A STUDY ON COCHLEAR IMPLANT AND SIGNAL PROCESSING STRATEGIES

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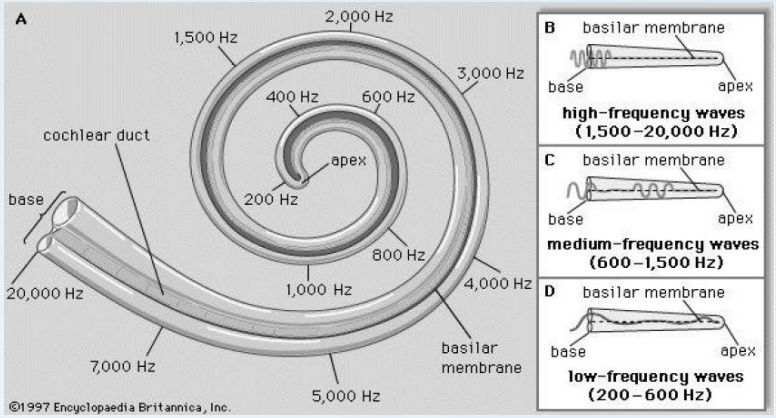
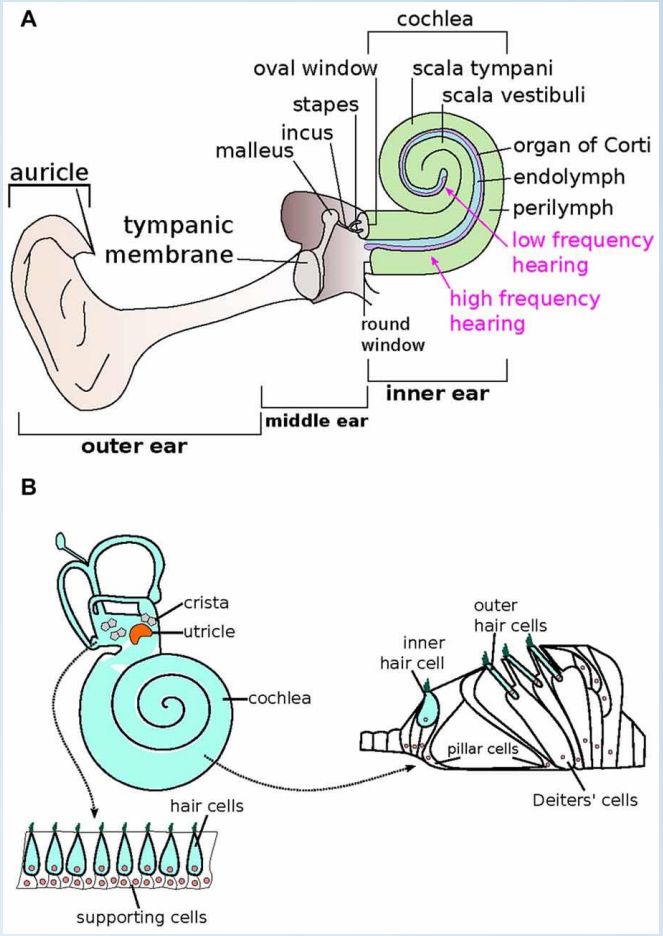
Introduction

Auditory system

- Distribution of frequencies in the cochlea





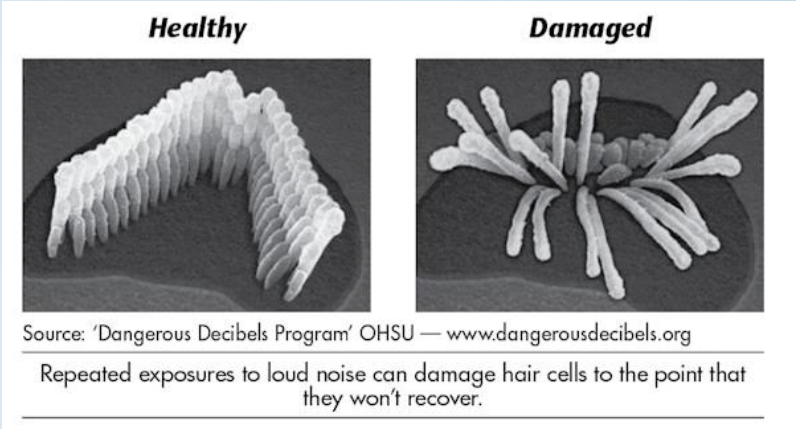
https://doi.org/10.3389/fnmol.2017.00236

Ref: [1], [2],[9]

Introduction

Damaged Hair Cells

- When the large number of hair cells are damaged, the inner ear can no longer process the sound as coming in
- To solve the problem, direct electrical stimulation of auditory nerves is needed
- This is where the cochlear implant can help as a medical device

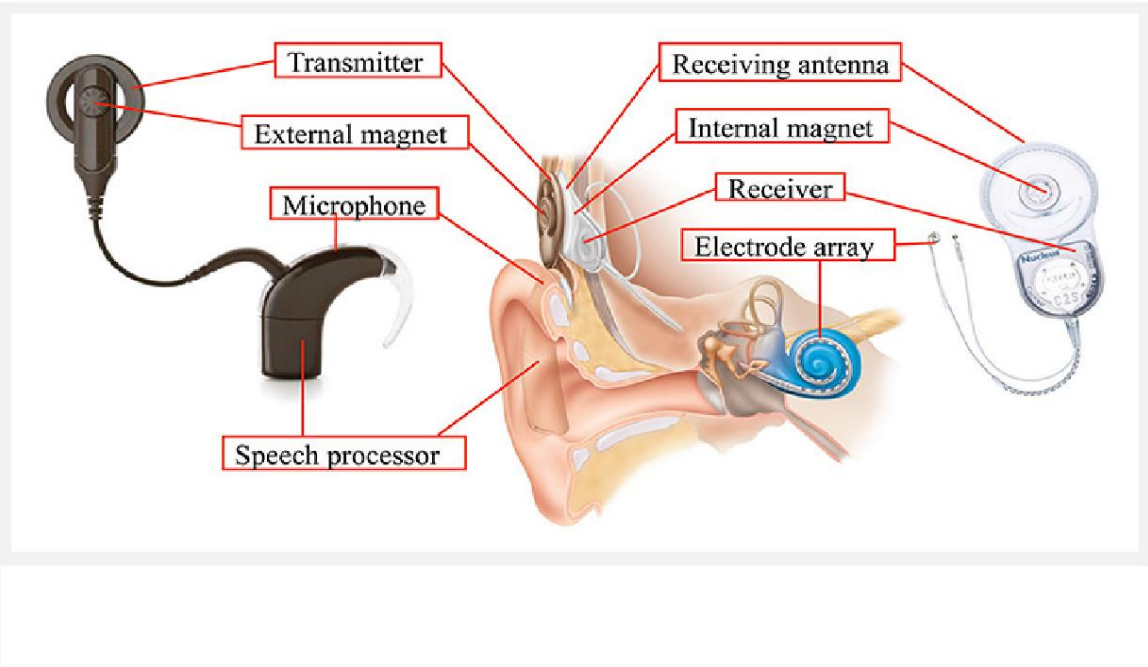


Ref: [1], [2],[9]

Introduction

Cochlear Implant Structure

- Microphone
- Signal Processor
- Receiver
- Transmitter
- Electrode Array
  - Consists of 6-22 intracochlear electrodes distributed along the length of the cochlea
  - Excite the nearby nerve fibers by the pulses



DOI:10.4414/smw.2014.13909

Ref: [1], [2],[3]. [9]

Classification of Cochlear Implant

Number of Channels:

- Single Channel Implants
- Multi-channel Cochlear Implants

Waveform Strategies

- Compressed-Analog (CA)
- Continuous Interleaved Sampling (CIS) strategy

Strategies based on feature extraction

- F0/F2
- F0/F1/F2
- MPEAK Strategy

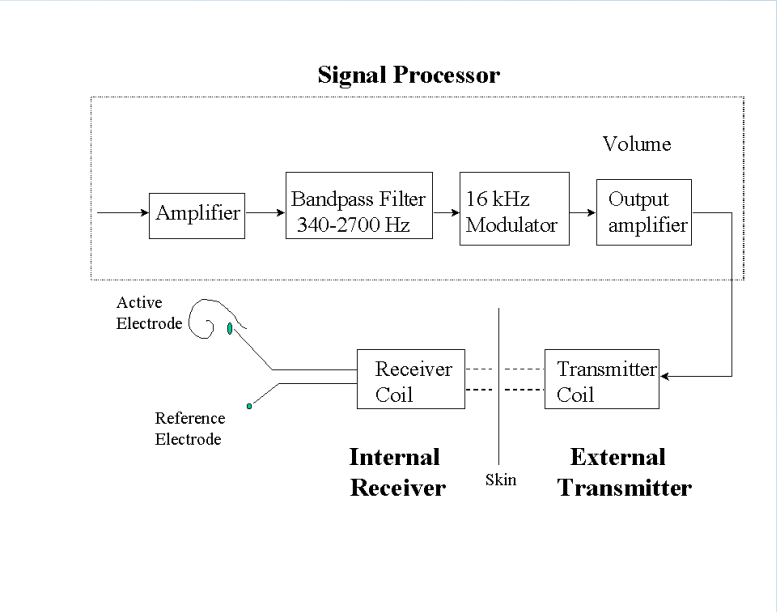
N-of-M Strategies

- Advanced Combination Encoders (ACE)
- SPEAK

Single Channel Cochlear Implant

- The first generation of CI
- Firstly introduced by William House in the early 1970s for 3M company

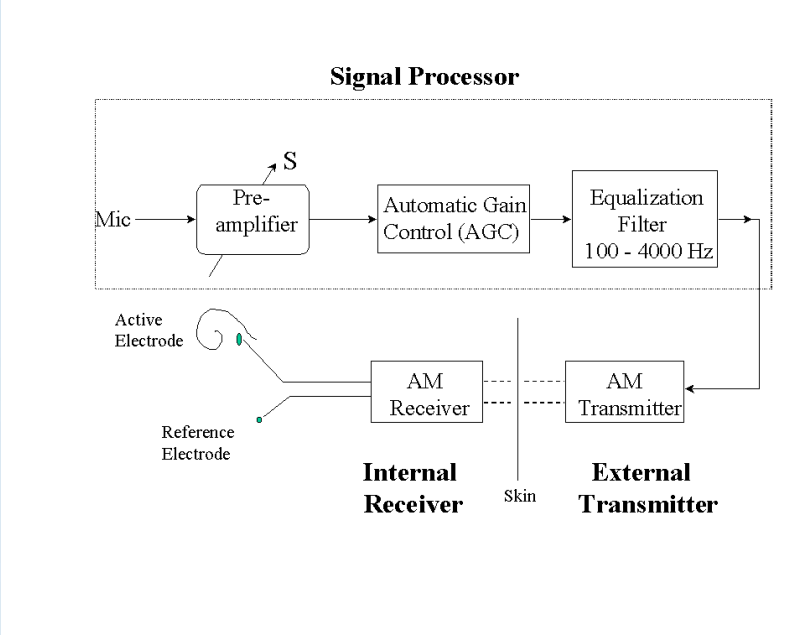
- Since it is Amplitude Modulated, so any fluctuation relating to the signal, is preserved.
- The processor does not limit the input dynamic range
- The shape of the signal is affected by the input signal
- The output would be clipped and the temporal information of the signal will be missed results in low speech recognition



Ref: [1], [2], [3]

Modification in Single Channel Cochlear Implant

- Method proposed at the Technical University of Vienna, Austria, in the early 1980s.
- Automatic Gain Control which is adjusted by the patient's dynamic range
- the temporal information of the speech are preserved
- The range of 100-4000 Hz contains the frequencies which are important for speech understanding
- A better speech perception and more accurate word identification in a sentence was acquired by this method



Ref: [1],[2] ,[3]

Single Channel Implant shortages

- There is only one electrode implanted in cochlea
- The frequency encoding cannot be achieved like cochlea frequency distribution
- Due to the refractory period of the nerve fiber on each action -potential, the temporal frequency encoding is limited to 1 kHz
- This temporal resolution is not sufficient for speech perception
- Few patients were capable of understanding speech with the limited spectral information

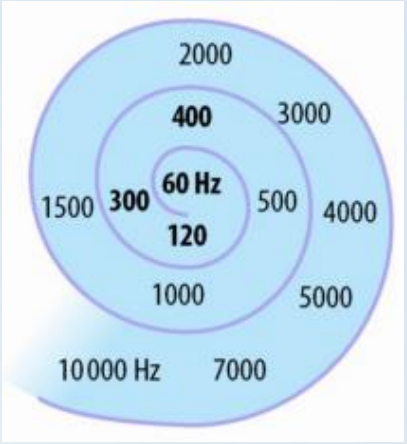
Ref: [1],[2],[3]

Multi-channel Cochlear Implants

Waveform Strategies
- Compressed-Analog (CA)
- Continuous Interleaved Sampling (CIS) strategy

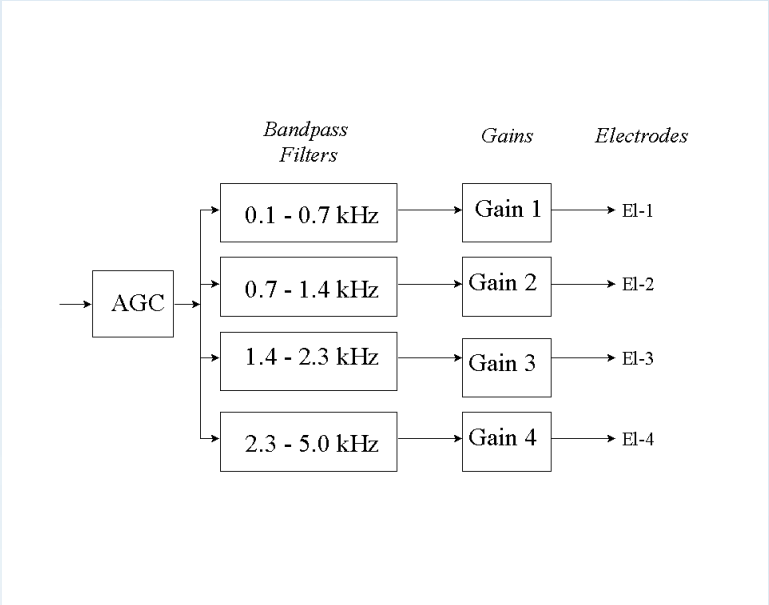
Strategies based on feature extraction
- F0/F2
- F0/F1/F2
- MPEAK Strategy

N-of-M Strategies
- SPEAK
- Advanced Combination Encoders (ACE)



