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REMOTE HEARING AID FITTING

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by

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A dissertation submitted to the Department of Electrical Engineering  
in fulfilment of the requirements for the degree of

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at the

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Supervisor

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## **Declaration**

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## ABSTRACT

Hearing aid fitting is a costly process due to the cost of hearing aids, audiologists' hourly rates, and large travelling distances caused by regionally sparse audiologist populations. This dissertation is focused on the development of a system which aims at reducing the severity of this problem. The proposed system features a field technician who will travel to regions with no access to an audiologist, and allow an audiologist to provide a remote hearing aid fitting service, by making use of the developed system. This will ultimately provide the patient with a low cost hearing aid. The design of the system is discussed and tests are conducted and documented with the aim of assessing the usability and requirements of the system. The results of these tests provide the system requirements of the field computer and discover that users find the system to be usable but unintuitive. Results also showed that the remote element does not affect puretone audiometry results significantly but increases the duration of hearing aid fitting by an average of 27 %. Overall, the testing has shown that significant improvements, such as improving the system's ease of use, can be made to the system, but in its current state it can perform its intended function and therefore proves the technical feasibility of remote hearing aid fitting.

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Dedicated to the memory of my grandfather

Sydney Charles Moore

who passed away during the course of this Masters project

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# INTRODUCTION

The human body is a complex combination of many systems which work together to allow it to not only survive but also thrive in its environment. It perceives the external environment through five sensory organs situated in the body. One of these organs is the ear and it is responsible for receiving sound [93, p1]. The ear is one of the body's natural transducers. It converts sound pressure waves into electrical signals which are then transmitted to the brain for interpretation. It can register a large range of frequencies and very low volumes while still making use of a wide dynamic range [86, p16-18]. Despite this, there are a multitude of causes for hearing loss ranging from noise induced aspects to age related causes [86, p312-388].

Depending on the damage suffered, it may occur that the subject's hearing ability is diminished but not destroyed [93, p195]. The causes of diminished hearing are varied but the result is that faulty signals are received by the auditory cortex [59]. Hearing aids are designed to correct for this diminished hearing ability. A perfectly customised hearing aid attempts to completely counter a specific patient's hearing loss such that the patient's sound perception is regarded as fully functional in everyday life. Thus, the sound intensity received by the brain must ideally be identical, whether transduced by a healthy ear without assistance or a diminished ear with amplification.

## 1.1 PROBLEM IDENTIFICATION

Hearing aid fitting is a highly specialised process due to the sheer complexity of the ear. This process requires specialist knowledge and equipment, creating the root problem:

*The high costs associated with hearing aids and the fitting thereof.*

Governments and other organisations, such as the South African government [73], may choose to subsidise patients in the publicly funded health care system who meet certain criteria, but this is not addressing the root of the problem. The high costs can be attributed to four distinctly separate causes:

- **Hearing aid cost:** For cosmetic purposes the hearing aid as a whole must be as small as possible and therefore each component has to be as small as possible. The battery has to be small but it must still power the entire device for extended periods. All components therefore need to consume as little power as possible. This miniaturisation and reduced power usage come at great cost when sophisticated amplification and signal processing techniques are used [62].
- **Equipment cost:** The hardware used to program hearing aids is specialised medical equipment and command high prices.
- **Audiologist reliance:** All hearing aids must be fitted by a qualified audiologist for the patient to receive maximum benefit from a hearing aid [31, p707-708]. Salary.com [64] shows audiologists, based on various factors such as qualifications, location, etc., are highly qualified personnel who are able to charge for their time accordingly.
- **Large travelling distances:** According to the South African Association of Audiologists, the majority of registered audiologists in South Africa are in densely populated areas such as Gauteng and Cape Town [73]. People who do not have easy access to transport will find it difficult to get to these audiologists. The poorer and more rural regions of the country have a sparser audiologist population and so patients must travel even further and wider in order to receive help.

These costs must, generally speaking, all be shouldered by the consumer. It is for this reason that hearing aids and their fitting are considered unnecessarily expensive.

## 1.2 SOLUTION OVERVIEW

The solution attempts to address each of the four major causes by suggesting counter measures:

- **Hearing aid cost:** The hearing aids themselves can be constructed with low cost components while still producing a good quality hearing aid.
- **Equipment cost:** Certain hearing aids can be programmed with low cost hearing aid programmers and care must be taken to ensure that the hearing aids constructed are compatible with one of these low cost hearing aid programmers.
- **Audiologist reliance:** There is no reason for the audiologist to be involved in the entire fitting process. It is their skill and training that is required to operate advanced software and make judgement calls. A large part of the hearing aid fitting process is routine. If less qualified personnel were to carry out the routine parts of the fitting process then the time each patient requires with the audiologist would be reduced. This allows an audiologist to assist from a remote location.
- **Large travelling distances:** If the less qualified personnel mentioned above could provide the means for the audiologist to interact with a patient remotely, the audiologist could conduct hearing aid fitting sessions in more locations without having to spend time travelling. Patients would then be required to travel shorter distances as the audiologist could extend their field of influence.

Using these four counter measures, it is postulated that digital hearing aids and their fitting can have their costs significantly reduced.

## 1.3 RESEARCH AIMS AND OBJECTIVES

The focus of this research project is on making hearing aids a financially viable solution to hearing loss for a greater percentage of the population.

The problem solution raises three major questions. The research will attempt to answer these fundamental questions:

1. Can a hearing aid fitting session be conducted remotely?
2. Will the system significantly reduce costs?
3. Can patients and audiologists accept this method as preferential to traditional fitting methods when cost and accessibility are considered major factors?

The final output of this research project is:

*A commercially viable remote hearing aid fitting system.*

#### **1.4 RESEARCH RATIONALE AND MOTIVATION**

Hearing loss can cause people to experience a number of hardships ranging from social effects such as isolation to psychological effects where the person feels inadequate [29, p11-23]. It is in society's best interest to correct this imbalance. The population who are living with hearing loss would have the potential to become more active in the economy of South Africa, thus raising their own standard of living.

However, with the costs currently associated with hearing aids and their fitting, hearing aids remain a luxury few can afford. This research attempts to reduce the cost of fitting a hearing aid by altering how a fitting is conducted.

#### **1.5 SCOPE AND LIMITATION**

The impact this system will have on the hearing aid market will be most significant in the low-end market of digital hearing aids especially in rural communities with limited health care and travel options. The impact on high end hearing aids is presumed to be very limited as patients who can afford private health care would choose the more personal service offered by a one on one fitting session with an audiologist.

The system does not aim to provide a complete audiology service allowing the audiologist to perform otoscopy, physical ear inspection, etc. The system scope only includes hearing loss analysis and hearing aid customisation.

## 1.6 DISSERTATION STRUCTURE

This dissertation was intended for use by engineers in the field of tele-audiology and tele-audiologists who wish to investigate remote hearing aid fitting, and an example of a system which provides a viable approach to remote hearing aid fitting.

The dissertation consists of six chapters each representing a significant stage in the research project:

- Chapter 1 introduces the study by discussing the problems and how they can be addressed. The objectives are listed and limitations are placed on the scope of the project.
- Chapter 2 begins the literature review by providing a brief overview of hearing aids with the focus on how they relate to the concept of hearing aid fitting. Conventional hearing aid fitting is then covered to provide background research to contrast and analyse the proposed fitting system with respect to the conventional fitting process. A brief study of network performance criteria and network traffic is included to provide sufficient background knowledge for network testing of the envisaged system. Finally, this chapter also discusses the design and purpose of five existing remote audiology systems. Brief evaluations of their designs and their testing highlight the shortcomings and advantages of each system.
- Chapter 3 presents the design of a new remote hearing aid fitting system and the reasoning behind it. It outlines how the hardware, software, and users interact with each other. A top down approach is used to gradually increase the design detail until such a point as the design is reproducible. This chapter also addresses the issue of the various services and accounts which are required for the functioning of the system and the set up, installation, and use of the system. Finally, a cost analysis shows what expenses are associated with the use of the system and how it compares to traditional hearing aid fitting.
- Chapter 4 discusses the specifics of four test suites such as test subjects used, the scenarios tested and the procedures used. These four test suites namely, resource

testing, user acceptance testing, unit testing, and comparative testing, are designed to quantitatively assess the viability and usability of the system.

- Chapter 5 communicates the results of the test suites discussed in Chapter 4. These results are then analysed and conclusions are drawn from these interpretations.
- Chapter 6 consists of three distinctly separate sections. The first section provides a summary of the text and notes major conclusions which were drawn from the design of the system and the interpretation of the results. The second section lists the avenues which potentially offer the chance for further development of this system. Finally, the closing findings addresses the issues of research aims and objectives and whether they have been achieved or not.
- Appendix A lists all additional documents which supplement this dissertation and the purpose of each of these documents. It also includes the timeline of the project showing all major sections, their durations, and start dates.
- Appendices B, C, and D contain supporting material such as the system Readme and network analysis summaries. These are included to supplement various sections throughout the dissertation.

## 1.7 SUMMARY

Hearing loss is a major problem for those living with this impairment. For those without the financial means, it is unlikely they will ever be able to correct their hearing loss. This research project will investigate the possibility of reducing the costs involved in hearing aid fitting. The proposed solution of creating a remote hearing aid fitting system is suggested and will be designed and tested. The testing of the system will provide answers as to whether the system is viable and if it does ultimately reduce hearing aid fitting costs.

## BACKGROUND LITERATURE SURVEY

To understand the idea of “remote hearing aid fitting” four core concepts on which this project is based, must be appreciated. This literature survey provides the relevant background knowledge to create a basis from which a remote hearing aid fitting system can be created.

Four topics are discussed in this chapter. Firstly, the composition of a general hearing aid and what is programmed or customised during a hearing aid fitting will be discussed. Secondly, conventional hearing aid will be discussed to discover why it has been so widely accepted and which elements make it successful. Thirdly, non-ideal network characteristics which affect data transfer across networks will be covered to provide the background knowledge for transmitting data across a network reliably. Finally, several existing remote audiology systems will be analysed. Their strengths and weaknesses will be discussed and conclusions will be formulated based on which concepts worked.

### 2.1 HEARING AIDS

A brief discussion of a general hearing aid is included as part of this background research to discover how a hearing aid works and how the concept of programming or customising a hearing aid fits in the overall scheme. The constraints that hearing aids operate within are also identified.

