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Understanding Hearing Through Cochlear Implants - A Simulation Model of the Hearing Perception

– Summary –

A thesis submitted for the degree of
Philosophy Doctor in System Engineering

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The subject of the present thesis entitled "Understanding Hearing Through Cochlear Implants - A Simulation Model of the Hearing Perception" was born out of my personal necessity and curiosity, during my period of research and preparation to be a father of a deaf child waiting to receive his cochlear implant. Making contact with many specialists and parents with similar conditions I quickly realized that Cochlear Implants are not a miracle cure and there is a long road to complete rehabilitation paved with many uncertainties and challenges to overtake. I didn't find answers for the questions I had, but I found that these questions were not raised only by me. Most importantly, almost everybody wanted to understand **how and what our children are hearing** and **how to maximize the chances of (re)habilitation** in an area where outcome relies not on only on the good expertise of all medical and technical personnel involved but seemingly on pure chances too. After many years of research and working together with my son and many other children, whose cochlear implants are being fitted by *Ş.L.dr.ing. Antonius STANCIU*, my findings were described and sustained in this present thesis under the scientific lead of *Prof.univ.dr.ing. Gheorghe-Daniel ANDREESCU*.

Chapter 1: Introduction

In Chapter 1, a short overview of the Cochlear Implant development history is presented based on the publications of (Hallpike & Rawdon-Smith, 1934), (A & C., 1957), (House WF, 1973) (House WF, 1976), (Chen & Zhang, 2006), (Wilson & Dorman, 2008), (Schnupp, et al., 2011), (Moctezuma & Tu, 2011), (Choi & Lee, 2012), (Eshraghi, et al., 2012), (Harczos, et al., 2013). Although electrically induced hearing sensations were first reported in the early 1800s by Alessandro Volta, the development of the first cochlear implants started only in the 1970s. During these developments, it was identified that there are two main mechanisms to analyse and identify perceived sounds:

- **Spatial cues** – the positions along the basilar membrane stimulated by the sound
- **Temporal cues** – the rate of the nerve firings created by sound

Based on these finding the first single electrode cochlear implants were developed, quickly followed by multielectrode cochlear implant systems. The single electrode cochlear implants were based on transmitting the sound information only relying on temporal cues, while multi-electrode cochlear implants mostly rely on spatial cues. In case of typical multi-electrode cochlear implants, the sound recorded by the microphone is split, using bandpass filters, into as many frequency bands as many electrodes the implant has. The amplitude envelope of the filtered signals is used to modulate the intensity of the stimulation levels of each electrode.

Due to technological constraints, the number of electrodes used to stimulate the cochlear nerves remained mostly unchanged during the years varying between 12 and 26 electrodes, therefore demanding for significant improvements in the sound pre-processing and coding strategies. Nowadays, hearing restoration levels and quality widely vary from patient to patient and from one cochlear implant type to the other. Perhaps the most important factors to influence the success of the hearing restoration are:

- The number and placement of the stimulating electrodes
- The stimulation strategy used to convert sound into electric stimuli (Moctezuma & Tu, 2011) (Choi & Lee, 2012) (Somek, et al., 2006).
- The ability of the patient to adapt and learn to interpret the artificially generated hearing sensation.

The last point in the list above, is also the most difficult to predict and control. It was observed that, even with identical cochlear implants, each patient will benefit differently.

There are three major categories of implant recipients with specific recovery expectations:

- **Patients with postlingual hearing loss**
- **Patients with prelingual or congenital hearing loss, with late implantation**
- **Patients with prelingual or congenital hearing loss, with early implantation**

In all of these categories, the success is conditioned by the right Cochlear Implant parameter fittings and attended hearing and speech therapy sessions, and even after the most successful recoveries, the hearing in complex auditory scenarios is highly inferior compared to healthy natural hearing.

Researchers have studied the nature of the perceived sounds, and based on auditory models and reports of postlingually deafened cochlear implant recipients, several models and software algorithms have been developed, to synthesize the sounds supposedly perceived by the cochlear implant users. (Mahalakshmi & Reddy, 2012) (Chilian, et al., 2011) (Loebach, 2007).

Such *auralization methods* and systems can be very useful in various areas of the cochlear implant research and utilizations:

- Objectively compare expected hearing quality with existing sound coding strategies;
- Test bench for development of new coding strategies;
- Improve fitting procedures;
- Help speech therapists to understand hearing through CI.

The existing auralization methods provide a good indication of how the sounds are perceived by mid-performing, mostly postlingually deafened cochlear implant users, but they fail to predict the hearing quality of peak performing patients.

The main objective of the present work is to **develop a reliable simulation model to predict, quantify and demonstrate the expected hearing performance of cochlear implant users** in a way which is easily comprehensible not only by tech professionals, but also by non-technical oriented people like speech-therapists, psycho-therapists, and maybe most importantly, by relatives of the patients.

