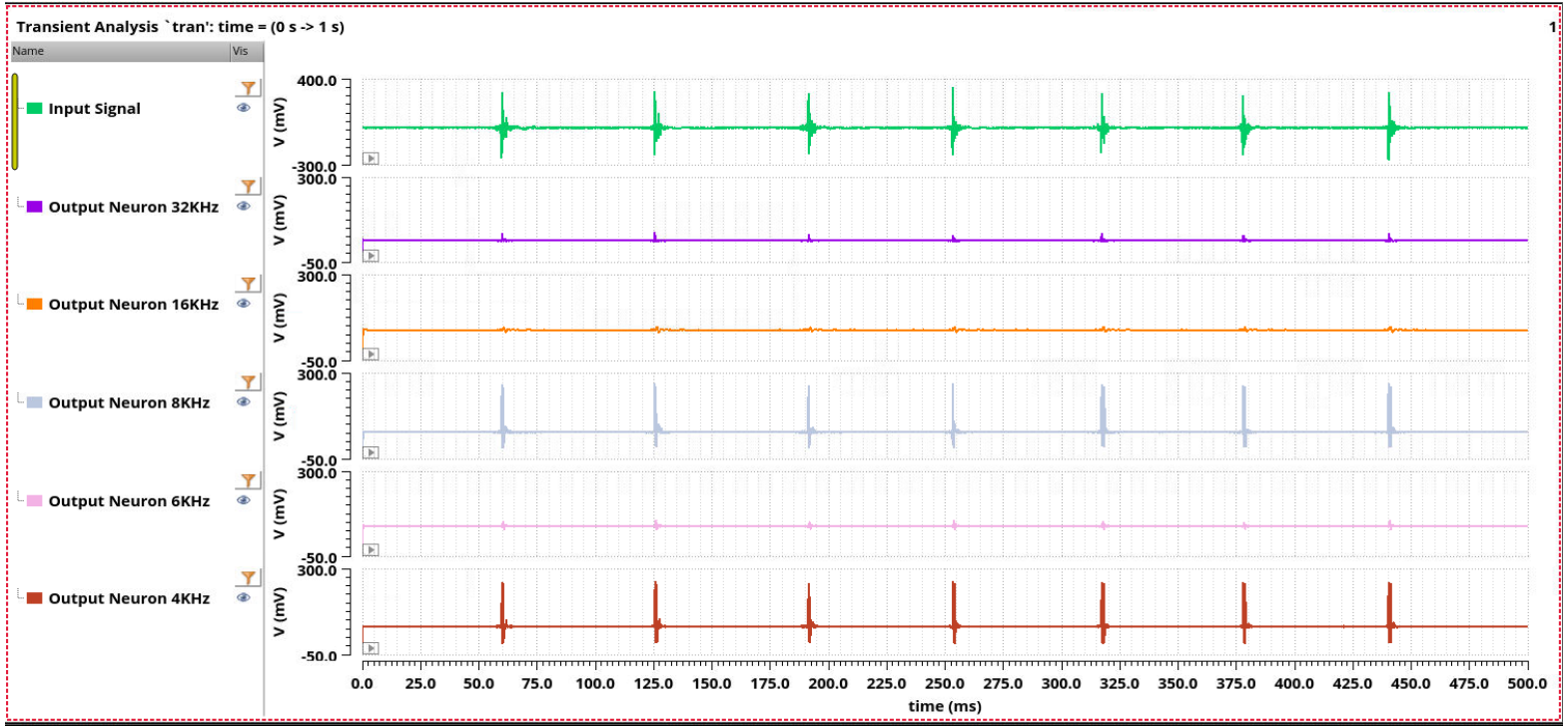
Response of the Cochlea to Sperm Whale Clicks (simulation in CADENCE)



Transient response of the cochlea to a train of Sperm Whale clicks (All Channels)