The Oxford Dictionary defines a hearing aid as “a small amplifying device which fits on the ear, worn by a partially deaf person” [52]. It is one means by which a person’s hearing

can be artificially improved without intrusive surgery. The device accepts sound from the external environment, modifies the waveform, and outputs it in the subject's ear.

### 2.1.1 Components

A general hearing aid has several basic components which work together and interact with the environment to provide a hearing aid's functionality [12, p17-83] [32, p8]. Each one of these components are reviewed in this section.

#### *Environment*

While not part of a hearing aid, the environment is none the less included at this point for completeness. The environment provides both the signal of interest and the background noise. The signal of interest is defined here as the stimulus that cannot be perceived, to a satisfactory degree, by their unaided ear as determined by the hearing aid wearer.

#### *Microphone*

A general purpose microphone outputs a current or voltage which is proportional to the rate of displacement of the cone. Effectively it converts sound into an electrical signal [12, p23-27] [74, p567-568]. Within the context of hearing aids, the purpose of the microphone is to pick up sounds which the ear itself would normally sense, to a satisfactory degree, and output the electrical signal.

In hearing aids, the choice of microphone is not a trivial decision as there are many different types [3]. Each type has been optimised for a specific environment. Microphone types can be classified according to their spatial sound sensitivity [65, p249-251]. This sensitivity (on the level plane) is often visualised using virtual polar patterns. Some common virtual polar patterns are shown in Figure 2.1. The resulting situation is one where no microphone type is superior in all situations.

The simplest choice is a single, omnidirectional, always-on microphone. It is low cost, simple, and occupies a small amount of space. This microphone has equal receptivity in all directions as seen in Figure 2.1(a). Omnidirectional microphones are used when the source direction is unknown or comes from multiple directions such as environmental

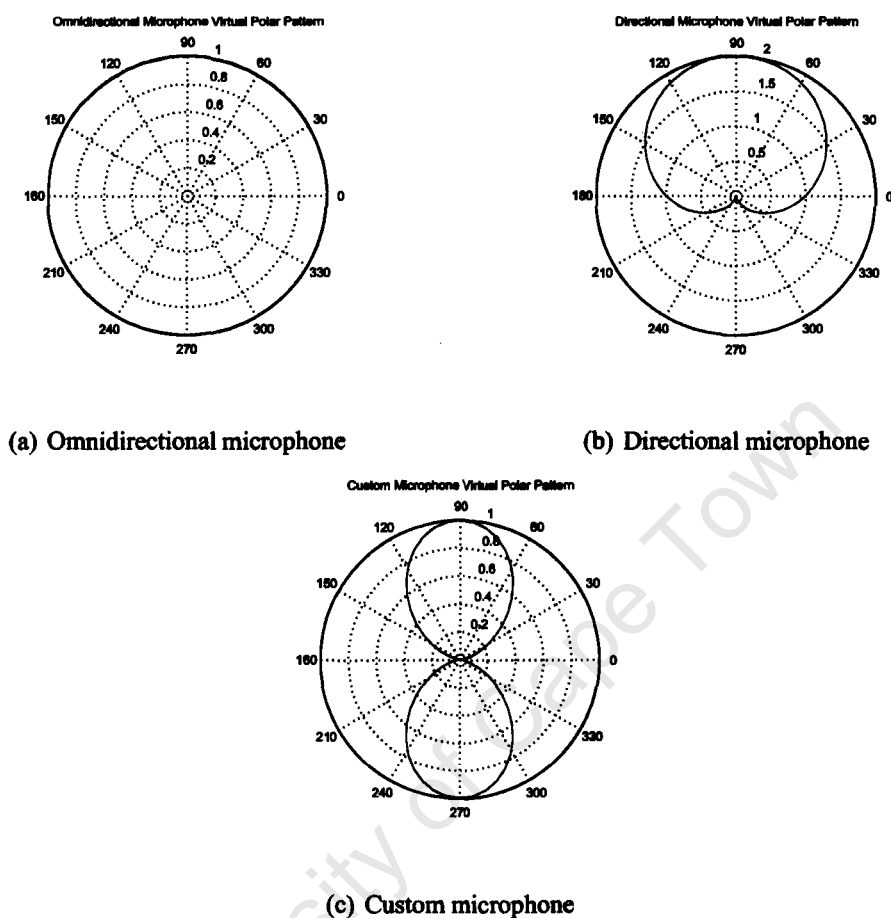


Figure 2.1: Example microphone polar patterns  
(Created with MathWorks Matlab 7.11.0)

sounds or meetings. However, when trying to focus on a particular sound source, such as a person speaking, the surrounding environmental noise serves to interfere with the source of interest.

Directional microphones attempt to correct for this pitfall in omnidirectional microphones. Directional microphones are designed with the focus on a particular direction as seen in Figure 2.1(b). The hearing aid wearer can orientate the microphone towards the source, focusing it on the area in which the sound source is located. The disadvantage of this is that the approximate direction of the source must be known in order to be detected sufficiently.

These two microphones can be used to complement each other. However, this in itself adds circuit complexity and increases the cost of the microphone component. Additionally, either the patient is required to manually select between these two microphones or the hearing aid's artificial intelligence must be able to choose which microphone is required based on the sounds received.

A fourth solution is to design a custom virtual polar pattern such as in Figure 2.1(c). This is implemented by creating an array of microphones in parallel with each other and allowing the signal processing stage to combine the signals. While this has the potential to provide the best sound quality it comes at the cost of increased power consumption, physical size, cost, and required artificial intelligence levels.

### ***Sound Enhancement Component***

The means by which sound is enhanced in hearing aids is very much dependant on the type of hearing aid. Three major types exist: analogue, digitally programmed analogue, and digital. Despite their vast differences, they still have the common goal of enhancing the sound in such a way as to be more useful to the patient than the original sound would have been. From the point of view of hearing aid, this is the most important component as it is this component which is customised and programmed to suit an individual patient's needs and environment.

In analogue devices, sound is firstly filtered into separate frequency bands. The sound from each frequency band is then individually amplified and superimposed upon one another. This stream is then sent out to the receiver. Digitally programmed analogue hearing aids are no different from analogue hearing aids except by the way in which the settings are customised.

Digital hearing aids make use of the Digital Signal Processor (DSP) at the heart of the amplifier to enhance the sound [12, p33-39][74, p568-570]. The DSP is a specialised microprocessor which can execute specialised operations on signals extremely fast and accurately. A sample and hold circuit or analogue to digital converter is used for digitising the input signal. The DSP then executes a Fourier Transform to separate the signal into a set of frequency bands. Amplification of each frequency band will then take place

and, depending on the DSP's features and how the DSP has been programmed, additional enhancements (feedback cancellation, limit compression, etc.) will be used to alter the signal. Finally, the DSP executes an Inverse Fourier Transform and outputs the sound wave and sends it to the receiver.

### *Receiver*

The purpose of the receiver is to convert analogue electrical signals into pressure waves resulting in sound [12, p39-41]. Receivers are so named by analogy with a telephone handset [34][p1]. In other areas of electronics, receivers are referred to as speakers. Generally receivers are enclosed in the hearing aid casing with a tube running from the receiver to the ear mould. High end hearing aids may locate the receiver in the ear mould itself, resulting in a shorter acoustical pathway for the sound to travel and thus less distortion.

### *External Shell*

The shell of a hearing aid is multi-functional: Firstly, it must protect the internals, such as the DSP, from environmental damage such as physical shocks and contact with water. Secondly, it must either camouflage itself against the patient's skin or create a visually attractive exterior. Finally, the shell must hold all the components together in one package yet still allow an auditory pathway for the receiver and microphone.

### *Power Source*

Electrical systems all require a power source of some type whether it be on demand (generators) or stored (batteries). Currently, the most popular choice among hearing aid manufacturers, based on cost and energy density, are zinc air button batteries [12, p46-47]. The lifespan of these batteries is about a week, depending on the hearing aid being powered and the extent to which it is used.

A modern possibility is for the battery to be rechargeable. This would effectively reduce the running costs of the hearing aid as far fewer batteries would be required. However, the disadvantage is that the hearing aid would require charging at regular intervals. A means to increase the usage interval between charges would be for the hearing aid to be recharged

during use. Use of external shell material which is partly comprised of miniature solar panels currently represents the best method of realising this possibility. This would allow the power source to be charged while in use when sufficient light is available.

### *Ear Mould*

Feedback is a major problem with hearing aids. This is due to the close proximity of the microphone to the receiver (see “Physical Size and Shape” in Section 2.1.2). Feedback is reduced by blocking the acoustic pathway between the microphone and receiver. With behind-the-ear (BTE) hearing aid models, an ear mould can block the gap which allows sound waves to reflect out the ear and eventually reach the microphone. However, the ear mould cannot completely block the ear from the external environment as the ear still needs to respire. Complete blockage of the ear creates the unwanted “occlusion effect”. Custom hearing aids (e.g.: in-the-ear (ITE) hearing aids) do not need ear moulds.

The ear mould stops this feedback from occurring and helps keep the hearing aid receiver directed into the ear while still allowing the ear to respire [12, p117-157] [65, p161-164]. Ear moulds come in a variety of types with a range of options including vents, tubing, material composition, colour and size [46]. Additionally, a relatively new option receiving wide acceptance is to have an open-fit hearing aid which requires no ear mould [37].

### *Ear*

As with the environment, the patient’s ear is not actually part of a hearing aid but it is included at this point for completeness. The final output of the hearing aid, directed through the receiver, is sound. This sound is directed at the ear and provides the patient with an audible sound based on the surrounding environment, which has been altered predominantly by the DSP as determined by its settings.

### *Component Overview*

All the previously discussed components work together to form a single hearing aid which is meant to artificially improve a person’s hearing. Figure 2.2 is a diagrammatic representation of the entire system and shows each major component and their interactions.

Other components are often part of hearing aids such as push buttons, tele-coils, remote controls, etc., but these simply enhance the capabilities of a hearing aid and are not part of the essential make up of a general hearing aid.