It is my considered opinion that the most appropriate method to demonstrate the hearing quality of a hearing-impaired person is to reproduce the sounds they perceive and replay it to normal-hearing persons. This is why the proposed target is to develop and implement a novel auralization method of the perceived sounds which transforms the electrical output of a cochlear implant into sounds relaying not only on the physiology of the ear, but also mimicking the brain ability to learn and adapt to new stimulation patterns.

Also, I had the opportunity to study and follow the evolution of more than 300 children with cochlear implants. These children are patients of the fitting specialist Dr. Ing. Antonius STANCIU, and they undergo periodic hearing tests and fittings. All these patients are MED-EL cochlear implant users, and all their audiograms and fittings are archived within the fitting software's database.

As a **secondary objective of the thesis**, I have proposed to **explore the possibilities to help these patients by providing various tools to aid the fitting process and troubleshooting of defects** using ideas and methods developed as a spin-off during the research efforts invested in the main objective of the thesis.

Figure 1 depicts the structure of the present thesis reflecting the duality of the research objective. The thesis starts with an introductory chapter (Chapter 1) consisting of a short overview of the history of the cochlear implants, and the presentation of the research objectives.

In Chapter 2 the anatomical structure of the ear and the neuro-sensory deafness is presented including relevant aspects of the mechanisms of hearing. In the same chapter, a review of the existing cochlear implants and their stimulation strategies is given.

In Chapter 3 the mathematical models necessary for the simulation of the ear are introduced. These models are focusing on the main structures of the inner ear: the basilar membrane, hair cells and auditory nerve firing model.

The **contributions** to the **main research objective** are described in Chapter 4. First, a simplified model of the cochlea is introduced and implemented, followed by a comparison between the existing auralization models and the newly proposed auralization model. The implementation of the newly proposed auralization model is detailed and experimental results are explained.

The **contributions** to the **secondary research objectives** are presented in Chapter 5, introducing MED-EL's cochlear implant system and describing five different original contributions related to it:

- Statistics of typical stimulation levels
- Computer-assisted fitting of cochlear implants – Tracking the Effective Stimulation Threshold
- Case studies of Fitting evolution
- Interfacing with Med-El Cochlear Implant Processors
- Intra-cochlear current flow model

Finally, Chapter 6 concludes the thesis presenting the summary of the contributions and comparing them to the original scope of the thesis.

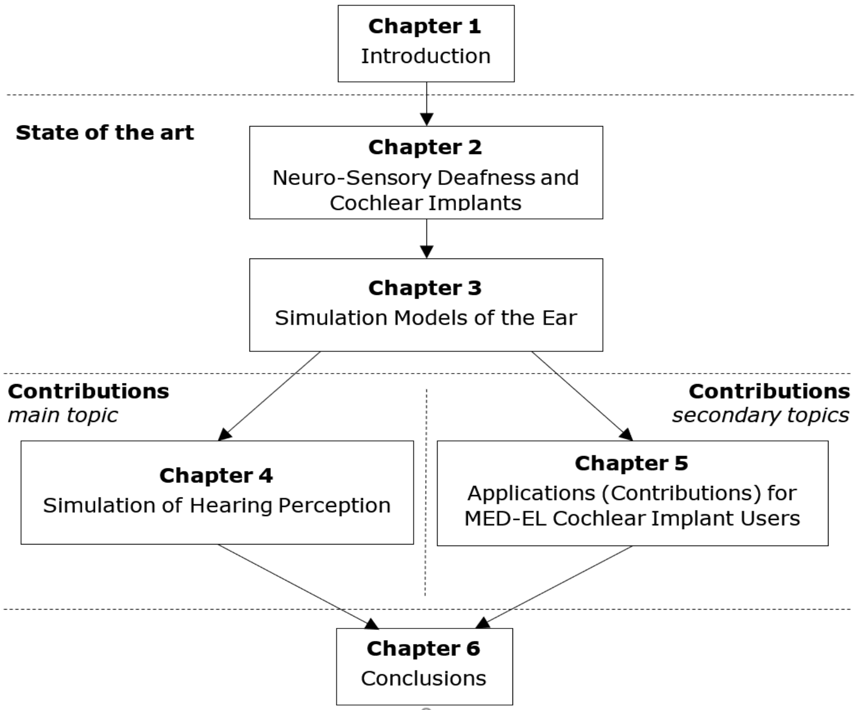

Figure 1: Thesis structure

Chapter 2: Neurosensory Deafness and Cochlear Implants

Being an *interdisciplinary research project*, the present thesis must provide a thorough introduction to both the medical and engineering aspects involved in the development of cochlear implants.

First, in Chapter 2.1 (**Introduction to the ear anatomy and causes of neuro-sensory deafness**), a short description of the *ear anatomy* is given, describing the organs and parts involved in the propagation of the sound wave from outside to the inner ear. The thesis provides a detailed description of the *inner ear structure, function and mechanisms* and examples of in vivo and in vitro measurements at different stimulation frequencies (Schnupp, et al., 2011).