Experimental results

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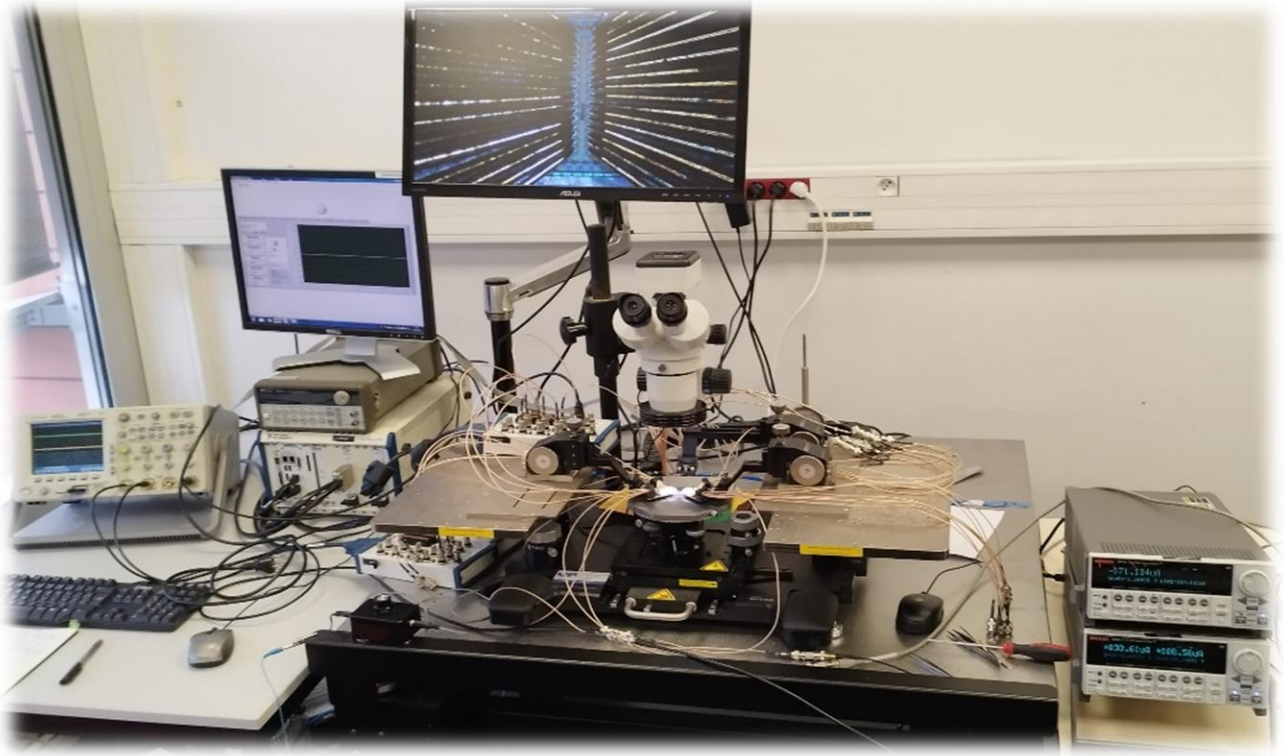
Artificial Cochlea:
Simulation / Experimental results



Characterization :
Use of a probe station

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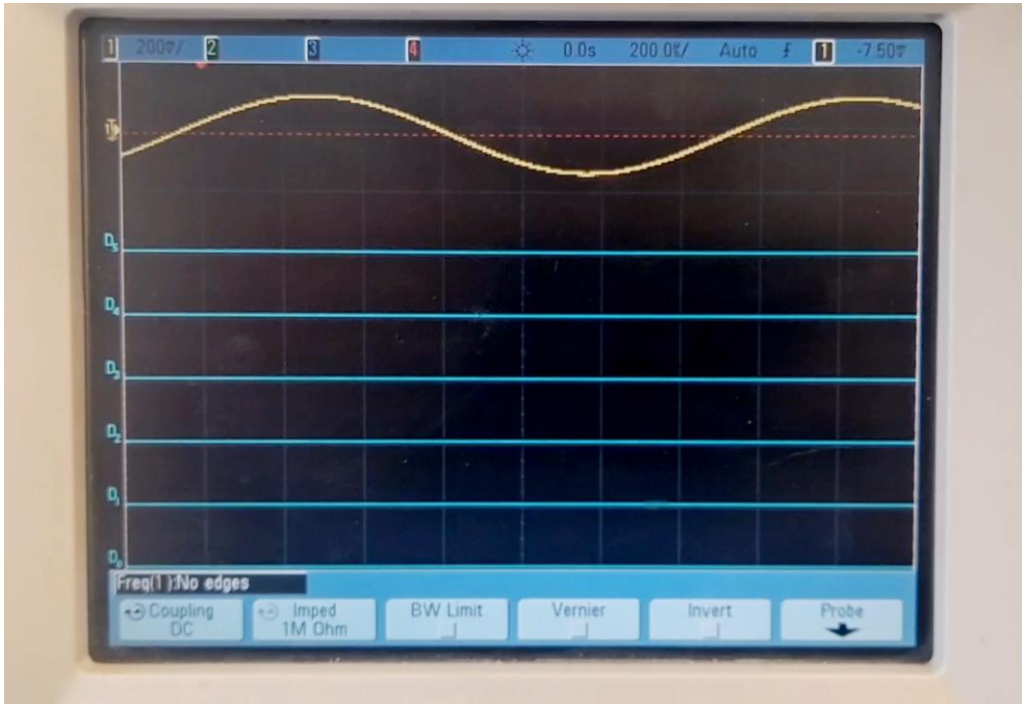
Artificial Cochlea:
Sweep of a sinusoïdal signal