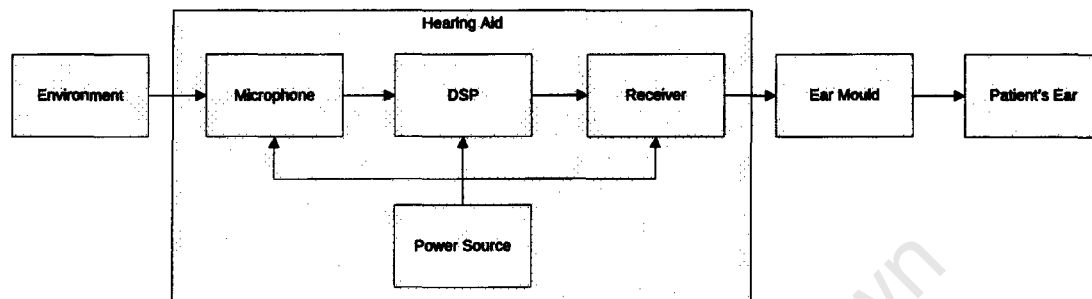


Figure 2.2: Hearing aid overview  
(Created with Microsoft Office Visio 2007)

### 2.1.2 Constraints

Due to the nature of hearing aids and where they operate, they have several constraints which they must operate within. The following list discusses these restrictions:

- **Power Consumption:** The power for the entire hearing aid is derived from a small, on-board battery. Batteries have limited energy stored within so the less energy the hearing aid uses the longer it will last before the battery has to be replaced or recharged.
- **Physical Size and Shape:** For cosmetic reasons hearing aids are required to be as small as possible but also have shape restrictions as they need to be moulded to fit around or in the location the hearing aid was designed for (behind the ear, in the canal, etc.).
- **Cost:** The target market of any product must always be considered. If a particular hearing aid is aimed at the less affluent end of the market then it would not be feasible to use the most sophisticated components as this will inflate the price beyond that which the target market is prepared to pay.
- **Performance:** The final constraint is how well the hearing aid can carry out its function. Finding the optimal performance of the hearing aid as a whole is a trade

off with the other three constraints. This optimal performance level is defined by the individual performance of the chosen components and their performance as a whole.

The hearing aids which the envisaged system is meant to program must successfully work within these constraints. If the hearing aids are unable to do this, the level of customer satisfaction is likely to be very low.

### **2.1.3 Conclusion**

Hearing aids are comprised of many components which work together to produce a signal to allow the hearing aid wearer to perceive sounds from the surrounding environment better than they could without the hearing aid. All the essential components of a general hearing aid have been briefly discussed and the concept of customising the hearing aid has been included. General constraints which all hearing aids are subject to are also identified to show the upper limits of certain resources. This section was included as part of the background research to complete the overall picture of fitting a hearing aid.

## **2.2 CONVENTIONAL HEARING AID FITTING**

In this text conventional hearing aid fitting is defined as the process by which hearing aids are fitted according to a patient's needs by an audiologist in physical contact with the patient. This process is the traditional means of fitting a hearing aid and all audiologists and people with hearing aids should be familiar with this process. Conventional, or local fitting, is discussed at this point to contrast and analyse the proposed fitting system with respect to a local fitting process.

The primary measure of success in hearing aid is how well the patient responds to using the prescribed hearing aid. A successfully fitted hearing aid ensures that favoured environmental sounds are amplified to a level which is audible without being excessively loud. The amplification of these favoured sounds must serve to maximise speech recognition while reducing background noise [79].

There are three distinct phases in conventional hearing aid fitting: Hearing loss diagnosis,

hearing aid customisation, and follow up. It should be noted that hearing aid fitting is by no means a set procedure: The patient is encouraged to constantly provide feedback which may introduce many iterations and feedback loops.

### **2.2.1 Hearing Loss Diagnosis**

Due to the wide variety of hearing loss types and complex equipment requirements the diagnosis of hearing loss is a complicated procedure (see Section 1.1). The principle of hearing loss treatment is to ascertain what has caused the hearing loss and how it can best be fixed or compensated for. Audiologists use a series of tests and observations to diagnose the patient's hearing loss.

Hearing loss diagnosis consists of two distinct examinations [31, p16-17]: The Neuro-otological examination is normally carried out by a general practitioner (GP) or some other medical practitioner. It consists of a patient history review and a physical inspection of the ear and the surrounding nerves and extremities. Should the GP feel the patient may need further treatment they will refer them to an audiologist for the second part of the examination. This second part, called the audiological examination, is the part which this research is concerned with. This second examination consists of puretone and/or speech audiometry and, if necessary, additional treatment and testing. Puretone and speech audiometry both have the common goal of trying to model, as accurately as possible, a patient's hearing loss. However, the methods employed are different as they have two different areas of focus.

Speech audiometry is the process of establishing how the hearing loss affects the patient's daily living and disruption of complex signals [58, p289-290] [74, p274-275]. Speech audiometry attempts to improve on puretone audiometry by focusing on speech patterns rather than pure sinusoidal waves and thus base the results on typical sounds which would be heard in everyday use [18, p239-240]. The downfall of this approach is that this audiometry does not produce results from which a hearing aid can be directly programmed.

Pure tone audiometry presents pure tones (sinusoidal waves) at different volumes and frequencies and uses the patient responses from these tones to build a model of the hearing loss [23, p79-81][39, p1-3] [74, p242-252]. Since a patient may sometimes hear a partic-

ular tone and other times they may not, a three dimensional matrix can be constructed to take this error factor into account (see Figure 2.3). If the patient consistently responds to a particular frequency-intensity combination then the probability of that tone being received by the patient in everyday conditions is acceptable. However, it has been found that the change between the tone being heard and not being heard is very abrupt and does in fact approximate to a step function. Hence this three dimensional matrix can be simplified to produce a two dimensional graph. This graph plots frequency vs sound intensity and is referred to as an audiogram. The plot shows the lower limit of a patient's hearing.

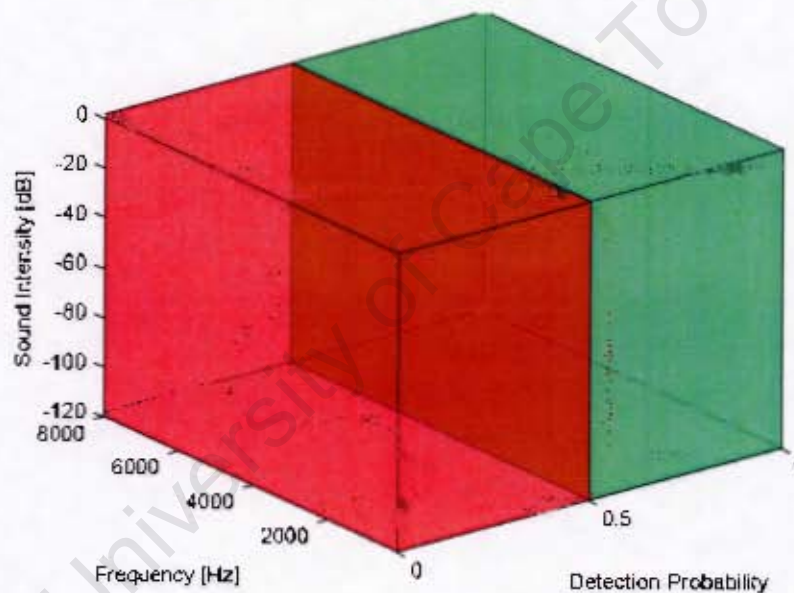


Figure 2.3: Detection probability  
(Created with MathWorks Matlab 7.11.0)

The disadvantage of puretone audiometry is that it focuses on a series of particular frequencies rather than a series of complex sounds such as those which are encountered in the environment and, most importantly, speech. However, its advantage is that it produces a quantifiable response which a hearing aid can be customised from directly. It is for this reason that puretone audiometry has been chosen for use in this research.

### Audiogram Construction

Both speech and puretone audiometry try to model a patient's hearing loss by ascertaining which tones are received by their auditory cortex at an acceptable level. Since no non-invasive method can access the auditory cortex, these processes must rely on the patient providing the audiologist with manual feedback when the tone has been perceived [23, p82]. Generally this is done by the patient sending a signal to the audiometer or audiometry equipment currently in use. When a response is received within an amount of time deemed suitable for a reaction, it is assumed that the patient has heard the tone. When it has been ascertained which sound intensity is the lowest that can be heard consistently, the data is recorded. This is done for each frequency band. The cycle is completed for air conduction and, if necessary, for bone conduction testing as well. Each ear is tested separately. The completion of this process produces a complete audiogram such as the example shown in Figure 2.4 (parameters will vary for each patient [23, p86]).



Figure 2.4: Typical audiogram

showing bone conduction results (arrows) and air conduction results (circles on right and crosses on left)(Created with Sound Design Technologies Soundfit 5.8.3.0)

### 2.2.2 Hearing Aid Selection

With the selection of a hearing aid the second phase begins: That of hearing aid customisation. Selection of a particular hearing aid is not only dependant on the patient's

requirements (hearing aid amplification levels, extra features, etc.) but also the audiologist's facilities. The style of the hearing aid (e.g.: BTE, ITE) is also chosen at this point.

As discussed in Section 2.1.2, the design of a hearing aid is a matter of trading off various constraints against one another. Therefore, some hearing aid models will have focused more on reducing physical size with a long lasting battery while others may focus on cost effectiveness. With this in mind it is evident that some models will be more suited to patients with a particular hearing loss type or severity while they are of little use to a patient with a completely different hearing loss pattern.

Each digital hearing aid model requires its own set of drivers to allow the computer to communicate with the hearing aid [80, p25]. Some of these drivers require software which is only available at a large cost to the audiologist. It follows that it is unlikely audiologists and patients in poor or rural areas will be able to afford expensive software and thus cannot fit some hearing aids aimed at the upper end of the market.

### **2.2.3 Ear Mould Creation**

As discussed in Section 2.1.1, ear moulds come in a variety of types with a range of options including vents, tubing, material composition, colour and size [46]. However, with the relatively new option of open-fit hearing aids, an ear mould is not necessarily required [37]. If an ear mould is desired, it is designed according to the patient's preferences and needs and is generally shaped first by creating an impression of the patient's ear and then creating a mould based on that impression.