Compressed-Analog (CA) approach

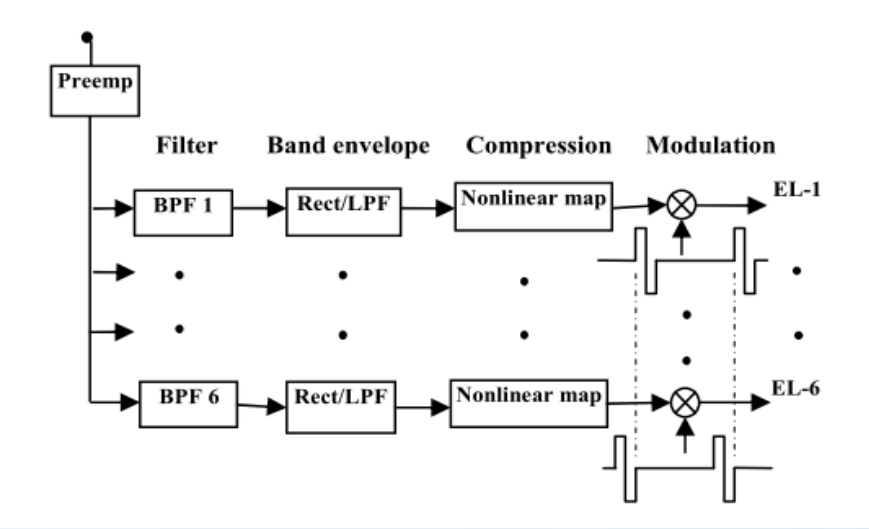
- This method was firstly used by Symbion, Inc., Utah and now it in no more applied to cochlear implants.
- the electrodes have 4mm distance one to another
- Simultaneous stimulation of four electrodes, results in electrode interaction
- Compared to the single-channel implants, this device was more successful in providing patients with speech understanding.



Ref: [1],[2],[3][9]

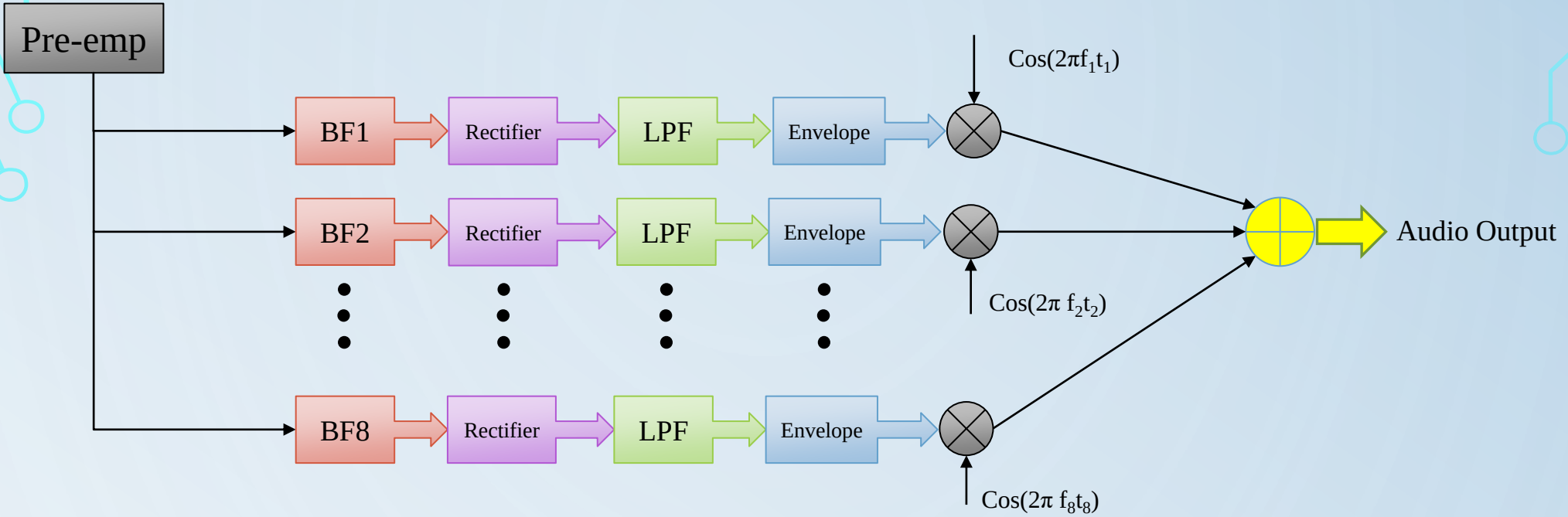
Continuous Interleaved Sampling (CIS) strategy

- Firstly proposed by Wilson B.S in1991
- Pre-emphasizing to increase SNR
- It uses 6 to 16 Band-pass filters
- Full wave rectification and a low pass filter with cut-off frequency between 200 to 500 Hz
- Compression Function maps the signal to the dynamic range of the patient
  - ➢ Logarithmic map for low-frequency channels and a more compressive map for high-frequency channels
- Trains of non-overlapping biphasic pulses are delivered to the electrodes in a way that only one electrode is activated at a time.
- The CIS strategy preserves the energy of the signal
- Better speech perception compared to single channel approach and also compressed analog strategy



Ref: [1],[2] ,[3],[4],[9], [11]

Implementing CIS Strategy in MATLAB



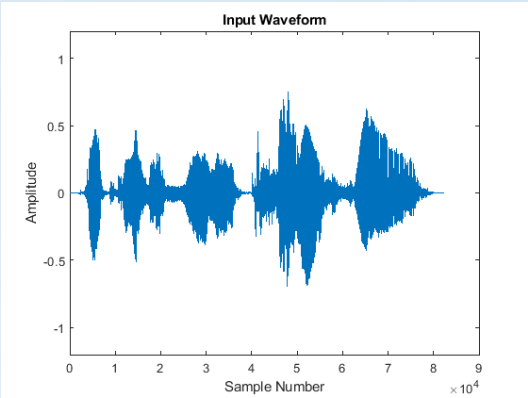
- Signal is sampled at 16 kHz
- Pre-emphasizing: second order Butterworth high-pass filter with cut-off frequency of 1200 Hz
- Bandpass filter bank: 8-16 channels
- Full wave rectification and low-pass filter
- Pulse generation is replaced with an acoustic output which is formed by using the detected envelope to modulate sine waves

Ref: [4], [7], [11]

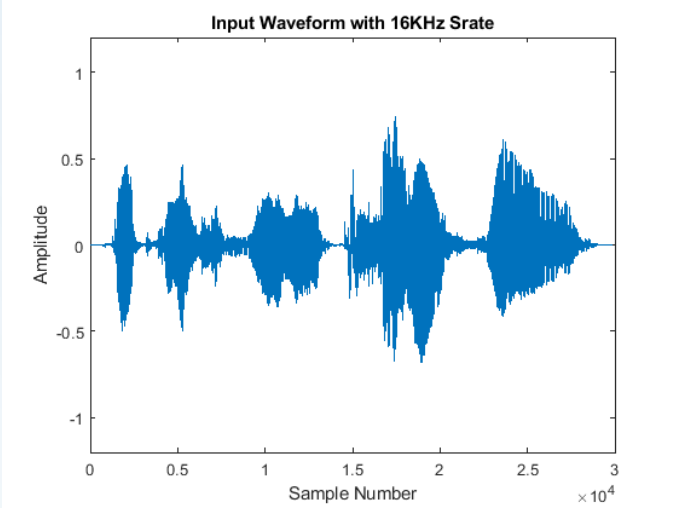
Implementing CIS Strategy in MATLAB

Sampled at 16 kHz

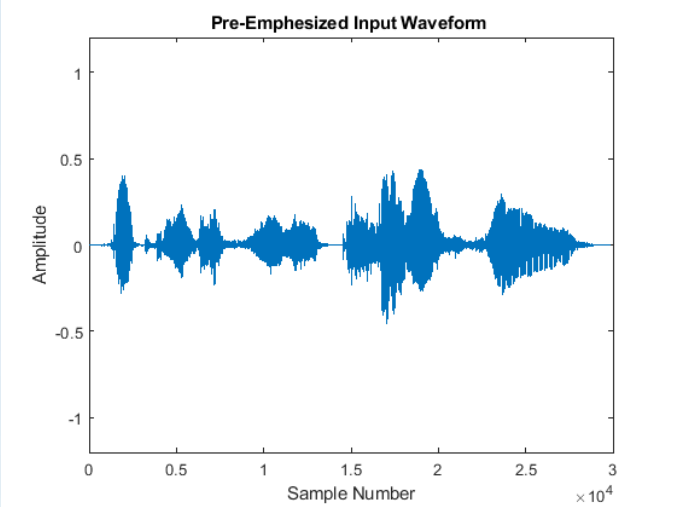
pre-emphasizing(BW HPF with cut-off freq:1200Hz)