Input Signal:

- Frequency: Sweep from 500Hz to 70KHz
- Amplitude : **100mV**

4KHz Channel

8KHz Channel

Response of the Cochlea to Sperm Whale Clicks (Experimental results)

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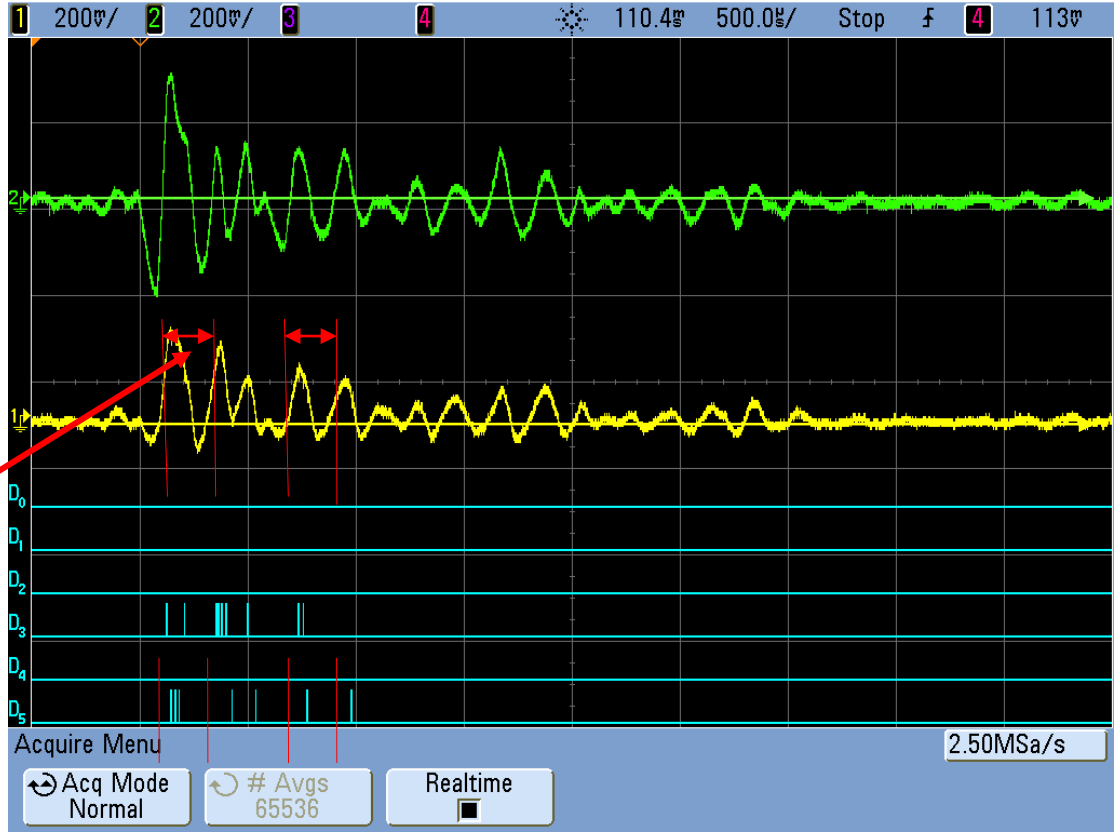
Agilent Technologies