### **2.2.4 Hearing Aid Customisation**

Each patient has a unique hearing loss pattern, personal preferences (number of selectable programs, microphone arrangement, etc.), and usual acoustic environments [12, p50-51]. Thus, each patient requires a uniquely customised hearing aid to correct for the loss. The patient has unique needs and desires which dictate the style of the hearing aid (e.g. ITE or BTE) while the hearing loss is quantified in the audiogram and it is these differences which must be taken into account when programming the hearing aid. Due to the existence of three distinctly different types of hearing aids there are three completely different

means by which a hearing aid can be customised. Each type will now be briefly discussed.

In the case of analogue devices, the audiologist adjusts variable components through external screws on the side of the hearing aid casing [12, p18]. This controls the filtering and amplification levels of each frequency band. Digitally programmed analogue hearing aids are similar to analogue hearing aids in that the internal modification of the waveforms is all completed by analogue circuitry [12, p52]. The difference is how these modification settings are adjusted. Digital control circuits adjust the characteristics of the analogue circuitry in digitally programmed hearing aids. The control circuits themselves are controlled through the use of external hardware which plugs into the hearing aid. Digital hearing aids are programmed either by a stand alone programming unit or, as is the case with newer systems, via a programming unit controlled from a computer [12, p53-54]. Specialised firmware allows the computer to communicate with the programming unit and specialised software, running on the computer, provides a visual interface for the audiologist to effectively manipulate the programming which controls the DSP. Articles [2, 48, 49, 56, 70, 85] show that it is generally agreed upon that digital hearing aids provide significant advantages over the other types.

The process of fitting and customising a hearing aid is inherently recursive as the process relies on feedback from the patient. While the audiogram is a good starting point for the customisation of a hearing aid, each patient has their own personal preferences, as discussed above. The audiologist may fine tune the hearing aid many times before the patient is content.

### **2.2.5 Follow Up**

The follow up session is essentially the final stage of the recursive hearing aid customisation process. However, this feedback is different from the original session in that the patient has had time to use the hearing aid in everyday acoustic environments [80, p156]. The duration of these trial periods are at the discretion of the audiologist but generally they must allow time for the patient to adjust to the hearing aid and use it in many different situations.

### 2.2.6 Conclusion

Russel et al. [63, p3] report that 4.2 million people in the United States of America use hearing aids. This can only be as a result of a generally accepted process using features which work well and contribute towards the satisfaction of the patient. These successful features must be implemented in the new system and where this is not possible suitable replacement methods need to be found. These successes are identified and discussed in the following list:

- **Personal Interaction:** The value of one on one personal interaction between a patient and the audiologist cannot be overestimated. The removal of a physically present audiologist in favour of a remote audiologist deems this feature fundamentally impossible. A suitable means for the patient and audiologist to interact must be found.
- **Feedback Mechanism:** The patient can attend supplementary sessions with the audiologist after a suitable trial duration. This allows the audiologist to fine tune the hearing aid customisation settings based upon the patient's real world experience with the hearing aid.
- **Hearing Loss Model:** Modelling a patient's hearing loss allows the audiologist to use a scientific approach rather than educated guesswork and subsequent corrections. The audiogram models the hearing loss in such a way that the audiologist can quantitatively understand the loss and directly use the model to customise the hearing aid.

Conventional, or local hearing aid fitting is a complex task which may in fact take place over many weeks, months, or even years as it allows for the audiologist to receive feedback from the patient. This section has provided a brief insight into the process and has broken the process into three separate phases. Figure 2.5 shows the overall fitting process.

Conventional hearing aid fitting has been defined as the process by which hearing aids are fitted according to a patient's needs by an audiologist in physical contact with the patient.

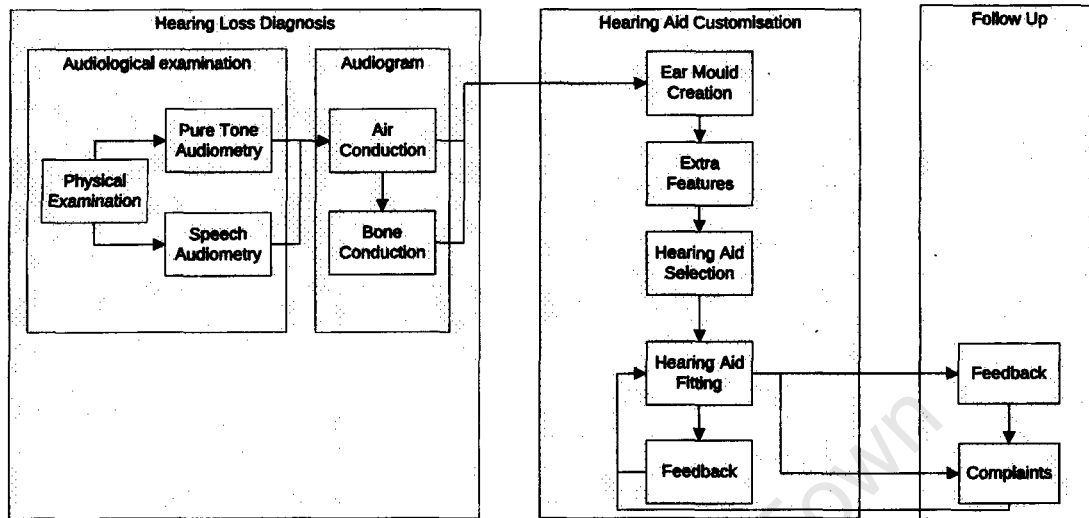


Figure 2.5: Hearing aid fitting procedure  
(Created with Microsoft Office Visio 2007)

Conventional, or local fitting has been discussed at this point to provide background research to contrast and analyse the proposed fitting system with respect to the local fitting process.

### 2.3 NETWORK CHARACTERISTICS

The proposed system, that of remote hearing aid fitting, requires the use of a network to transmit data between end user systems. These networks suffer from many non-ideal characteristics which are exacerbated by high demands such as long distances between end user systems, large amounts of data, and external use of the network. A brief study of network performance criteria and network traffic is included at this point to provide sufficient background knowledge for network testing of the envisaged system.

#### 2.3.1 Network Performance Criteria

The performance of a network can be predicted according to four measurable concepts [38, p634-637]. These concepts are now discussed:

### *Latency*

Defined as the round trip time of a single data packet between two nodes [38, p59-60]. Packets suffer from several types of delays at each node, all of which add up to the final latency experienced.

Processing delay ( $d_{\text{processing}}$ ) is introduced by the examination of packet headers, error checking, and actual processing of information by the CPU [38, p60-61].

Queuing delay ( $d_{\text{queuing}}$ ) is caused by packets queuing for transmission until such time as the node has sent all packets previously enqueued [38, p61]. Programs which communicate over Transmission Control Protocol (TCP) require acknowledgement packets to be sent back before the next data packet will be sent. With most network applications sending packets over TCP, the potential exists for large amounts of data to queue up and thereby increase the queuing delay.

Transmission delay ( $d_{\text{transmission}}$ ) is caused by the node holding data while it is waiting for a complete packet to arrive [38, p61]. Again, the use of TCP packets will cause network applications to feel the effect of this delay.

Propagation delay ( $d_{\text{propagation}}$ ) is the time a signal takes to travel across the physical medium once it has been transmitted by the node [38, p61-62]. This is proportional to the distance between two nodes. All network traffic is affected by this delay.

The equation 2.1 summarises latency

$$\text{Latency} = d_{\text{processing}} + d_{\text{queuing}} + d_{\text{transmission}} + d_{\text{propagation}} \quad (2.1)$$

The cumulative effects of all the delays involved in data transmission create the non-ideal network characteristic of latency.

### *Jitter*

Jitter is the variability of latency or packet delay within the same packet stream [38, p636-637]. As each packet can, theoretically, travel on different paths each with their own throughput rates, latency can be unpredictable.

### ***Packet Loss***

Packets which arrive either after a predefined interval, not at all, or corrupt all add up to cause packet loss [38, p63-66].

### ***Bandwidth***

Bandwidth is the rate at which data can be transferred by a network [38, p68-71]. This is the area which is consistently being improved upon. Thus, it is assumed that any bandwidth limitations which currently exist will be improved upon rapidly in the next few years.

#### **2.3.2 Network Traffic Protocols**

Two basic communication protocols are used by the majority of applications and services on computers to transmit data. Both of these work on the Internet Protocol (IP) but have significant differences.

User Datagram Protocol (UDP) is a simple protocol in that it adds very little to the IP packets. The most notable point is that it does not implement a reliable data transfer scheme. Transfer Control Protocol (TCP) provides a reliable alternative to UDP. TCP establishes reliable data transfer by requesting delivery notifications and providing congestion awareness. Based on these brief descriptions of the two protocols it would seem TCP is the obvious choice in every situation. However, this is not the case as software which is not adversely affected by a small percentage of lost packets, such as with video conferencing software, has no need for a reliable data transfer scheme. TCP is used by software such as remote desktop applications as, ideally, the user wishes to transmit every mouse and keyboard event.

#### **2.3.3 Network Quality Requirements**

For users to consider applications usable, the software needs to be executed at a rate which is perceived to be acceptable. Most applications can be executed without significant delays, but for applications which require large amounts of data transferral, this requirement is not always met. Interactive video is considered the most data intensive software when

compared to remote desktop applications as larger areas of the screen change frequently and each end user sends video data packets in video conferencing software. Therefore, if QoS requirements are met for video conferencing, theoretically the requirements for remote desktop software should also be met.

As video conferencing software does not have defined network Quality of Service (QoS) requirements, there is no agreed upon definition of what quality is considered acceptable. Kurose and Ross [38, p619] stated that for voice communications, latency of 150 ms is not perceived by the listener, while latency of 151-400 ms is considered acceptable, and latency of 401+ ms is considered unacceptable. Szigeti [76, p39] stated that when using video the following requirements are normally considered acceptable:

- Packet loss < 1 %
- One way latency <= 150 ms (round trip time of 300 ms)
- Jitter <= 30 ms
- Over provision bandwidth requirement by 20 % (e.g.: a 150 kbps video conferencing session requires a 180 kbps line)

If these network requirements can be met, video conferencing software and remote desktop software should run at a quality which is perceived to be acceptable by the users.

## 2.4 EXISTING REMOTE AUDIOLOGY SYSTEMS

While the concept of conducting audiology tasks remotely is relatively new, systems have been developed which work well within certain constraints. This section investigates all existing systems which are unique in some aspect and offer suggestions for improving the envisaged system.