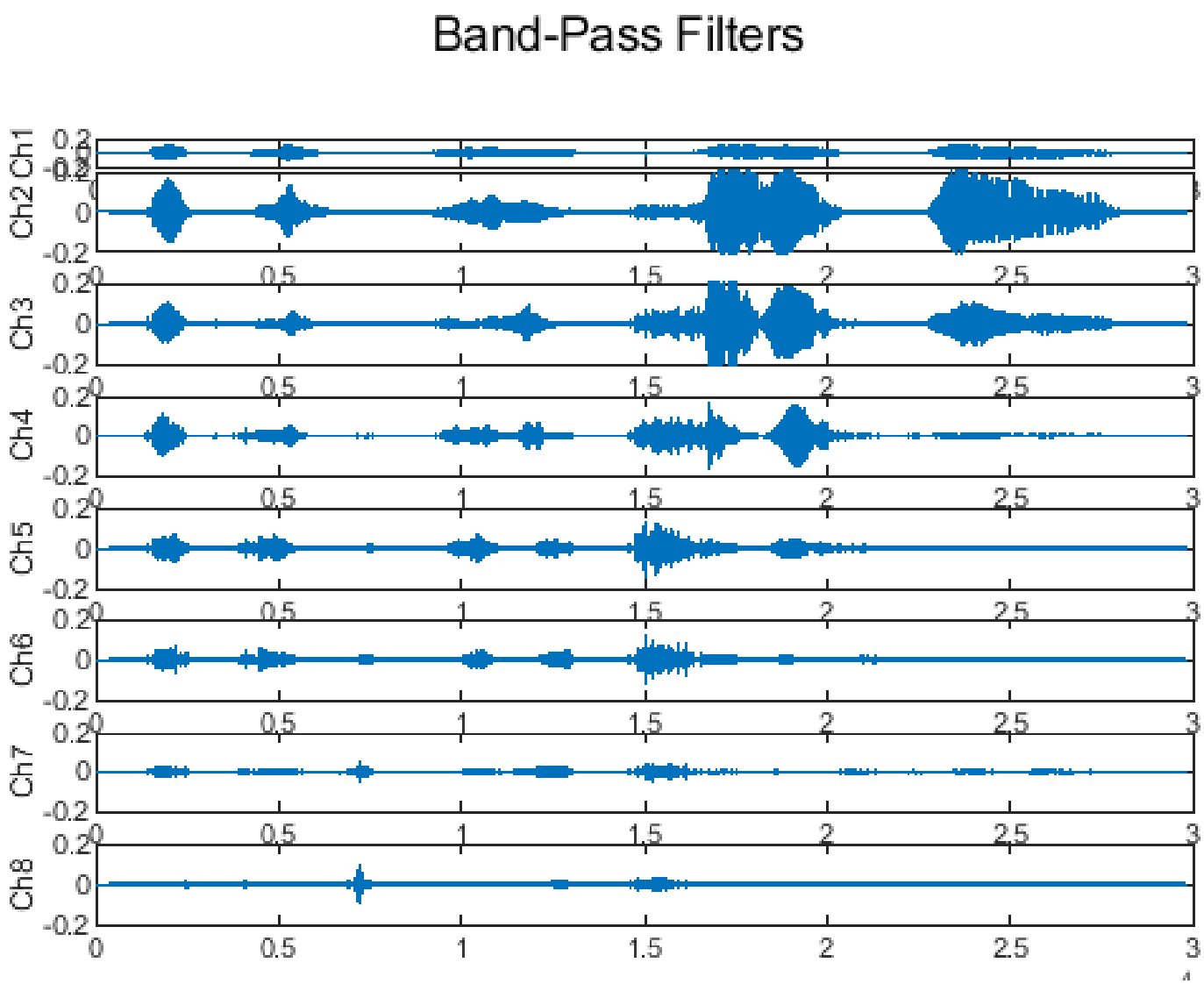

```
[P,Q] = rat(16000/Srate);
NewSig = resample(MonoSig,P,Q);
NewSig = NewSig(:,1);
fs = P/Q*Srate;
```




```
fc     = 1200;
w      = 2*fc/fs;
[b,a]  = butter(1,w,'high');
SigPreEmp = filter(b,a,NewSig);
```