It is shown how the basilar membrane decomposes the sound signal into its composing frequency components, how these individual mechanical vibrations are transposed into electrical cell polarization with the help of the hair-cells and finally how these potentials are triggering the cochlear nerve cells to induce hearing perceptions. The frequency-specific stimulation locations are marked in a simplified visual representation of the cochlea's spiral and cell polarization patterns are shown at frequencies varying from 300 Hz to 5 kHz. Based on in-vitro recordings it is concluded that at low frequencies the nerve firings patterns are preserving the phase end frequency of the stimulation sound showing that not only the stimulation location plays an important role in the sound perception but the temporal pattern of the nerve firings too.

Most importantly, it is highlighted that the destruction of the hair cells makes it impossible to perceive sounds and that this is the most predominant cause of deafness also known as neuro-sensory deafness.

The geometry of the cochlear structure is presented too, highlighting the cochlear ducts filled with peri- and endolymphatic fluids, which can be used to introduce electrodes to the vicinity of the cochlear nerves in order to artificially replicate the hair-cells function.

A simplified visual representation of the unrolled cochlea is introduced to be used in the rest of the thesis.

In Chapter 2.2 (**Introduction to cochlear implants**) the structure and functioning of modern cochlear implants is presented (Hochmair, et al., 2007) (Defense R&D Organization) (Moctezuma & Tu, 2011) (Mahalakshmi & Reddy, 2012) (Zeng, et al., 2015) (Ghildiyal, 2016).

It is shown that today's cochlear implants are composed of three major parts: The external sound processor, the internal stimulation circuit and the electrode array. The external sound processor is worn behind the ear and coupled magnetically for signal and power transmission to the internal stimulation circuit implanted in the temporal bone of the skull. The Electrode array is inserted as deep as possible into one the cochlear duct through the round window or through a hole drilled into the cochlea, and it is connected through a flexible cable to the stimulation circuit.

Depending on the manufacturer, different electrode array insertion depth and position are used. Photographs and radiography images are shown to highlight the differences of the existing approaches:

- **Free-floating long electrodes for total cochlear coverage** – to maximize the stimulation area while reducing the number of stimulation channels
- **Peri-modiolus pre-curved short electrodes** - to minimize the distance between the electrodes and hearing nerves allowing higher channel density while reducing the stimulation area.

In Chapter 2.3 (**Simulation Strategies**) the complete list of cochlear implant manufacturers is given and existing stimulation strategies are categorized and described.

The following list presents the list of manufacturers as of the now and the coding strategies used:

Company	Stimulation Strategies
Cochlear	ACE – Advanced Combination Encoder CIS – Continuous Interleaved Sampling MP3000 / PACE – Psychoacoustic ACE SPEAK – Spectral Peak Strategy
MED-EL	HDCIS – High Definition CIS FSP/FS4/FS4P – Fine Structure Processing
Advanced Bionics	CIS – Continuous Interleaved Sampling HiRes/HiRes120 – High-Resolution Strategy MPS – Multiple Pulsatile Sample
Oticon	Crystalis/MPIS – Main Peak Interleaved Sampling
Nurotron	CIS – Continuous Interleaved Sampling APS – Advanced Peak Selections Symphony - Virtual channel strategy

Figure 2: Processing strategies used by manufacturers (Wilson & Dorman, 2008) (Choi & Lee, 2012) (Somek, et al., 2006) (Zeng, et al., 2015)

A clear distinction is made between strategies emphasizing **Coarse Features** of the sound and strategies emphasizing **Fine Features**. Strategies focusing on coarse features aim to provide good speech understanding, while the strategies focusing on fine features are more general approaches trying to improve general hearing quality including music perception. The coarse structure strategies are further divided into **Explicit Feature Extraction strategies (**identifying specific features of the spoken language like relevant formants) and **Implicit Feature Extraction** (focusing on complete transmission of the sound's spectral image). In all cases, the detailed description of selected coding strategies is provided:

- **Feature Extraction Strategies** - speech perception oriented, aiming to provide necessary information for useful speech perception. (Fundamental Frequency - F0; Formants - F1,F2; Envelope)
    - **F0/F1/F2 Strategy** – Transmits F0 as rate coding; F1 and F2 as place coding; Envelope as stimulation intensity.
    - **MPEAK Strategy** – Similar to F0/F1/F2 Strategy with 3 additional channel transmitting envelope of high-frequency channels regardless of the formants of the sound.
- **Variations of N-of-M Strategies -** divides the audio frequency band in M channels, each channel being assigned to an electrode of the cochlear implant. At a given moment, only N of the most powerful components are transmitted.
    - **Advanced Combinational Encoder (ACE)** – Variation of N-of-M Strategies using 22 electrodes with 6 to 10 concurrent stimulation sites
    - **Continuous Interleaved Sampling (CIS)** – Variation of N-of-M Strategies where N=M.
- **Fine Structure Strategies**
    - **Stimulation using virtual channels (HiRes120)** – Using 16 electrodes and current steering technique the number of stimulation areas is increased to 120 virtual channels.
    - **MED-EL's Fine Structure Processing (FS4P)** – A variation of the CIS strategy using 12 electrodes, with rate coding and parallel stimulation at the first 4 electrodes (low frequencies < 1Khz).