### 2.4.1 Telephone Based Testing

Smits et al. [71] describe the development and testing of an automatic speech-in-noise testing system. It measures the speech reception threshold by presenting a series of triple

digit numbers across the phone to the user. The computer then automatically judges responses based on the keys the user presses on the telephone.

### ***Design***

The article does not discuss any specific implementation details over and above the fact that the server makes use of a sound card and modem.

### ***Evaluation***

This system is meant to provide an easy to access diagnostic test for prospective audiology patients to diagnose their own hearing loss. This text has shown that a diagnostic test does not provide sufficiently accurate and repeatable results for the fitting of a hearing aid. The service which this system provided is termed diagnostic as it does not monitor or control the external environment and is not calibrated by a standardised process. It is therefore noted that for any system which intends to fit hearing aids, the hearing loss diagnosis hardware must be calibrated and must either monitor or control the external environment.

Automating the system increases its availability to a theoretical 24/7 uptime and allows concurrent access. While these advantages are significant, the computer's inability to interpret unexpected commands, not to mention the issue of calibration, makes the possibility of expanding the system's capability into hearing aid customisation impractical.

The restrictions that the use of a telephone interface (instead of a computer interface) place on the system is extensive. In South Africa, current land line rates would be a significant factor in determining fitting costs based on the latest rates available on the Telkom website [78]. It is however undeniable that the telephonic interface does render the system highly accessible and easy to use as the user only needs access to a land line telephone.

#### **2.4.2 Online Home Testing**

A special subset of hearing tests can be used by people without assistance by accessing online hearing tests. Several such examples are available at the Phonak [55], Siemens [67], and Starkley [75] websites. Generally, these follow a three step approach:

1. Hardware calibration whereby the computer speakers' volume is normalised
2. Automated testing where sounds are played and the user provides some form of feedback
3. Program provides a recommendation as to whether the user should seek a professional opinion

Another hearing aid test type simply gives the user access to a matrix of pure tones [89]. This program makes no attempt to make recommendations or indeed even interpret results. Interpretation of the results is entirely left up to the user and their intuition.

### ***Design***

These tests are accessed through online websites and generally make use of a flash object embedded in the website. The flash object allows access to the computer's speakers or headphones and allows the user to provide feedback signals within the test.

### ***Evaluation***

All four online hearing tests cited above provide explicit warnings that the data collected cannot be used as clinically valid data. The results are for illustrative purposes only and cannot replace a professional hearing evaluation. Therefore, these tests can produce a qualitative analysis by providing distinct outcomes (hearing is acceptable or consult a medical professional) to be used as guidelines. As such, they could be used by people who wish to enquire into whether or not they require professional advice.

This set of hearing tests which have been classified as online home testing systems, have once again highlighted the need for a controlled or monitored environment and calibrated hearing loss diagnosis hardware. However, these tests have also shown that computer based online systems provide a high degree of flexibility and availability to anyone with a computer connected to the internet.

### **2.4.3 Remote Testing and Hearing Aid Fitting**

Pearce et al. [54] presented an investigation into providing hearing assessment, hearing aid fitting, and hearing rehabilitation to adult clients in remote areas. A custom system designed specifically for the purposes of the study was constructed and five distinctly different cases were examined.

#### *Design*

Hearing assistants, located from within the visited communities, were trained to assist the remote audiologist in various tasks which could not be executed remotely. These assistants performed the initial interaction with the patient and carried out the various tasks as required by the audiologist.

Telecommunication was handled through a wireless broadband mobile card operating at 7.2 Mbps. This was used by video conferencing units (VCUs) and pcAnywhere provided the remote desktop functionality. The equipment selected for the system was chosen based on their robustness, portability, and commercial availability. A portable computer, audiometer, hearing aid programmer, video otoscope, and tympanometer were chosen for the system.

#### *Evaluation*

The creation of ear impressions and customised ear moulds relied on a local audiologist owning the required equipment. While this is an excellent means of reducing costs and required equipment, there is no guarantee that any local audiologists will have this equipment or even be within close range. An alternative solution was proposed, where the hearing assistant could create a custom ear mould on site. Currently however, due to legal constraints, a qualified clinician is required to perform this task in person. The paper suggests that high resolution scanning may replace ear impressions in the future which would increase the possibility of hearing assistants legally executing this task remotely.

Remote video otoscopy allowed the audiologist (with a high bandwidth connection) to physically inspect the patient's ear for any defects and/or blockages. In one particular case which this paper investigated, remote video otoscopy allowed the patient to be treated

directly and alleviated the need for hearing aid fitting.

A high bandwidth connection also allowed the use of video conferencing software for general interaction with the hearing assistant and patient. In one case this paper investigated, video conferencing software allowed the audiologist to perform a remote demonstration of the everyday use of a hearing aid. This could be a useful tool when educating patients on day to day use of hearing aids.

This paper found that the use of a local hearing assistant over a hearing assistant in the employ of the audiologist had many benefits: Patients are often more willing when dealing with familiar people and a local hearing assistant is not required to travel excessively and may know other community support services. What the paper fails to mention is the disadvantages to this approach: Lengthy training to familiarise the hearing assistant with remote audiology tasks and the use of the particular remote system. The problem of who to use as the hearing assistant when no one from the local community is suitable is also not discussed.

#### **2.4.4 Central Server Based Testing**

The system investigated by Yao et al. [92] was a web service based tele-audiology system. The system was created to improve accessibility of traditionally under-served communities.

##### ***Design***

In contrast to other, existing tele-audiological services already offered, this system made use of a central server for hosting the software and for centralised logging and data storage. Both the remote audiologist and the hearing assistant make use of client computers while only the system administrator is envisioned to require access to the server for purposes of maintenance and upgrading. The server provided access to the software and audiometer through an online website which the remote audiologist and hearing assistant access through web browsers on client computers.

### *Evaluation*

The centralised server architecture reduces the cost and complexity required for each client machine as the server shoulders the majority of the processing and storage burden. However, the operational model dictates each audiologist and hearing assistant require a computer. This is in addition to the web server and (if separate) the data server. Client-server architectures only become cost effective on a large scale such as if the system frequently has multiple patients undergoing simultaneous testing. This is due to the increased hardware requirements of a server.

Network access is a major consideration for client-server architectures: Transmitted data volumes are larger than on peer to peer architectures as all data storage and processing is handled on the server. Server bandwidth requirements increase as a function of the number of expected concurrent fitting sessions which can take place. The use of client-server architecture also creates a single point of failure. Should the web server lose connectivity, all fitting sessions will be halted and, depending on the design of the system, possibly lead to data loss or corruption. Mirrored web servers can reduce the bandwidth requirements of a single server by distributing concurrent fitting sessions and also increase server redundancy by removing the single point of failure.

The client computers did not require installation of specialised software as web browsers were used in preference to stand alone applications to provide the application interface. Theoretically, any computer with the necessary hardware requirements met, could be used as part of this system without any set up and installation procedures.

#### **2.4.5 Intercontinental Remote Testing**

De Wet et al. [11] presented a study on the viability of remote audiology across large distances. A suitable testing platform was developed and tests were carried out on 30 adult patients. The results were then compared to results from conventional hearing assessment techniques.

### *Design*

The audiologist controlled the PC based software through the use of desktop sharing software while the hardware set-up and initial patient interaction was handled by a field clinician. The audiologist interacted with the patient and hearing assistant through the means of video conferencing software.

A portable audiometer, the Kuduwave 5000 clinical audiometer, was used in conjunction with a portable computer which itself had a webcam, speakers and a microphone. The video conferencing software used was Skype version 4 and the desktop sharing software used was Teamviewer 4.

### *Evaluation*

The study investigated two issues: What clinical differences emerged when conducting hearing loss analysis remotely when compared to face to face results, and whether inter-continental distances between patient and audiologist is technically possible. The focus of this study was not the creation of a thoroughly tested remote system but the results which were produced through the usage of it. Despite this, the testing framework design and the tests themselves provide suggestions for the development of the proposed system.

Test results showed a distinct correspondence between remote and local hearing loss diagnosis results with 98 % of thresholds within 5 dB or less of each other. Average reaction time for remote testing was 13 ms longer and test durations were between 0.5 and 5.9 minutes longer than local testing. The findings indicated no clinically significant difference between the two types of audiometry but the testing session durations were significantly longer when conducted remotely. The study also proved that a distance of 14 680 km between patient and audiologist is manageable.

Remote desktop sharing through the means of Teamviewer was found to be adequate for the experiment. Initial connections were made by means of a unique identification number and password combination and communication across the internet was encrypted. Teamviewer is free for private use but not for commercial use, which is the area the system is intended for. A Teamviewer business licence currently costs R 4 579 [77]. This would

drastically increase the cost of fitting procedures as this cost would have to be recovered over time. Teamviewer works on a multitude of computer and mobile phone operating systems and hardware platforms and is easy to use once the user can grasp the concept of a screen within a screen.

Video conferencing software was provided by Skype video conferencing software which was also found to be adequate according to the paper. Skype is free for commercial use when connecting to another computer over the internet [68]. It offers unverified encrypted communication [8] and makes provision for low bandwidth connections by allowing only voice or text communication. Skype works on a multitude of computer and mobile phone operating systems and is easy to use.

The clinical audiometer chosen was the Kuduwave 5000. It is medically calibrated before the point of sale [35] and does not require a soundproof booth [19]. The software for the Kuduwave works within all modern Microsoft operating systems and requires two free USB 1.1 ports (Universal Serial Bus) [36]. However, the software requires activation [36] before use which requires time for Geoaxon administrative systems to respond. Additionally, the Kuduwave itself, costs R 55 000 [19] which greatly increases the cost of the system.

Overall, the system proved the viability of remote hearing loss diagnosis and provides valuable suggestions for the design of a remote hearing aid fitting system and the testing thereof: The Kuduwave provided an excellent portable clinical audiometer and the remote element was handled through a combination of video conferencing software and remote desktop software. However, the system has several significant pitfalls which it is hoped the envisaged system will improve upon: Perhaps the most significant shortcoming of this system is the lack of hearing aid customisation functionality which is provided for. While the focus of the system is exclusively on hearing loss diagnosis and thus makes no attempt to correct for this, the customisation of hearing aids, in accordance with the hearing loss findings, is the logical next step. Teamviewer is an expensive software component which could be replaced by software which is more suited for the use of tele-audiology. Finally, Skype provides unverified encrypted communication. Other video conferencing software could be used instead of this component to assure users of the security of the system.