TUE OCT 24 17:13:08 2023



250µs

Sperm Whale click

Single output pad of Filters bank available

Analog output 4KHz

8KHz Channel

4KHz Channel

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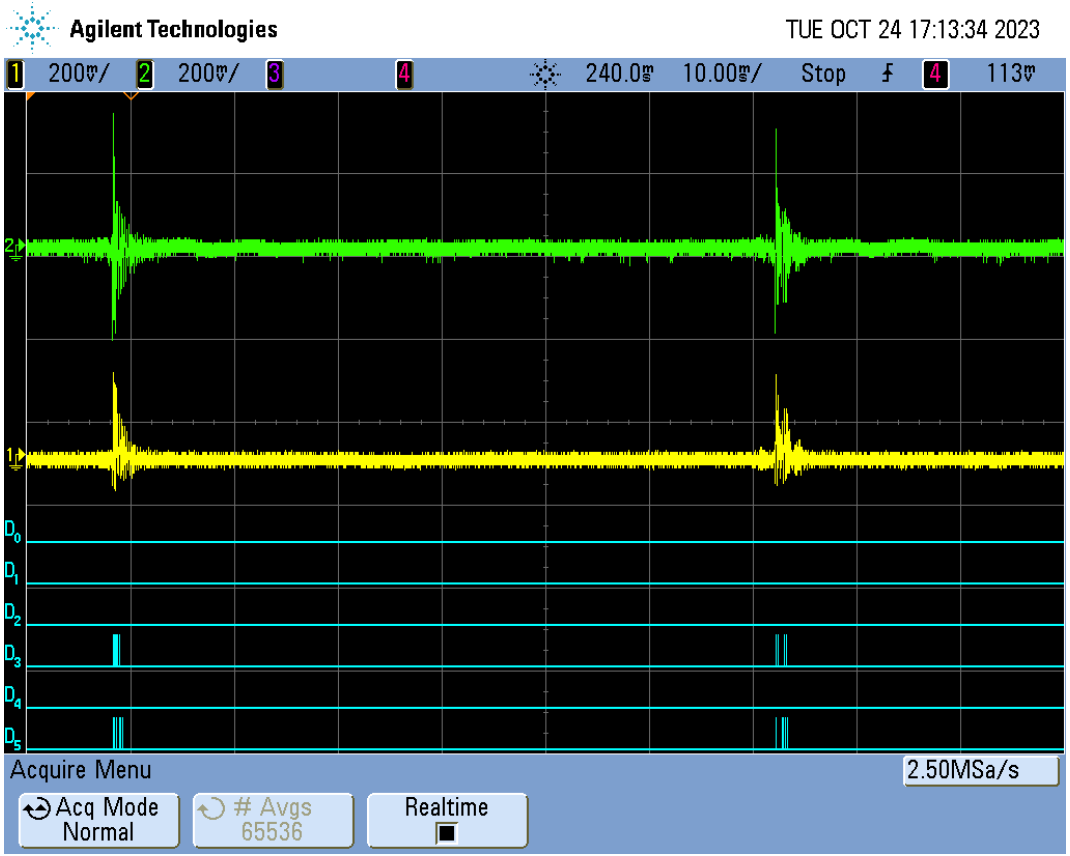
Response of the Cochlea to Sperm Whale Clicks (Experimental results)



Sperm Whale click

Analog output 4KHz

8KHz Channel

4KHz Channel

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Power consumption ?

CMOS Microchip 1500*250µm²

8 Channels

With buffers (required for characterization) :
~ few microWatts / channel

Without buffers (required for characterization) :
100 nanoWatts / channel

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Artificial Cochlea successful

https://hal.science/hal-04463709v2

Classification of Cetecean

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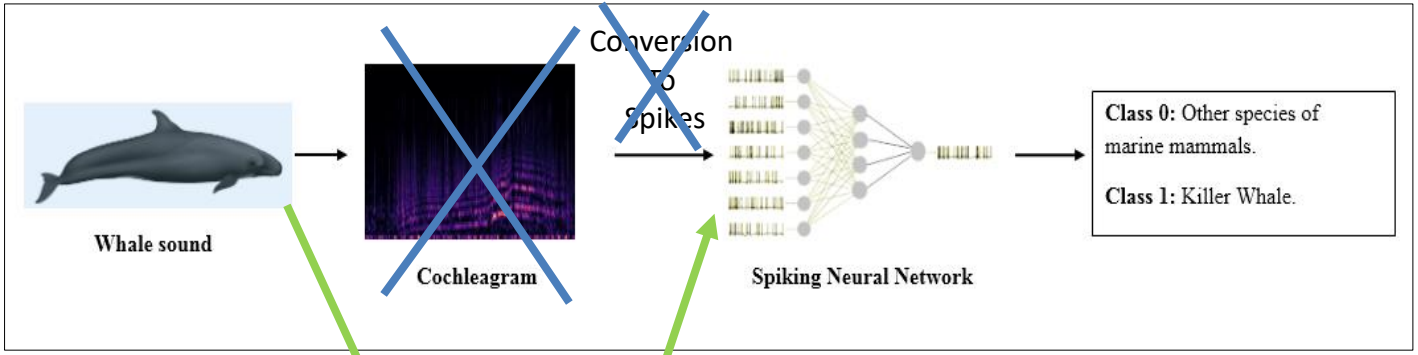
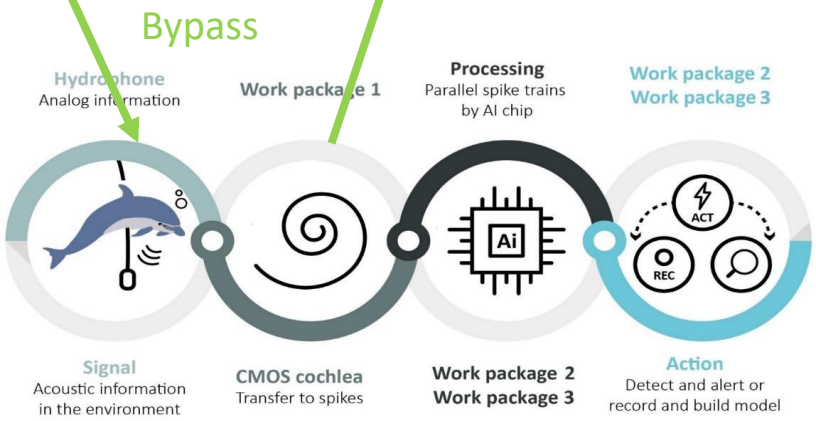
Binary Classification : Two classes are used, the first class contains several species of marine mammals while the second class corresponds to a particular Cetacean