Finally, the **Current Challenges of Cochlear Implant Technologies** are presented in Chapter 2.4.

Chapter 3: Simulation Models of the Ear

During the incipient phases of the development of the new auralization method, the existing ear simulation models were studied and applied in preliminary tests of the simulation of the hearing perception. In this chapter, the found mathematical and signal processing models of the healthy ear are presented and discussed (Patterson, 1992) (Yushi Zhang, 2006) (Meddis & Lopez-Poveda, 2010) (Zhang, 2010) (Miller & Matin, 2011) (Schnupp, et al., 2011).

There are three delimited sections of the ear, named according to their position: outer, middle and inner ear. The sound wave travels through each section entering at the outer ear and exiting through the round window of the cochlea in the inner ear, each section having its own function in the hearing process.

From a mathematical point of view, the sections can be viewed as complex transfer functions, characterized by their input signals, output signals, and transfer functions.

Ear Section	Input Signals	Output Signals
Outer Ear Conveys, shapes and amplifies the sound vibrations of the air.	**Primary** Air pressure function **Secondary** -	**Primary** Tympanic membrane Displacement **Secondary** -
Middle Ear Transduces air vibrations into liquid vibrations. Limits the amplitude of the vibrations, protecting the cochlea	**Primary** Tympanic membrane Displacement **Secondary** Stapedius Muscle Tension	**Primary** Oval-window membrane Displacement **Secondary** -
Inner Ear (Cochlea) Spectral decomposition of the liquid vibrations. Translates mechanical vibrations into nerve impulses	**Primary** Oval-window membrane Displacement **Secondary** -	**Primary** Auditory Nerve Impulses **Secondary** Basilar membrane displacement Inner/Outer hair cell polarization Inner hair cell gain factor

Figure 3: Input and output signals of the ear sections.

In Chapters 3.1 (**Outer Ear**) and 3.2 **(Middle Ear)** the sound conduction function of the outer- and middle- ear is presented. Their function in sound channeling, sound localization and sound intensity tempering are discussed and it is concluded that their role in understanding how persons with cochlear implants are hearing is reduced. Therefore, the study is focused on the inner-ear models presented in Chapter 3.2 (**Inner Ear**).

The inner ear (cochlea) is the "transducer" part of the ear. Its main function is to translate mechanical vibration, conveyed by the outer and middle ear, into electric impulses carried by the specialized nerve structures to the brain to be interpreted as meaningful sound perceptions. In terms of signal processing the structures of the cochlea are highly nonlinear.
By analyzing the models present in the literature, a schematic principles model of the cochlea is presented identifying four principal components:

- Basilar Membrane Model – A filter-bank composed of band-pass gamma tone filters modelling the displacement of individual segments of the basilar membrane
- Inner Hair Cell Model – A filter-bank composed of non-linear filters modelling the

polarization of the hair cells at the vicinity of the individual basilar membrane segments

- Outer Hair Cell Model – A filter-bank composed of non-linear filters modelling the mechanical amplification function of the outer hair cells
- Synapse Firing Model – A filter-bank composed of stochastic firing models of the synapses as a response to the cell polarization

Details regarding the implementation of the **Gammatone Filter Bank and the Basilar Membrane model** are presented in Chapter 3.3.1. It is shown that these types of filters can be calibrated to closely resemble the movements of the basilar membrane in most mammals. The mathematical formulation of the impulse response is given and the frequency selectivity is discussed.

It is shown that there are more complex phenomenological nonlinear basilar membrane models available in the literature, but the accuracy of this simple linear model is more than enough for the purpose of the current work.

The **Inner Hair Cells and Auditory Nerve Model** based on the work of (Zhang, et al., 2001) is presented in Chapter 3.3.2. In this case, the polarization of the inner hair cell is modelled using a serialization of a simple nonlinear element and a low pass filter. The obtained cell polarization patterns are well reflecting the polarization patterns measured and published in the literature.

The synapse model presented and chosen to be used reflects the stochastic nature of the firing and models the recovery time of the auditory nerve. The depiction of the inner hair cell and synapse models and the formulas used for implementation are shown in this chapter.

Model for the Outer Hair Cells and their effect on the Basilar Membrane is not discussed as they are not necessary for the validation of the auralization method.

Chapter 4: Simulation of Hearing Perception

The **main research objective** of the thesis is to **develop a novel auralization algorithm capable to synthesize the sounds perceived by cochlear implant users**. The implementation details, simulation results and experiments are detailed in chapter **Error! Reference source not found.**.