#### **2.4.6 Summary**

This section has investigated all existing systems which are unique in some respect and offered suggestions for the design of the envisaged system. The design and purpose of five separate systems have been discussed and brief evaluations of the designs and their testing are covered to highlight the shortcomings and advantages of each system.

Telephonic systems provide a high degree of accessibility and simplicity and have the potential to be automated. However, when compared to computer based systems, telephonic systems are restrictive and can be expensive due to current telephone land line rates. Online home testing systems suffered from a lack of standardised and calibrated hardware but did show the flexibility and availability of online computer based systems. Section 2.4.3 showed the viability of both testing for hearing loss and fitting hearing aids remotely. This section also showed that the use of local hearing assistants have significant advantages but these are likely to be outweighed by their disadvantages when used commercially. The use of a client-server based architecture is a costly choice unless the system will be used on a large scale due to the increased expenses of a web server. Finally, Section 2.4.5 has proved quantitatively that remote hearing loss diagnosis over long distances is feasible and the associated effects are clinically insignificant. However, session durations were noticeably longer. This section also provided excellent suggestions for the design of the envisaged system and several system components.

#### **2.5 SUMMARY**

The purpose of this chapter was to provide the relevant background knowledge to create a basis from which a remote hearing aid fitting system can be created. Four core concepts on which this project is based are covered to enlighten the reader on the concept of “remote hearing aid fitting”.

The composition of a general hearing aid was discussed with the focus on the DSP and how hearing aid fitting relates to it. Conventional hearing aid fitting was discussed and several key successes were identified which partly explain why it has been so widely accepted. Non-ideal network characteristics, such as latency and bandwidth, which affect data transfer across networks was covered to provide the background knowledge for trans-

mitting data across networks reliably. Finally, several existing remote audiology systems were analysed. Several key conclusions were drawn from the discussion of each system. These conclusions cover aspects from the overall architecture of the fitting systems to the choice of components.

University of Cape Town



## SYSTEM DESIGN

This chapter is dedicated to the design of

*A commercially viable remote hearing aid fitting system.*

The design has four distinct stages:

1. **Architecture:** The overall structure of the system is discussed by analysing databases and the means of communication.
2. **Design:** Advances the design from a Graphical User Interface to a class diagram.
3. **Components:** Selection of individual components to implement the system.
4. **Finalising:** Discusses issues such as licensing, packaging, use, and costs.

These four stages document the design of the system along with the reasoning behind all design choices.

### 3.1 ARCHITECTURE

The design of the architecture is the logical starting point for designing a system of this nature. Only once issues such as how the database will be maintained and the means of communication have been addressed, can the system start to take shape.

### 3.1.1 Communication Models

When creating a networked system, two distinctly different communication models exist: Peer to peer and client-server [24, p11-17]. Each has its own strengths and weaknesses and these will be discussed in this section. The section is concluded by making a final decision on which architecture is most suited for the system in question.

For the purposes of simplicity and reliability the system has been designed to work on existing networks and protocols. These protocols are discussed in Section 2.3.2.

The client-server model is based on requests sent from the clients to the server. This server is then a critical component and, should it fail, the system will be unusable. Server failure could be caused by a power outage, server hardware or software failure, or network disruptions. Creating redundancy by providing a backup server would decrease this vulnerability but increase costs.

Peer to peer architecture is inherently redundant. Should a peer fail the other peers can continue with no critical disruption to the network.

The amount of data exchanged between the server and clients is dependant on the level of processing and storage which is completed on the client [7, p427]. Fat clients would require very little communication while thin/zero clients would rely on the server heavily for processing and storage and thus the network will require more bandwidth. If multiple clients are in use simultaneously, the problem will only worsen as the network path common to all clients will carry all communication.

Peer to peer architecture requires all end systems to function independently. Therefore, all processing and storage is done on the local end system and network utilisation is minimised.

The main cost considerations when considering which architecture should be used are end systems and network bandwidth. Peers are stand alone systems and while their price does vary greatly, they are generally priced between clients and servers [24, p12-17]. In client-server systems the end system which will be doing the most processing and storage will generally have an inflated cost. If the processing and storage is predominantly done

on the client side then fat clients will be required and their cost will be similar to a peer end system. The server price would complement the average price of clients. Any server redundancy increases the cost of a client-server system quite dramatically.

### Summary

Table 3.1 provides a summary of the issues which communication models present. Based on these arguments the model of choice is a peer to peer model.

Table 3.1: System architecture comparison

System Architecture	Peer to Peer	Client-Server
Cost	Lower	Higher
Scalability	Good	Good
Network traffic	Small	Large
Single point of failure	No	Yes

### 3.1.2 Database

The database is responsible for recording all information collected from patients. The usual critical properties (atomicity, consistency, isolation, and durability) [5, p9-15] of databases must be enforced but the physical security must also be handled for ethical reasons. This security must provide a high degree of confidentiality

Two different approaches can be used when considering the location of the database. A centralised database would be especially useful if an audiologist had multiple hearing assistants or worked in a team of audiologists as all users would have access to all the patients.

The second option is to have distributed local databases on the field computers themselves. Data access latency would be considerably less when compared to using centralised databases. However, the significant downside to locating the databases on field computers is the inherent risk associated with mobility (hardware failure from rough use) and crime [47, p632-639]. Additionally, non-field staff cannot access the data.

Whether the database is stored on a central server or on field computers the issue of data

security is an important one [6]. If the data storage device were to fail all data would be lost. Thus the database must have a shadow copy, preferably one where the process of backing up is automated.

This issue brings about a third option: A combination of the first two options in that a local copy of the database is kept on the local field computers while online file hosting services allow data to be backed up either automatically, or on demand to a remote shadow database. This solution provides the most advantages: The audiologist can have all data available from any end system they choose while having little danger of data being lost. This third option is the solution most suitable for the system.

### 3.2 DESIGN

The design of this system's components and their interaction follows a formalised iterative design process used widely in the software design industry for the development of object orientated systems. It is known as the ICONIX process. This process is designed for use in systems with a substantial human-computer interface while placing emphasis on maintainability and reusability [60].

The process features ten distinct steps each with the goal of advancing the overall design of the system from the informal description stage to a class diagram. This allows the system design to be explained in a specialisation flow i.e.: From the general to the specific. A graphical user interface provides the initial structure of the program from which the system is expanded upon.

1. Problem statement<sup>1</sup>
2. Graphical user interface (GUI)
3. Domain modelling
4. Use case modelling
5. Requirements review

---

<sup>1</sup>Situated in Section 1.2.

6. Robustness analysis
7. Preliminary design review<sup>2</sup>
8. Sequence diagram
9. Class diagram
10. Critical design review<sup>2</sup>

This dissertation follows this ten step process allowing the reader to move through the design of the system as it is gradually built.

### 3.2.1 Graphical User Interface (GUI)

The GUI gives an early idea of the system's design. The GUIs show the interfaces for both the audiologist's computer and the field computer at major points in the system's use. Figure 3.1 show these GUIs.

Figure 3.1 (a) shows how the operator of the field computer initiates the connection between the field computer and the audiologist's computer. Once this connection has been established the main focus of the field computer's screen becomes the text or video of the audiologist as seen in Figure 3.1 (b).

Figures 3.1 (c) and 3.1 (d) show the audiologist's screen once the connection has been established. First the hearing loss is diagnosed (Figure 3.1 (c)) and then, based on the diagnosis data, a hearing aid is programmed (Figure 3.1 (d)).

### 3.2.2 Domain Modelling

Step two in the ICONIX process is used to identify the problem space conceptual objects and the relationships between them [60, p23-47]. Devices such as audiometers and hearing aid programmers are complex devices requiring certification and calibration and are well established in the field of audiology [57]. Thus, the system must be built to incorporate existing versions of these devices rather than the creation of new, custom devices.

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<sup>2</sup>Although the ICONIX process identifies this step as a milestone, it adds little to an already mature design. It is included at this point from a completeness point of view but is omitted in the design stages.

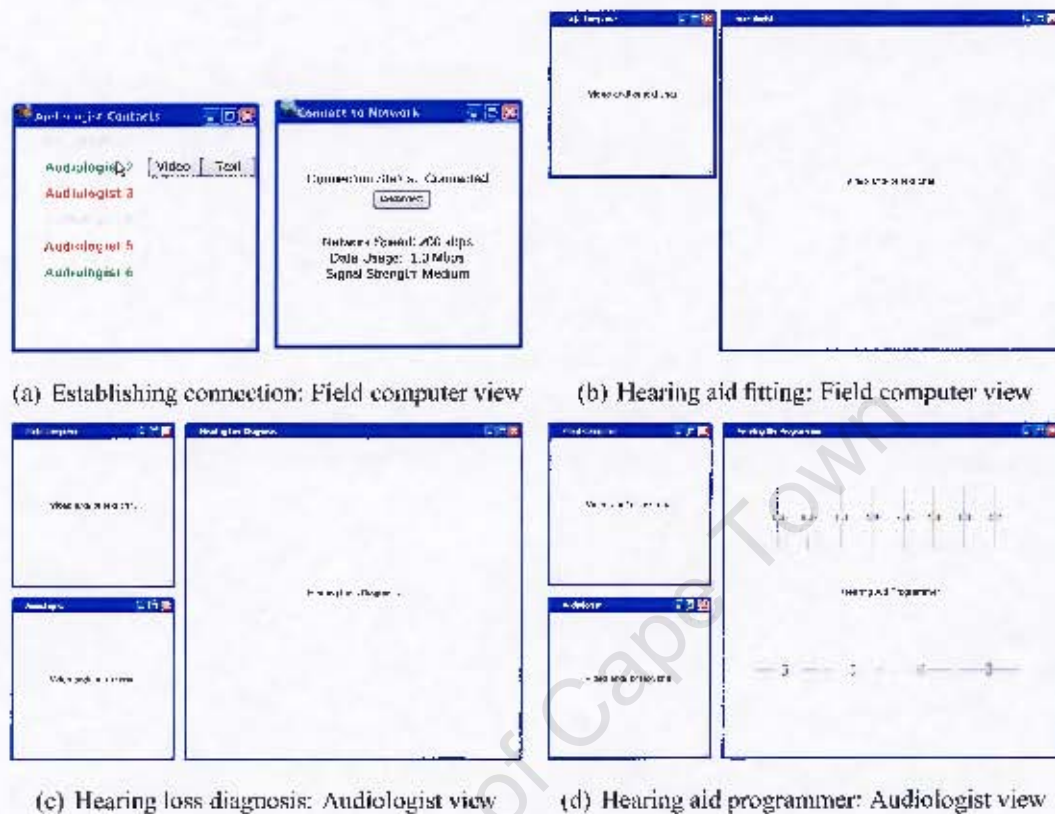


Figure 3.1: Prototype GUIs  
(Created with Microsoft Office Visio 2007)

Figure 3.2 shows the domain model and how the field computer is central to the system. Firstly, the field computer makes use of a 3G card and its software to connect to the internet. Secondly, it allows the audiologist to communicate with the patient through video and text based conference software. Thirdly, it will also control the audiometer and hearing aid programmer through the use of specialised software suites. Finally, the field computer hosts the remote application execution software. This software will allow the execution of the audiometer and hearing aid programming software on the field computer (server), but with the interface presented on the audiologist's computer (client).