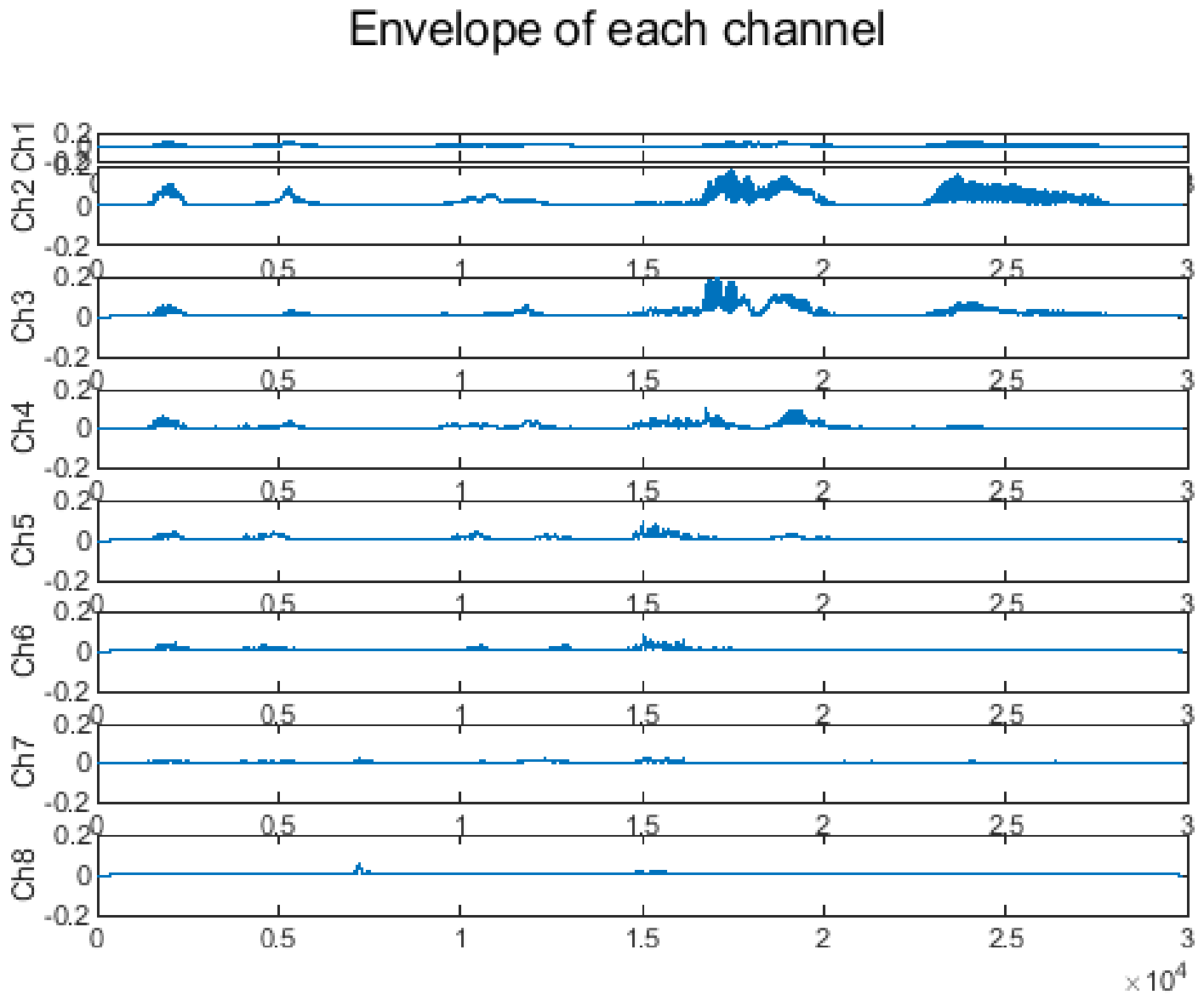


Implementing CIS Strategy in MATLAB



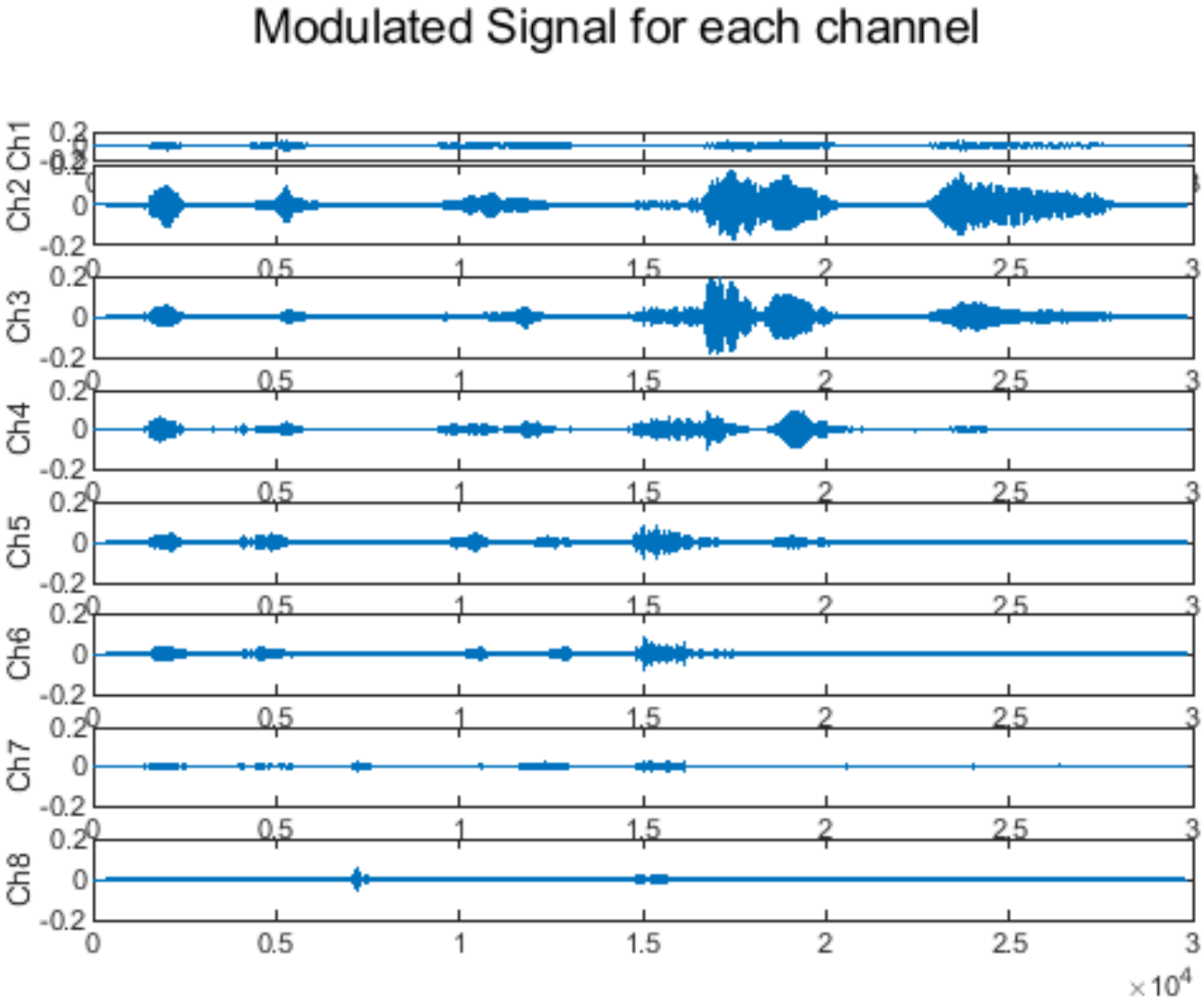

```
lowerband = 100;
higherband = 500;
ChBand = 500;
filterOrder = 2;
BandFiltSig = butterBandpassFilter(SigPreEmp, lowerband, higherband, fs, filterOrder);
```

Implementing CIS Strategy in MATLAB



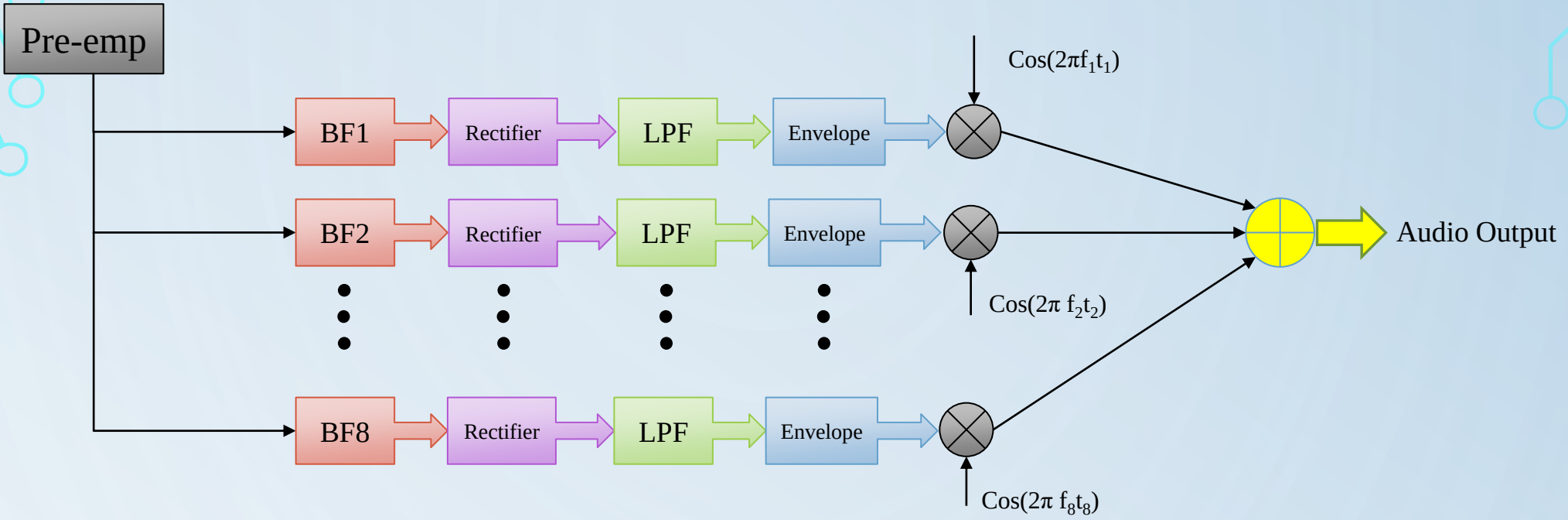

```
RectSig = abs(BandFiltSig);
SigEnvelope = butterLowpassFilter(RectSig, 400, fs, filterOrder);
```