Based on clinical experiments, simulation software h been developed before to **synthesize sounds as they are perceived by cochlear implant users (auralization)**, making possible to assess expected hearing quality by technicians and fitting specialists (Mahalakshmi & Reddy, 2012), (Chilian, et al., 2011), (Loebach, 2007).

Although these simulation algorithms are based on observations from real-life experiments, the resulted synthesized sounds seem to underestimate the hearing quality of the patients. This is underlined by the opinion of **cochlear implant users who declare that they perceive the synthesized sounds unpleasant and lower in quality than the usual sounds**, and also by the fact that many implant users perform very well with musical instruments despite the result of the simulations where no music or melody appreciation is predicted (Drennan & Rubinstein, 2008), (Wang, et al., 2011).

In our option, the **discrepancy between predicted and experienced hearing quality is given by the fact that hearing simulations are executed considering strictly sound perception patterns identified in natural hearing, and ignores the capability of the brain to adapt to new stimulation patterns**. This idea is reinforced also by the observation that most electric stimulation experiments were done on adult implant users who lost their hearing at a later stage in their life, already learning to interpret natural stimulation patterns (postlingual deafness). Therefore, the results of the experiments rarely reflect newly learned pattern recognition capability. In experiments with prelingually deafened patients, it is possible only to assess the capability of differentiation between different stimuli (Wang, et al., 2011), but not to compare the hearing sensations to the sound they were perceived before the hearing loss.

Chapter 4.1 (**Base Model of Natural Hearing**) aims to analyze the nerve impulse patterns created by the natural hearing and identify a new method to estimate the perceived sound only using these patterns. In this chapter, a simplified middle ear simulation model is proposed, implemented and executed. The proposed model is built using the already known models: Basilar Membrane models based on gamma-tone filter model; Inner Hair Cell polarization model and Synapse firing model. The simulation model is implemented using Java programming language and an own developed signal processing library.
The simulation results, using 312 channels for Basilar Membrane and Inner Hair Cell modelling and 6240 Synapses, are displayed and discussed in this chapter. It is shown that the polarization and nerve firing patterns are in alignment with the information available in the literature. Moreover, it is shown that it is plausible to identify frequency components within the nerve firing pattern using image analysis opening a way for the development of a novel auralization algorithm.

Based on these findings, the general formulation of a newly proposed auralization method is formulated and depicted schematically. In this approach, the stimulation sound is converted into nerve impulses using: a.) the simplified ear model; b.) A cochlear implant model with an intracochlear current spread model and electric nerve stimulation model. Using supervised machine learning techniques, the auralization system is trained to recognize individual frequency components in the nerve firing pattern, thus providing the spectral image of the perceived sounds, which is then reconverted into sounds using a sound synthesis module.

The simulation results and the proposed auralization methods are published in a **conference paper**:

A.M. Kuczapski, G.-D. Andreescu, „Modelling and simulation of hearing with cochlear implants: A proposed method for better auralization”. *Proc. 6th International Workshop on So Computing Applications (SOFA 2014), Timisoara, Romania, July 2014, vol 2; Advances in Intelligent Systems and Computing*, vol. 357, pp.753-767, Nov. 2016. (WOS:000452854600003).

Already existing auralization methods are presented, discussed and compared with the proposed auralization method in Chapter 4.2, concluding that no other methods were developed to model the brain’s ability to adapt to new stimulation model.

In Chapter 4.3 (**New Auralization Method using Autocorrelation based Pattern Recognition**) the proposed auralization model is further developed and a simple yet robust and effective learning method is presented. It is shown that applying a simple row-wise autocorrelation method over the nerve firing pattern images the patterns are transformed in a more structured form, making it easy to identify the corresponding frequency spectrum of the perceived sounds. It is also shown, that by generating the autocorrelated nerve firing images for a large number of frequency mixes, it is possible to programmatically identify the part of the images which is common and specific to a single frequency.

Based on the above findings an automated training algorithm was developed which is capable of identifying 312 distinct frequency-specific **Auto-correlation Masks.**

At any given moment the **row-wise cross-correlation** coefficients between the **momentary auto-correlation image** of the nerve firings and each **frequency-specific autocorrelation masks** can be calculated. It is observed that these cross-correlation coefficients are proportional to the perceived intensity of the frequency corresponding to the auto-correlation mask. This method is used to implement the **Frequency Detector Components** to continuously estimate the frequency spectrum of the perceived sounds. Because the relation between the cross-correlation coefficients and the frequency component amplitude is not linear the exact relation is determined during the learning phase using generated frequency samples at different amplitudes.

In Chapters 4.3.1 and 4.3.2 the row-wise auto- and cross-correlation formulas are presented and the algorithms for learning the frequency-specific masks, the algorithm to determine the relation between the cross-correlation coefficients and the frequency component amplitudes, and the algorithm to calculate the momentary perceived audio spectral image are described.