### 3.2.3 Use Case Modelling

Use case analysis is the basis of the ICONIX process and is the element which gives the system under creation a focus on the users and their interaction with the system [60,

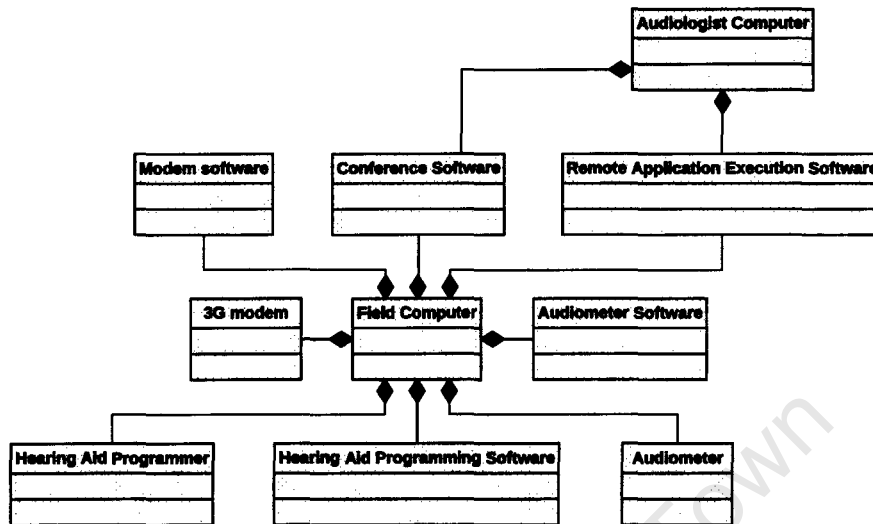


Figure 3.2: Domain model  
(Created with Microsoft Office Visio 2007)

p49-81]. The very nature of the system, being a specialised hearing aid fitting service, is a linear procedure with little opportunity for the user to deviate off the main sequence of events on a macro scale. Thus, the system has only one use case with three alternate flows deviating off the basic flow towards the conclusion of the fitting. This is shown in Figure 3.3.

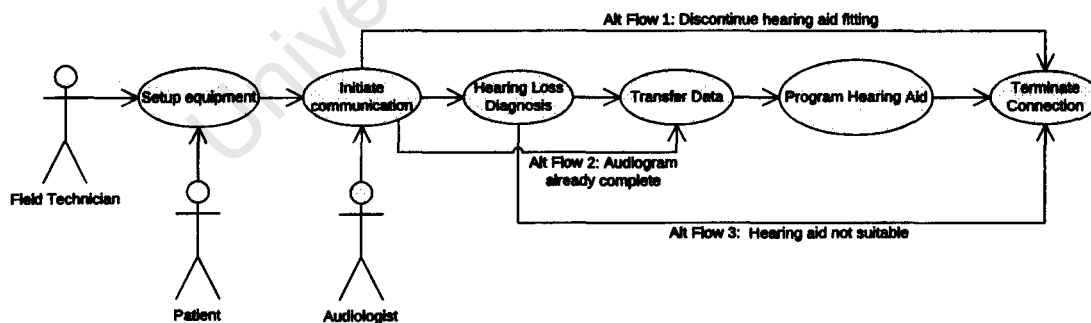


Figure 3.3: System use case  
(Created with Microsoft Office Visio 2007)

**Basic Flow:** A hearing assistant, who has travelled out to the location of the patient, locates the patient and a suitable location for the fitting session to take place. The hearing

assistant then sets up the equipment and initiates either text or video based communication between the audiologist and the patient. The audiologist now carries out the hearing loss diagnosis procedure. With the information (audiogram) gathered from this diagnosis, the audiologist can program a hearing aid. When both the audiologist and the patient are happy with the hearing aid, the audiologist terminates the connection.

**Alternate Flow 1: Discontinue hearing aid fitting:** After communication has been initiated the audiologist may decide not to carry out the fitting procedure. The audiologist terminates the connection.

**Alternate Flow 2: Audiogram already complete:** After communication has been initiated the audiologist may decide that an existing audiogram can be used to program the patient's hearing aid. The audiologist then transfers the data, programs the hearing aid, and terminates the connection.

**Alternate Flow 3: Hearing aid not suitable:** After the audiologist has carried out the hearing loss diagnosis, they may decide a hearing aid will not be beneficial to a particular patient. They will then store the audiogram in a database for future use external to this system and terminate the connection.

A noteworthy point is the introduction of a hearing assistant. It must be assumed that all patients do not know how to handle hardware such as audiometers and hearing aid programmers. Therefore, the audiologist requires a physical assistant present at the scene to interact physically with the patient. Additionally, the hearing assistant will then be responsible for the transportation of the equipment and the initial interaction with the patient. The hearing assistant requires no specialist audiology or computing knowledge but has been trained to perform the tasks which are required in the field.

#### 3.2.4 Requirements Review

This milestone is used to verify that the domain model and the use case model can work together [60, p83-97]. The requirements review also validates that these two models meet the system requirements originally specified by the problem statement and prototype GUIs.

This section lists the requirements and the reason why they need to be met:

- **Simplicity:** All users are considered to have no specialist computer knowledge. Tools such as video conferencing applications are likely to be new to most users. As such it is imperative that the use and set up of the system, which could already be considered complex, is simplified as far as possible.
- **Network bandwidth:** With the patient and audiologist being physically separated, the need for digital communication is essential. Target markets for the system will include locations with limited internet access. Therefore, the system must work in areas with extremely low bandwidth internet access.
- **Portability:** The hearing assistant will be solely responsible for transporting equipment to sites. One person can only transport a limited amount of equipment and so number of items, their weight, and dimensions must all be minimised to maximise portability.<sup>3</sup> Additionally, component robustness must also be given due consideration.
- **Cost:** The system aims to provide a low cost hearing aid fitting system. This can only be done if all costs are minimised where possible.
- **Power:** The use of electronic systems demands a supply of power. Modern portable computers can power themselves and many peripherals for many hours at a time. However, the combination of powering these devices and running processing intensive applications greatly decreases the time the system can be used on battery only.
- **Clinical Reliability:** A system providing a clinical service to the general public needs to be reliable and provide repeatable results. This requires that all components work individually, and as part of the system, in a reliable way.

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<sup>3</sup>In some situations certain system elements may be left unused in favour of more suitable technologies. e.g.: Some clinics may provide in-house internet access which is superior to the means provided by the design of the system. Regardless, the system is designed for a worst case scenario.

- **Security:** Patient details contain contact information and clinical data. This data is private and its accessibility should be limited as far as possible through the use of secure data transmission and storage.

### 3.2.5 Robustness Analysis

Step five in the design process is the final step in object discovery and is used to decide which objects (these were established in the Domain Model (see Section 3.2.2)) will interact with each other to achieve the desired flows in the use case (see Section 3.2.3) [60, p101-141]. Figure 3.4 shows the outcome of the robustness analysis.

Introduced here is the separation of the remote application execution software into a server and client. This is done to separate the responsibilities of the field computer and audiologist's computer. Also shown is the hearing assistant which was introduced in Section 3.2.3 and how they are responsible for the field hardware.

Each individual system, the audiometer, the hearing aid programmer, the remote program control software, and the conferencing software, all pass data, specific to their tasks within the individual systems. Each subsystem is critical to the functioning of the overall system.

### 3.2.6 Sequence Diagram

With the completion of object discovery the first steps in detailed design can take place. Sequence diagrams allocate behaviour to all the objects identified in the robustness diagram (see Section 3.2.5) and, more importantly, defines the sequence of these events [60, p185-230]. Figure 3.5 shows the interaction of these events.