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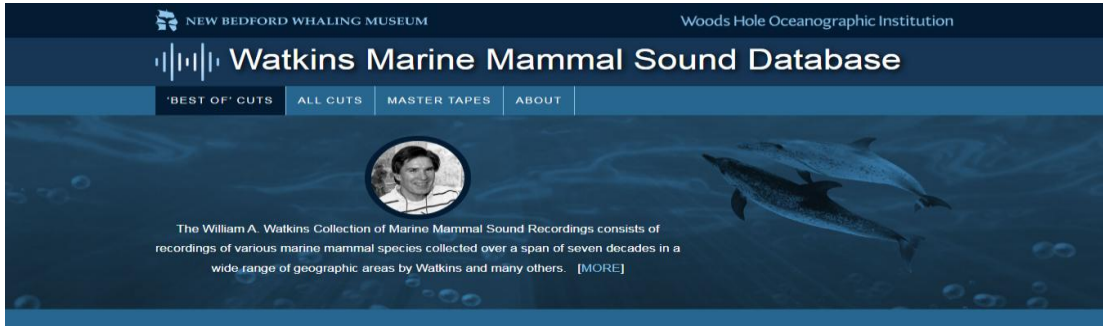
Dataset



Beluga, White Whale

False Killer Whale

Atlantic Spotted Dolphin

Bowhead Whale

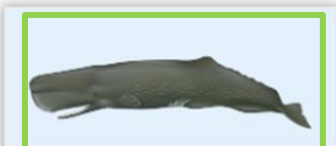
Clymene Dolphin

Long-Finned Pilot Whale

Melon Headed Whale

Northern Right Whale

Ross Seal


Sperm Whale

Frequency Response of the 16-Channels Cochlea

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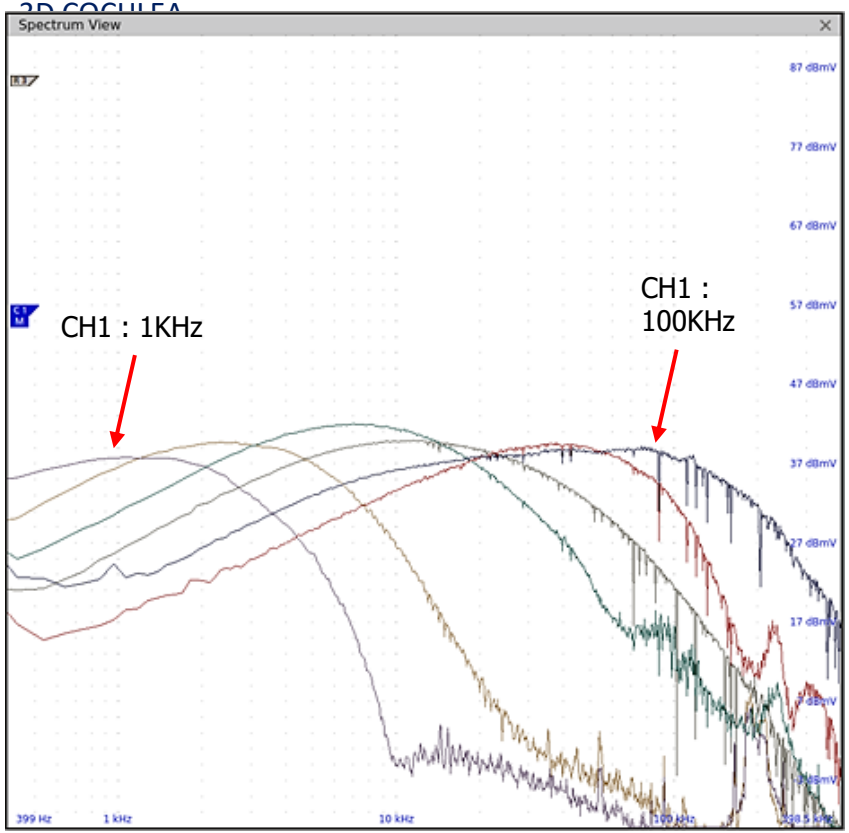

The frequency response of the channels 1 , 4, 8, 9, 12 and 16 is shown in the figure .