Frequency detectors based on nerve firing autocorrelation masks are not only sensitive to the trained frequencies but to the frequency vicinity too. How broad this vicinity is, depends on the cochlear nerve firing pattern model, allowing a quantitative estimation of the frequency discrimination capability of the modelled hearing.

Chapter 4.3.3. studies the frequency detectors selectivity and provides simulation results regarding the natural hearing model. It is shown, that the frequency response characteristics of the frequency detectors in case of the natural hearing model closely resembles the characteristics of the human ear as known from the literature, concluding that **although the learning algorithm of the frequency-specific autocorrelation masks of the cochlear nerve firing patterns is completely agnostic of the spatial and temporal cues, it seems to correctly estimate the pitch perception quality of natural hearing**.

Calculating the same frequency response characteristics of a model trained using nerve impulses generated by two different cochlear implant types, in Chapter 4.3.4 the differences between the ACE coding strategy and the FS4P coding strategy is simulated and discussed.

It is demonstrated that the FS4P strategy is significantly better in transmitting fine structure at low frequencies than the ACE strategy, whoever using ACE strategy the spectral resolution of high frequencies is better.

These findings show that the developed method, besides the auralization, **is a valuable tool to objectively asses the quality of the perceived sounds using different stimulation strategies**.

The method to transpose the spectral image of the perceived sound into audible sounds is described in Chapter 4.3.5 (**Auralization Vocoder**), while software implementation details and system architecture is presented in Chapter 4.3.6 (**Implementation of the New Autocorrelation based Auralization Method**).

The **experimental validation** of the proposed auralization method is presented in Chapter 4.4 (**Experimental Results to Validate the New Auralization Method - Cochlear Implant User Feedbacks**). As there are no validation methods found in in the literature regarding auralization, the following criteria were defined:

An auralization can be considered as an accurate representation of the sounds perceived through the modelled cochlear implant, if and only if:

1. **The generated sound was created only using the electric impulses created by the cochlear implant.**

2. **A cochlear implant user, using the same type of cochlear implant like the one modelled in the auralization process, cannot hear the difference between the original and the synthesized sound.**

Using these validation criteria, two sessions for validation experiments were conducted:

I) In the first session, five patients were identified with MED-EL Tempo+ Cochlear Implants using coding strategies similar to the ACE but with only 12 electrodes. In these experiments, during an informal interview, sample sounds were replayed both *in the original and synthesized form and the participants were asked to identify* which version *is more pleasant to hear*. In most cases, the synthesized sound was perceived by CI users as good or better compared to the original sound.
Based on these experiences a more elaborated method was developed to conduct the second session of experiments.

II) In the second session of experiments, we had 15 patients participating, with age varying between 9 and 18, and with various types of cochlear implants and settings. Individual experiment sessions were conducted with each participant. During one session, between *15 and 25 randomly selected audio samples were replayed* (Auralized or Original) and for each sample the following form was completed:

1. The ID of the audio sample – sentence ID, speaker gender and noise level
2. *Sentence understood* - by the participant
3. *Number of retries* – asked by the participant in case it wasn't sure
4. Final *number of misunderstood words* – filled by the tester
5. *A quality score (1-10)* – how natural is the sound.

Using the collected data, the percentage of correctly understood words was calculated in case of natural and auralized audio materials.

The experiment shows the capability of the auralization method to express the sounds perceived by cochlear implant users, however it also highlights the importance of a good calibration and accurate modelling of the targeted cochlear implant model and configuration.

The simulation results and the developed auralization methods are published in a **conference paper** and a **patent request**:

A.M. Kuczapski, G.-D. Andreescu, „New Autocorrelation based Self-Learning Method to Detect Sound Spectral Components in Cochlear Nerve Firing Patterns in Case of Cochlear Implants", in *Proc. 40th International Conference on Telecommunications and Signal Processing (TSP 2017)*, Barcelona, Spain, July 2017, vol. 1, pp. 429-434. (WOS:000425229000095).

A. M. Kuczapski, „Metodă pentru auralizarea sunetelor percepute prin intermediul implantelor cohleare"/" Method for auralizing sounds perceived by cochlear implants, involves transmitting radio signal to cochlear implant processor and recording electric stimulation impulses generated by cochlear implant processor", *OSIM Romania*, Patent No. RO131096-A0, May 2016

Chapter 5: Applications (Contributions) for MED-EL Cochlear Implant Users

The **secondary objective of the thesis** is to **explore the possibilities to help cochlear implant patients by providing various tools to aid the fitting process and troubleshooting of defects** using ideas and methods developed as a spin-off during the research efforts invested in the main objective of the thesis. These findings and results are presented in chronological sequence in Chapter 5.

As, during the experiments and research activities I have been mostly interacting with users of Med-El Cochlear Implants, the following contributions are directed toward this implant system.