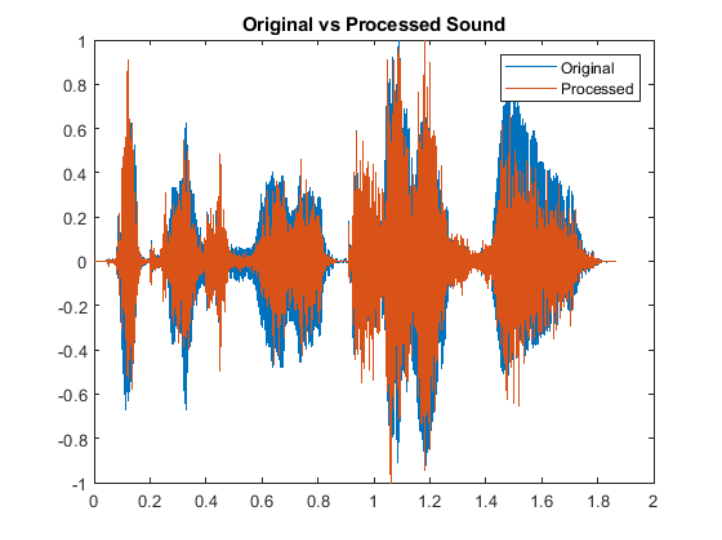
Implementing CIS Strategy in MATLAB




```
CenterFreq = (lowerband + higherband) / 2;
[r, ~] = size(RectSig);
timeDuration = r/fs;
time = linspace(0, timeDuration, r);
CosSig = cos(2*pi*CenterFreq*time);
ModSig = SigEnvelope.*(CosSig);
```

Implementing CIS Strategy in MATLAB





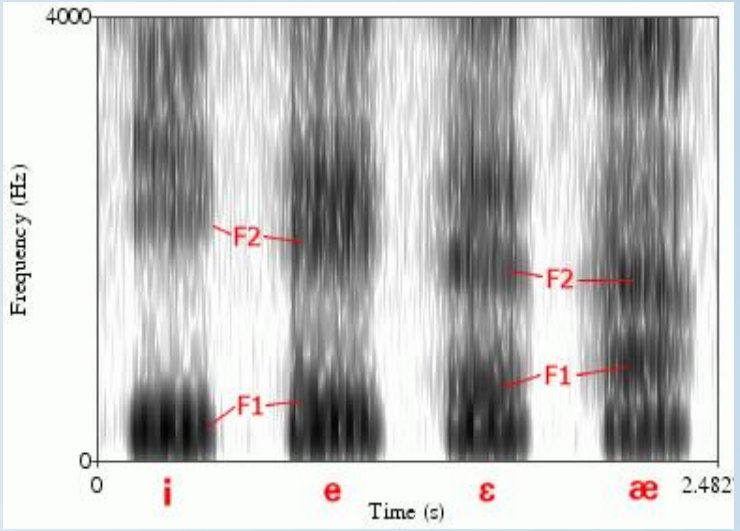

```
OutputSig = OutputSig + ModSig;
```

Strategies based on feature extraction

F0/F2 and F0/F1/F2 Strategies

Formants:

- The resonant frequencies of the vocal tract are introduced as the formants. Their energy around a particular frequency can be seen in speech spectrogram.
- Formants mostly occur at 1000 Hz intervals.
- The lowest frequency of a periodic waveform is known as fundamental frequency or F0.
- F0, is crucial for sound discrimination, music perception and detecting pitch

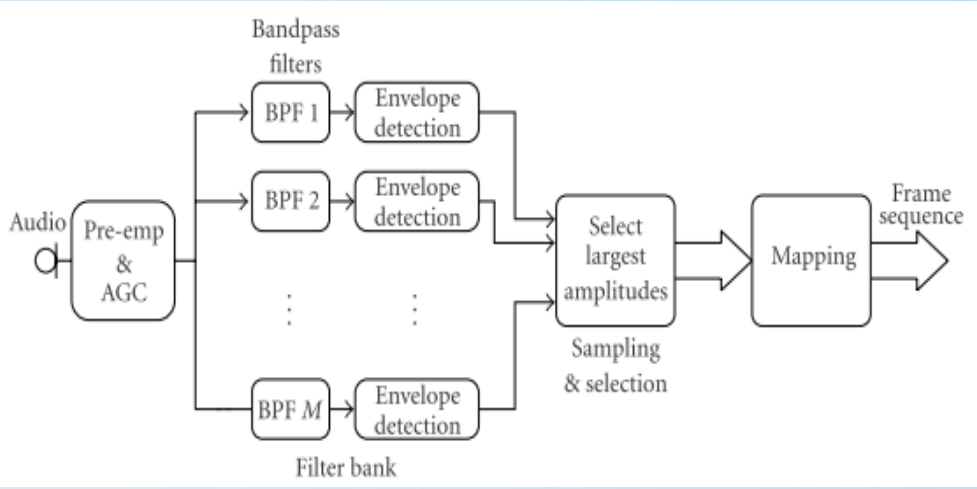


- These strategies extract formant frequencies by applying relevant lowpass filter and zero-crossing detector.
- The number of electrodes implanted in cochlea is 22
- Electrode are assigned based on formant frequencies
- They did not yield significant improvements on consonant recognition due to missing higher frequency information

Ref: [1], [2]