The central frequency of channel 1 is 100 KHz.

The central frequency of channel 16 is 1KHz.

Sperm whales emit ultrasound (up to 100 kHz)

Transient response of the 16-channels cochlea to a train of sperm whale clicks

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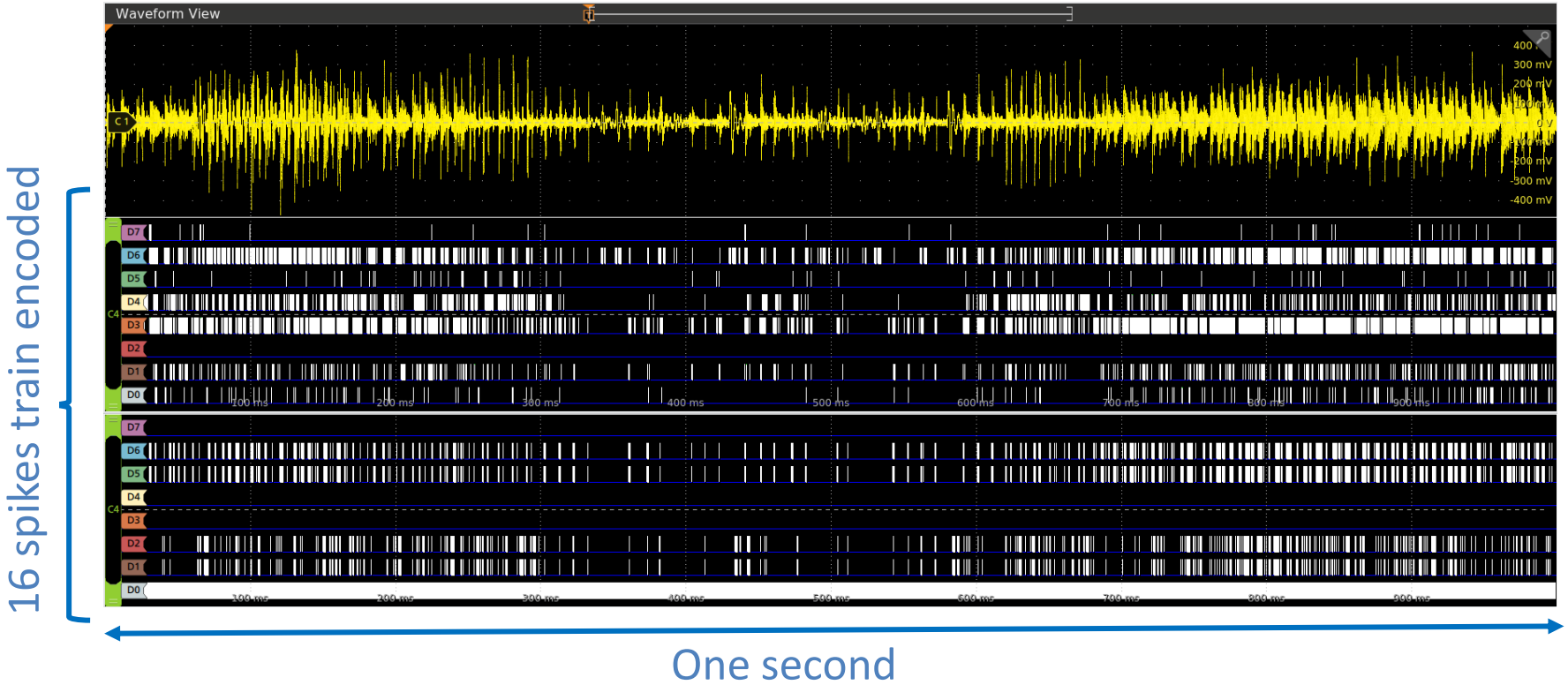
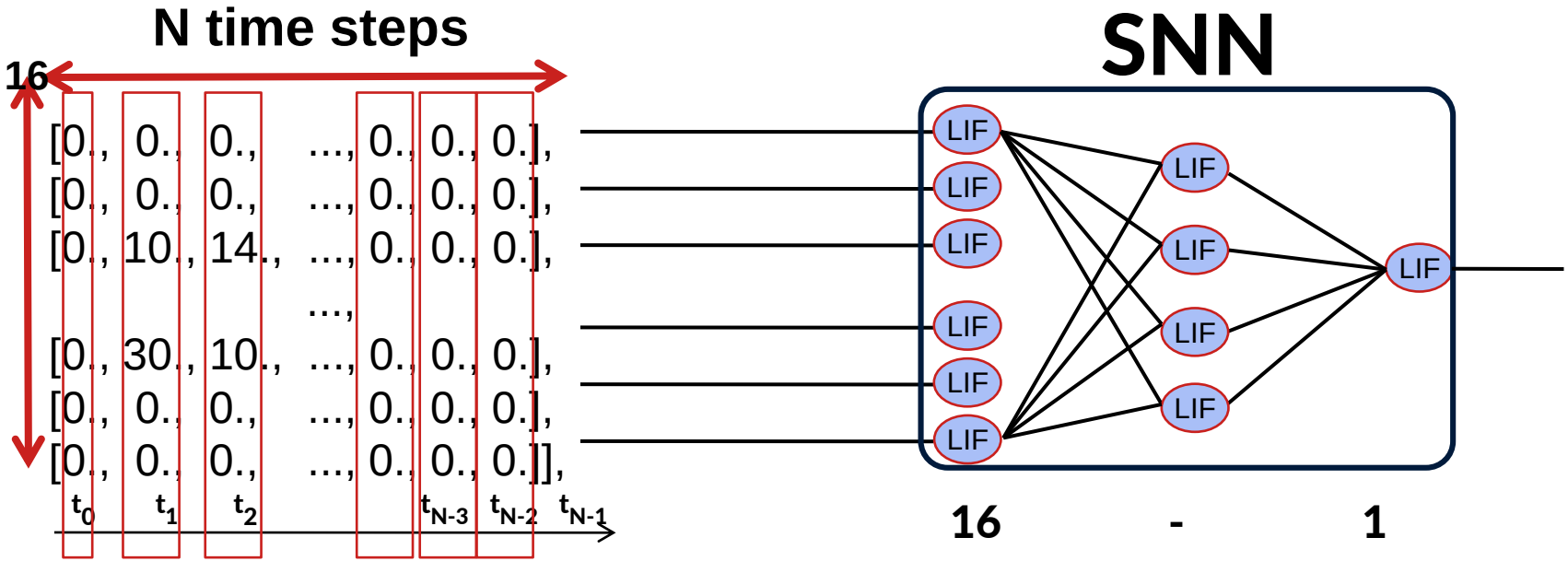
ULP SMART
3D COCHLEA