In Chapter 5.1 (**The Maestro Cochlear Implant System**) a description of MED-EL's Cochlear Implant system is given with details regarding the fitting parameters and general functioning. The most important fitting parameters are:

- **THR (Threshold) Levels** – the base level of the electric stimulation current (at silence) of each electrode
- **MCL (Most Comfortable Level)** – the maximum stimulation level of each electrode
- **Maplaw** – The curve mapping the audio levels to stimulation levels.
- **AGC (Automatic Gain Control) settings –** parameters for setting the reaction speed of the automatic gain control system

Based on the data collected in the Maestro Fitting software of more than 150 pediatric patients, recorded over 10 years of fitting practice (Stanciu & Hellmuth-Zweyer, 2015), typical stimulation levels were calculated and described in Chapter 5.2 (**Statistics of Typical Stimulation Levels**). These stimulation levels were correlated with the restored hearing thresholds of the patients and it was highlighted that in our interpretation patients with high stimulation levels have lower chances to attain low hearing thresholds than those with low or very low stimulation levels.

In Chapter 5.3 (**Computer Assisted Fitting of Cochlear Implants – Tracking the Effective Stimulation Threshold**) the current fitting procedures are reviewed and a new helper method is developed. It is shown that using free field audiograms as base for fittings can improve hearing restoration quality, and a new derived fitting parameter is introduced: Effective Stimulation Threshold (EST). This parameter is calculated for each electrode, based on the THR, MCL, Maplaw and hearing thresholds measured in free field audiometry, and it estimates the electric stimulation level that causes conscious hearing sensations for the patient under regular listening scenarios.

The formula to calculate EST is presented, and in addition the mathematical formula of the maplaw curve is identified.

It is shown that EST levels are good indicators of the sensibility and health of the stimulated auditory nerves, and in case of a slow ramp-up fitting approach the evolution of the EST levels are following a typical curve. If the EST levels are not following the expected curves, it may indicate cochlear implant defect, overstimulation of the auditory nerve or even degradation of the auditory nerves.

As an outcome of these contributions, a computer software is developed and presented, designed to help fitting specialists to automatically follow the EST curves and to identify new fitting parameters.

Typical and pathological evolutions of the EST curves are exemplified in Chapter 5.4 (**Case Studies of Fitting Evolution**) using fitting data of four patients collected over several years.

The contributions of Chapters 5.1 – 5.4 are published in a **conference paper** and also presented as e-poster at a **symposium**:

A.M. Kuczapski, A. Stanciu, „Assistive tool for cochlear implant fitting: Estimation and monitoring of the effective stimulation thresholds", *Proc. IEEE 10th Jubilee Int. Symp. on Applied Computational Intelligence and Informatics (SACI 2015)*, May 2015, vol. 1, pp. 307-311. (WOS:000380397800056)

A.M. Kuczapski, A. Stanciu, „Computer Aided fitting, estimation and long term monitoring of effective stimulation thresholds for children with cochlear implants". Extended Abstract / E-Poster at the *12th European Symp. on Pediatric Cochlear Implantation*, Toulouse, Jun. 2015. (Extended abstract / E-Poster)

The next contribution **Interfacing with Med-El Cochlear Implant Processors** is presented in Chapter 5.5**.** It was developed out of the necessity to collect real electric impulses and used them as input for the developed auralization method. A real-time data acquisition system is developed to be connected to a cochlear implant processor in order to record and display the generated stimulation impulses on a computer display. The sampling rates are 83KSPS/channel for 12 analog channels and 1MSPS in a single-channel configuration. The proposed system is developed for MED-EL Opus 1, Opus 2 and Sonnet cochlear implant processors with the following main parts: i) I100 Detector Box that transduces the information received from the CI processor antenna into electric pulses, similar to an implanted receiver/stimulator; ii) 12 channel real-time analog data acquisition module developed using Arduino Due and a custom developed voltage adaptor circuit (shield); iii) PC connected through USB to the data acquisition module running a Java software developed for monitoring, real-time visualization and auralization. A software tool is presented that displays in real-time the stimulation levels and sound levels and also the fitting parameters for each cochlear implant channel. Such visualization can be used by cochlear implant specialists to optimize the fitting procedures, for demonstrations, and for fault detections of: microphone, automatic gain control, and fitting procedure. A simple real-time auralization system is implemented. It approximates and replays the perceived sound by using the registered pulses.

The developed system is presented in a **conference paper:**

A.M. Kuczapski, G.-D. Andreescu, „Real-time interfacing for fault detection and auralization with MED-EL cochlear implant processors", *Proc. IEEE 11th Int. Symp. on Applied Computational Intelligence and Informatics (SACI 2016)*, Timisoara, Romania, May 2016, vol. 1, pp. 191-195. (WOS:000387119900034).