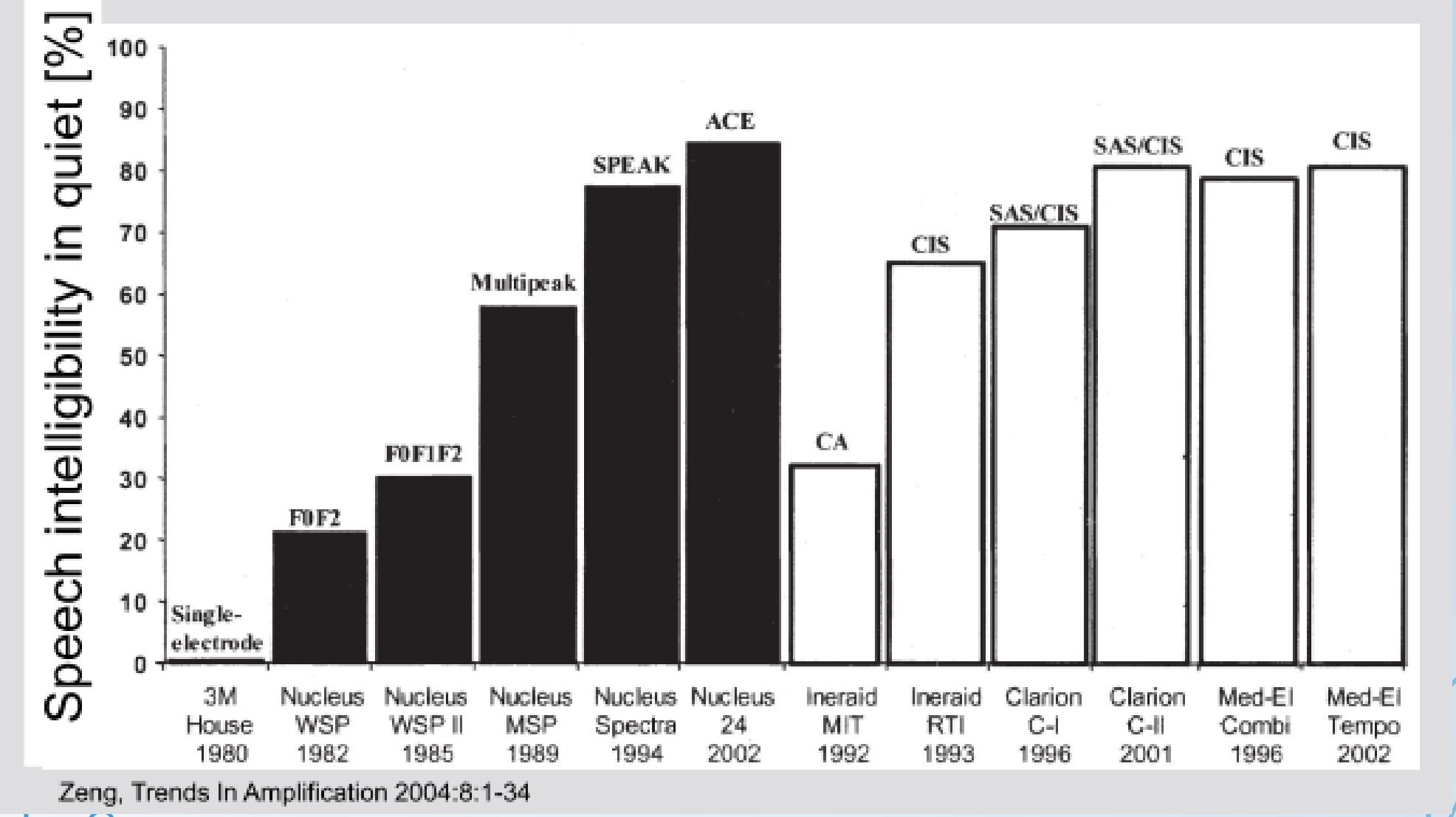
Advanced Combination Encoders (ACE)

- Speech processor designed for Nucleus 22 by Cochlear Corporation
- Based on the N-of-M principle
- The original signal divides into M bands,
- Envelope information for every frequency bands is extracted,
- The N bands with highest amplitudes are selected for electrode stimulation
- The device is using an array of 22 electrodes(M).
- It calculates the spectrum energy on each envelope
- In each cycle, only 8-12 channels with highest amplitudes are selected to stimulate the corresponding electrodes and build the final signal



Ref: [1], [2],[5], [9]

Comparison between different strategies



Zeng, Trends In Amplification 2004:8:1-34

Ref: [3]

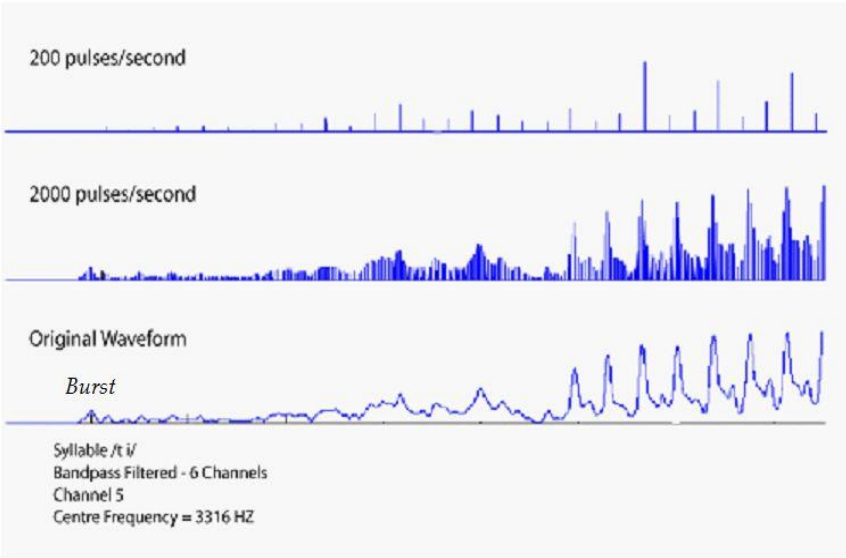
Factors Effecting Cochlear Implant Performance

Stimulation Rate

The rate of stimulation is defined on each electrode as the number of cycles per second

- It determines the temporal resolution of the restored signal
  - ➢ The ability of the system to detect amplitude changes over time

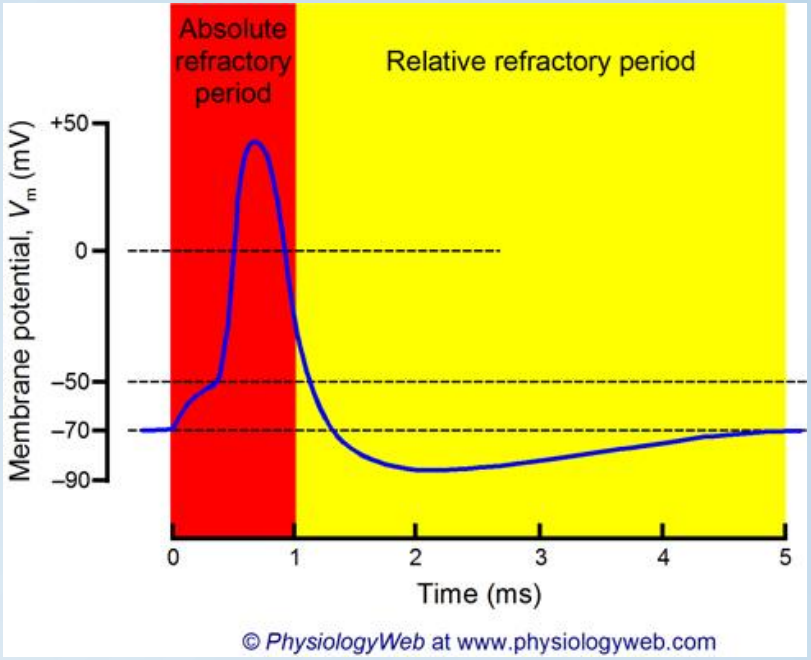
- The more stimulation rate provides more information extracted from the original signal
- Significant improve in speech recognition cannot be necessarily achieved by increasing number of pulses per second
- Except for a small difference for vowel recognition in quiet, there were no significant differences in performance by increasing stimulation rate[]



Ref: [2], [3],[6], [10]

Factors Effecting Cochlear Implant Performance

- Refractory period is the time duration which a cell is not capable of repeating an action potential
- At low number of pulses per second, the action potential can occur for every cycle
- Higher stimulation rate is limited by the refractory period
- Neurons only fire preferred phases of the sound in each cycle (Phase Locking)
- The rates of stimulation higher than 800 pps per channel lead to poor phase locking



Ref: [2], [3],[5],[6], [10]