SFNN :



Passing data **step by step**, the input size for all the experiments is 16

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Experiments:

- **The spike timing (Time aspect):**
  - **T_{acc} : 0.5 to 10 m Sec: N = [1, 2, 4, 5, 10, 20]**
- **Input size of 16 ⟶ network size: [16, 1], [16, 32, 1], [16, 64, 1], [16, 128,1]**
- **The number of spikes (Frequency strength):**
  - Accumulated data VS Max_One_Spike

Model/ Data	Accumulated data	Max_One_Spike
Feed Forward NN	24 simulations	24 simulations

NOTE:
To have enough spikes at the output, thresholds of [.5, .3] are utilized (With thresholds of [.8, .7] and [.6, .4], we got less accuracy).

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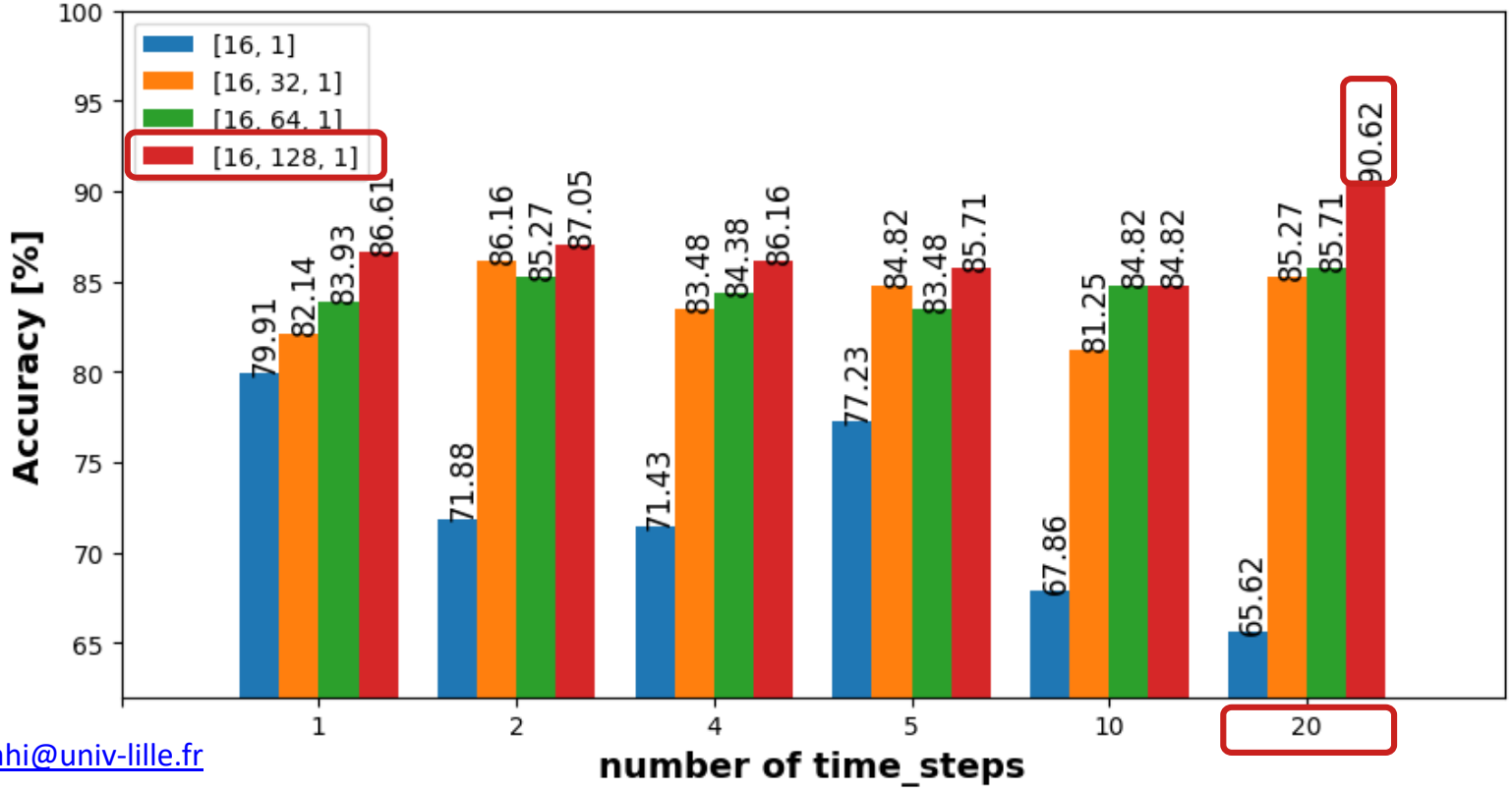