The final secondary contribution presented in this thesis is described in Chapter 5.6 (**Intra-Cochlear Current Flow Model**). In preparing for future work, to better estimate current spreads inside the cochlea, a **3D current spread simulation model was developed**. High-resolution cochlea models are not publicly available therefore, we a computer program was developed to generate an approximated **voxel model of the cochlea**. In such a model, the three-dimensional space is divided in a finite number of cubes of identical sizes called voxels (i.e. volumetric-pixel). Each cube represents a homogeneous space with various characteristics like color, material type, etc. Afterwards, using the generated voxel model of the cochlea, **we have developed and implemented and algorithm and a software application to numerically approximate the current flows and potentials within each voxel**.

The formulas describing the relation between the potentials and current flows between adjacent voxels are described, and an iterative solving algorithm is presented. The 3D cochlea model is generated using simple geometric shapes with dimensions and tissue resistivity collected from the literature. The simulation model is executed for individual electrode stimulation resulting in current densities and potentials in all voxels as there are induced by the currents injected. These results can be used to calculate the current densities and potentials for any combination electrode stimulation currents applying the superposition theorem.

Chapter 6: Conclusions

In the final chapter of the thesis (Chapter 6 – Conclusions) it is concluded that the research objectives of the thesis were satisfied and the contributions are presented:

Introductions and presentation of the State-of-the-Art:

- Introduction to the ear anatomy and causes of neuro-sensory deafness (Chapter **Error! Reference source not found.**):
- Overview of the existing cochlear implant systems (Chapter **Error! Reference source not found.**-0):
- Introduction of the existing ear mathematical models (Chapter **Error! Reference source not found.**):
- Overview of the Maestro cochlear implant system (Chapter 0):
- Review of existing auralization methods (Chapter **Error! Reference source not found.**):

Original Methods, Models and Results (Main Research Objective):

- New auralization method using autocorrelation-based pattern recognition (Chapter 0):
- Frequency responses of the frequency detectors using stimulation through cochlear implants (Chapter **Error! Reference source not found.**)
- Validation criterion of the auralization model - Cochlear implant user feedbacks (Chapter 0)

Original Methods, Models and Results (Secondary Research Objective):

- Statistics of typical stimulation levels (Chapter 0):
- Computer-assisted fitting of cochlear implants – Tracking the effective stimulation threshold (Chapter 0)
- Case studies of fitting evolution (Chapter 0):
- Interfacing with Med-El cochlear implant processors (Chapter 0):
- Intra-cochlear current flow model (Chapter 0):

Contributions - Developed Software Modules:

All methods, algorithms and experiments were implemented and executed using Java 1.8 programming language. The main *developed Java libraries* during the research project are the following:

- Generic signal processing framework in Java
- Adaptation of Zhang auditory model implementations from C++ to Java

- Simplified ear model
- Image processing library
- Library for electric and current density field modelling in non-capacitive medium
- Cochlear model generation method

The contributions of the current thesis are disseminated in the following publications and conferences:

A.M. Kuczapski, G.-D. Andreescu, „Modelling and simulation of hearing with cochlear implants: A proposed method for better auralization". *Proc. 6th International Workshop on So Computing Applications (SOFA 2014), Timisoara, Romania, July 2014, vol 2; Advances in Intelligent Systems and Computing*, vol. 357, pp.753-767, Nov. 2016. (WOS:000452854600003).

A.M. Kuczapski, G.-D. Andreescu, „New Autocorrelation based Self-Learning Method to Detect Sound Spectral Components in Cochlear Nerve Firing Patterns in Case of Cochlear Implants", in *Proc. 40th International Conference on Telecommunications and Signal Processing (TSP 2017),* Barcelona, Spain, July 2017, vol. 1, pp. 429-434. (WOS:000425229000095).

A.M. Kuczapski, A. Stanciu, „Assistive tool for cochlear implant fitting: Estimation and monitoring of the effective stimulation thresholds", *Proc. IEEE 10th Jubilee Int. Symp. on Applied Computational Intelligence and Informatics (SACI 2015)*, May 2015, vol. 1, pp. 307-311. (WOS:000380397800056)

A.M. Kuczapski, G.-D. Andreescu, „Real-time interfacing for fault detection and auralization with MED-EL cochlear implant processors", *Proc. IEEE 11th Int. Symp. on Applied Computational Intelligence and Informatics (SACI 2016)*, Timisoara, Romania, May 2016, vol. 1, pp. 191-195. (WOS:000387119900034).

A. M. Kuczapski, „Metodă pentru auralizarea sunetelor percepute prin intermediul implantelor cohleare" / "Method for auralizing sounds perceived by cochlear implants, involves transmitting radio signal to cochlear implant processor and recording electric stimulation impulses generated by cochlear implant processor", *OSIM Romania*, Patent No. RO131096-A0, May 2016

A.M. Kuczapski, A. Stanciu, „Computer Aided fitting, estimation and long-term monitoring of effective stimulation thresholds for children with cochlear implants". Extended Abstract / E-Poster at the *12th European Symp. on Pediatric Cochlear Implantation*, Toulouse, Jun. 2015. (Extended abstract / E-Poster)

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