Factors Effecting Cochlear Implant Performance

Number of Electrodes

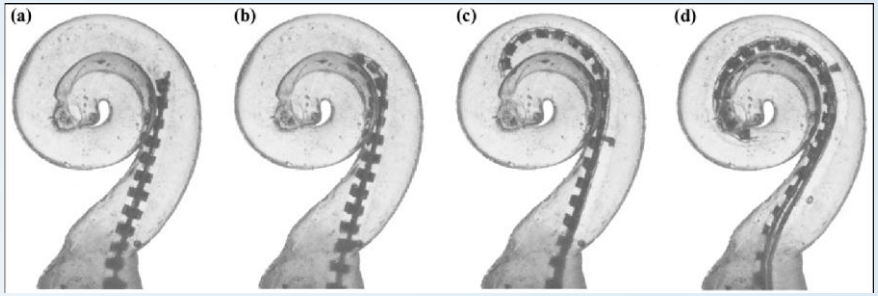
- Number of electrodes determines the spectral resolution of the processor
- Pitch discrimination is highly dependent on the distribution of electrodes in the cochlea
- Few electrodes are not capable of restoring original signal, perfectly.
- Experiments suggest that patients do not use the full spectral information and only seven to ten channels are being used for speech recognition
- One hypothesis justifies this issue due to the electrode interactions [5]

Ref: [2], [3], [5], [10]

Factors Effecting Cochlear Implant Performance

Location of the Electrodes

- There is a typical distance of 22-30 mm between the electrodes
- The electrode array is not fully inserted into the cochlea
- This creates a mismatch between the analysis and stimulation frequencies
- The low frequencies between 200 to 1200 Hz are located in the depth of 540 º in the cochlea
- The current available cochlear implants are not able to insert the electrodes deeper than 400 º due to the possible intracochlear damages and tearing the basilar membrane



Ref: [2], [3], [10]

Factors Effecting Cochlear Implant Performance

Availability of Noise

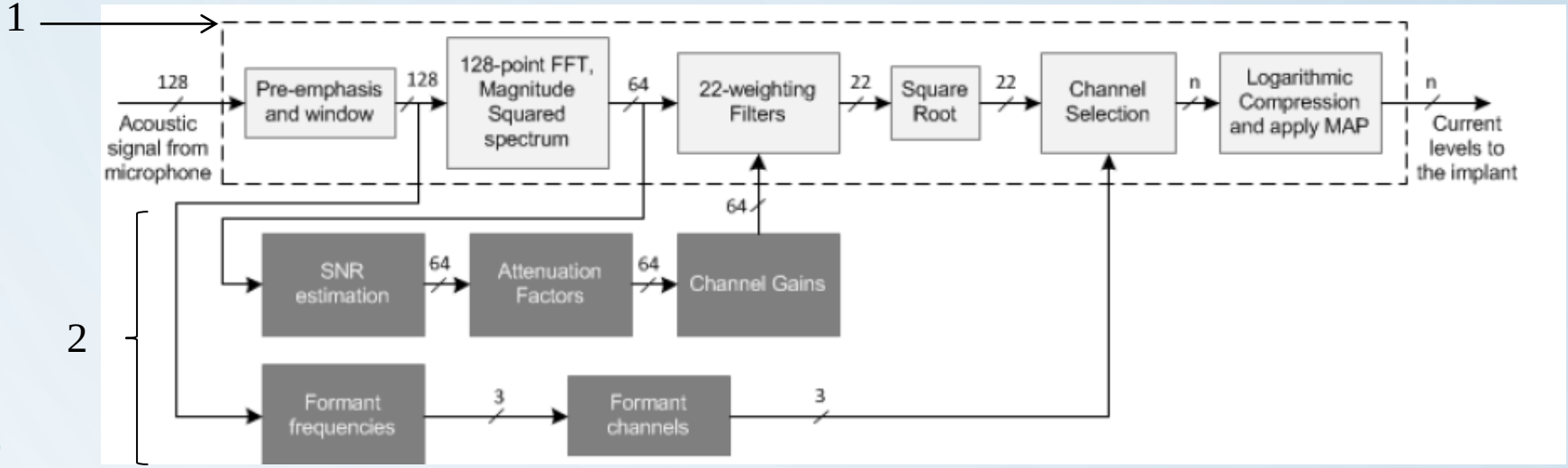
- The users have reported poor speech recognition in noisy conditions
- Noise is dynamically changing in daily communications
- Results in the lack of spectro-temporal details in the processed speech
- Noisy conditions seem so stressful for the users and demand lip reading to communicate
- Strategies based on N-of-M principle, are highly affected by noise
  - The highest amplitudes of the spectrum may not always the main components of the speech signal
  - In presence of noise, the processor may select some high peaks of the noise as the target

Ref: [8]

Improving CI performance in noisy conditions

There are two stages in the proposed study:

1. Simulation of standard ACE strategy
2. Modifying the output by adding specific features



Improving channel selection of sound coding algorithms in cochlear implants, Ali et al, IEEE, ICASSP 2014

Ref: [8]

Methodology

Formant Frequencies

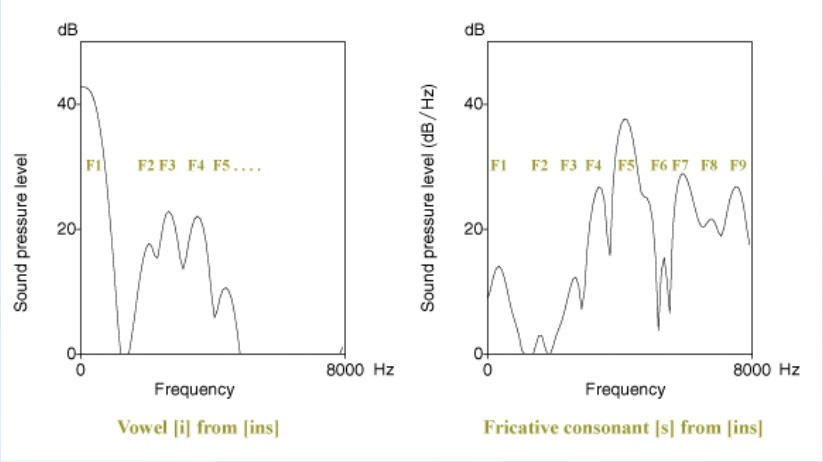
- Highest energy carries the most useful information of the speech, called formant frequencies
- When the background noise is high, the noise amplitude masks the formants
- The proposed algorithm extracts the first three formants and gives priority to their channels
- Linear Predictive coefficient (LPC) estimates formants in the speech signal
- The formants are the roots of LPC function

$$s[n] = \sum_{k=1}^{p} a_k s[n-k] + e[n]$$

Linear Predictive Coefficients

linear combination of past samples

error between the signal and predicted value



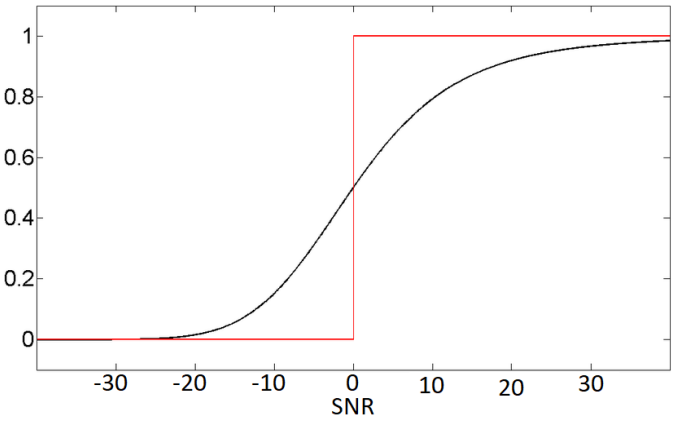
person2.sol.lu.se/SidneyWood/praate/whatform.html

Ref: [8], [12]

Methodology

Giving attenuation factor according to SNR

- Binary masking
- Soft masking



Ali et al, IEEE, ICASSP 2014

- In two different noise conditions, the speech intelligibility have been compared with standard ACE
- According to the patients, there was a slight to better speech intelligibility and quality for the proposed method

Ref: [8]

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