SFNN with Accumulated data:

Max accuracy: 90.62% @ T_{acc}: 1 ms (20 time_steps), Thresholds: [.5, .3], Model: [16, 128, 1]



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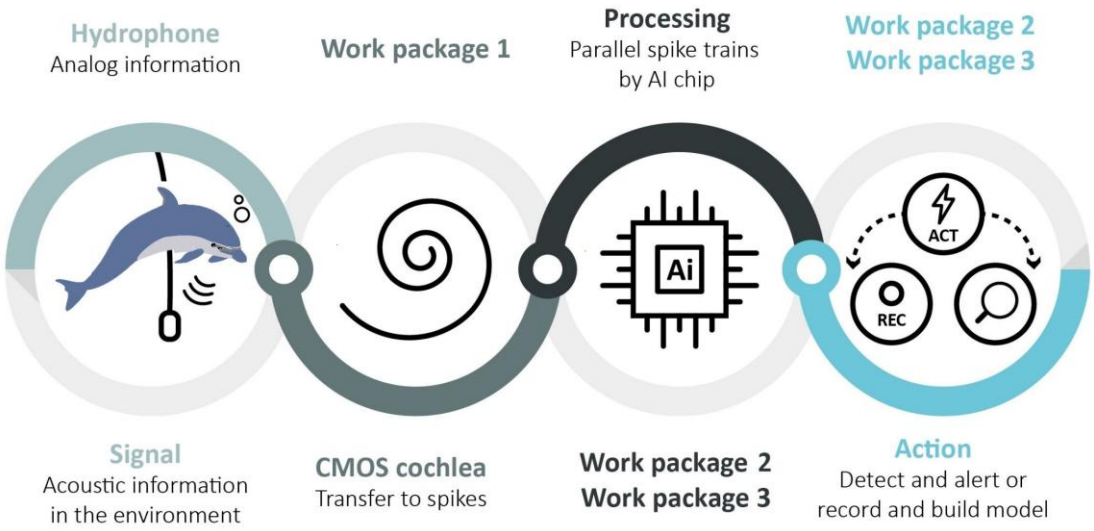
Future work on the classification

- Try to classify more than 2 classes
  - 10 classes on the dataset
  - Use recordings of our partner in Toulon (with noise)
- Implement the neural network on an FPGA
  - To package the sensor and the classifier together

Capteurs acoustiques bioinspirés

pour l'étude des milieux marins

- Traitement complètement analogique
- Électronique ultra-basse consommation d'énergie
- Biomimétisme de la cochlée humaine



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