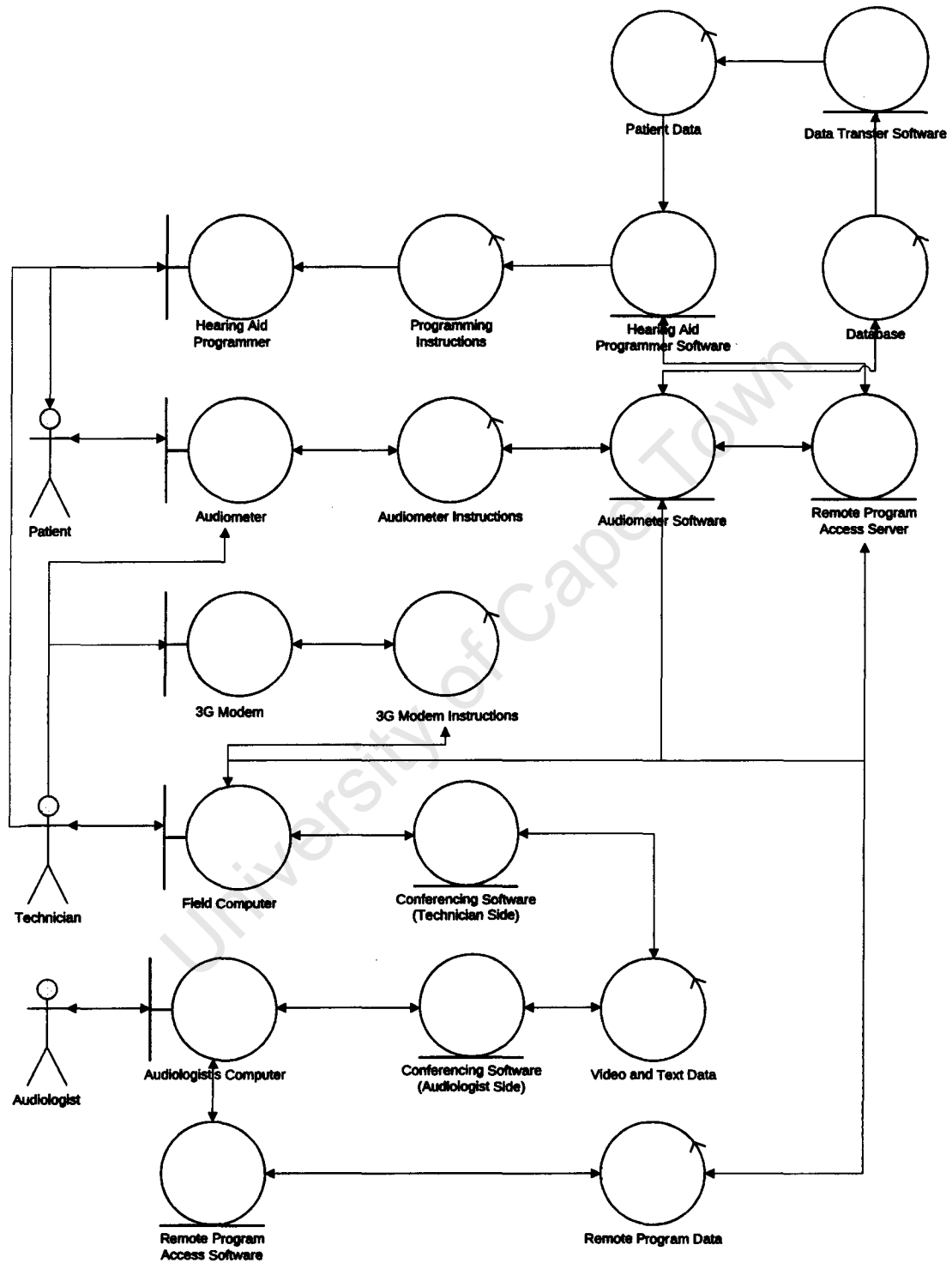


Figure 3.4: Robustness diagram  
(Created with Microsoft Office Visio 2007)



The sequence diagram shows users, hardware, and major software components and the order in which they send specific messages.

### 3.2.7 Class Diagram

The class diagram is the finalisation of the domain model (see Section 3.2.2) using the unified modelling language (UML) [60, p297-325]. All domain model components are given attributes and functions as needed according to the sequence diagram in Figure 3.5. Figure 3.6 shows the final class diagram.

When compared to the domain model the notable difference is that each component now has responsibilities in the form of functions which, together, carry out all the tasks the system needs. The functions however, are very generalised as at this point components have not been chosen.

Introduced here is DNS update software. This is used for the purpose of making the contact details of the remote application execution server publicly accessible. A more in depth explanation of this software and the need for it can be found in Section 3.3.15.

## 3.3 COMPONENTS

With the architecture and design of the system in place, specific components can now be chosen to fill each role. In this section both hardware and software components are individually discussed, although in many cases the choice of hardware dictates the use of specific software.

### 3.3.1 Computer Operating System

The computer operating system allows programs to communicate with hardware and provides an environment which allows users to interact with software.

Microsoft Windows is the world's most popular computer based operating system [84]. As such most computer literate people are familiar with its use. Additionally, most new computers currently on the market are sold with a preloaded version of Windows installed [1]. Therefore, the operating system of choice for both computers is Microsoft Windows

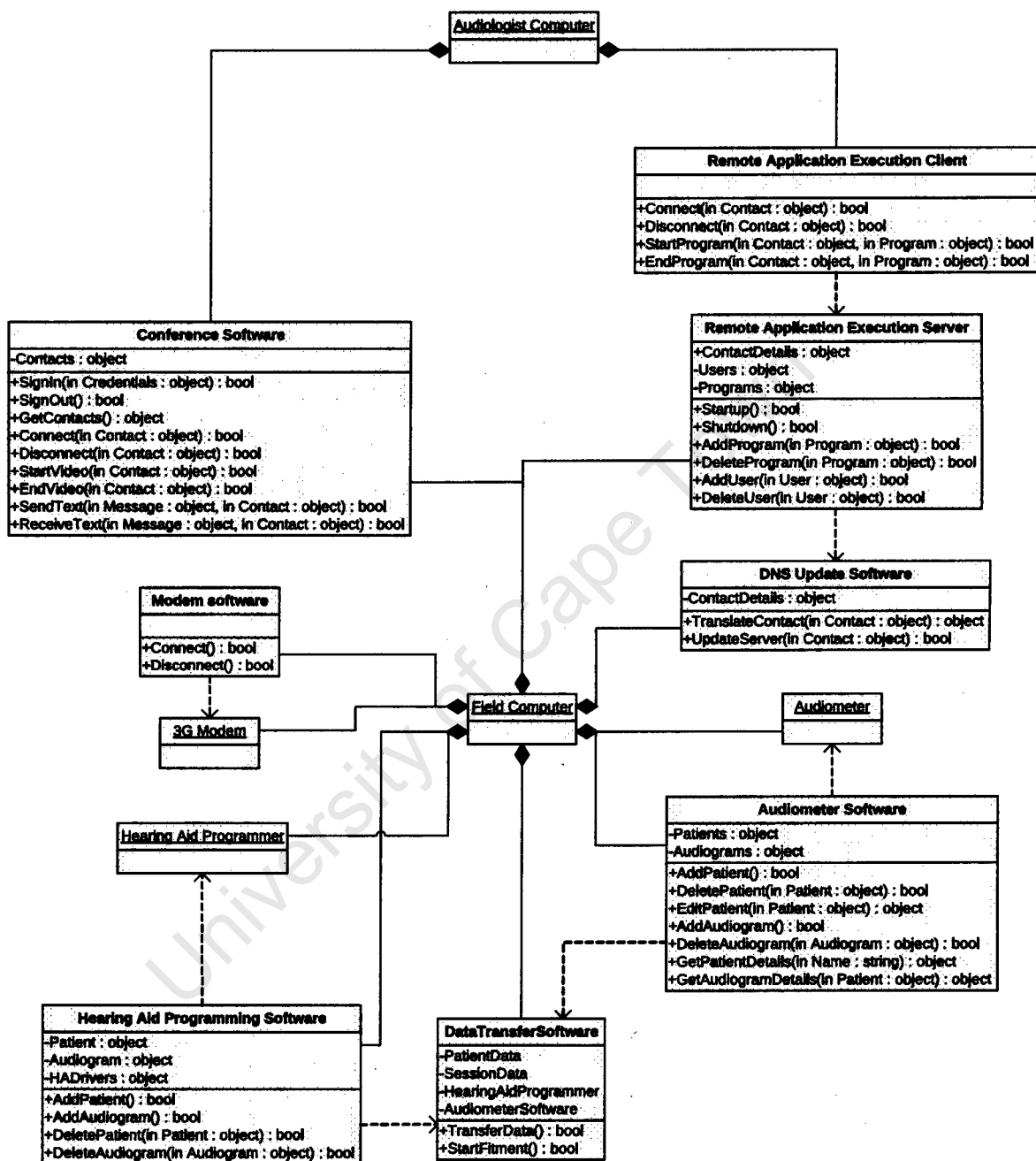


Figure 3.6: Class diagram  
(Created with Microsoft Office Visio 2007)

7 [44]. Theoretically, the system should work with Microsoft Windows XP, Vista, or 7 but it has only been tested on Windows XP and 7.

### **3.3.2 Computers**

Two computers are required to operate the system, however their roles are vastly different and therefore have different requirements.

The first computer is the field computer. It is used as the direct controller of the audiometer and hearing aid programmer. Additionally, it provides the means for the hearing assistant and patient to communicate with the audiologist.

The second computer is used by the audiologist to indirectly control the audiometer and hearing aid programmer. It is also used to provide the second link in the communication channel between the field computer and the audiologist.

Due to the wide variety of products available on the market and the rate of technological change, only the current requirements (see Section 5.1) for each computer (as opposed to an actual computer model), as needed by the hardware and software chosen, will be stipulated along with a suitable choice for the field computer. While the audiologist's computer is an essential component of the system, it does not have much in the way of requirements. Additionally, it is a fair assumption to presume that all audiologists have a computer at their practice [30, p405-476]. For these reasons a computer for the audiologist has not been chosen.

The Gigabyte Q2005 netbook [20] was chosen as it meets all the requirements in Table 3.2, which shows the field computer's requirements. It has a built in WiFi transceiver, has two multicore processors with 2 GB DDR3 RAM memory, 6 cell battery life rated to last approximately 5 hours when in use for fitting sessions (see Section 4.1.3), and three usb ports.

### **3.3.3 Hearing Aid Programmer**

The purpose of a hearing aid programmer is to customise the DSP according to the audiogram data points and all the selections made by the audiologist [12, p52-53]. It serves as

Table 3.2: Computer requirements

Computer	Field Computer	Audiologist's Computer
Portable	Yes	No
Operating System	XP/ Vista/ 7	
Processor	Intel Atom 1.50 GHz	
RAM	2 GB	
Sound devices	Speakers and Microphone	
Webcam	Yes	
Free USB ports	3	0
Internet Access Type	Wired/ Wireless (as required)	

an interface between the controller (modern systems use a computer) and the hearing aid and converts the computers signals into a set which can be understood by the DSP.

Table 3.3 shows a comparison between the two commercially available modern hearing aid programmers. Purely from a portability point of view the NOAH Link appears to be the obvious choice. Bluetooth wireless communication requires less wiring and allows for a larger degree of freedom for the patient. However, the NOAH Link price<sup>4</sup> is considerably larger than the HI-PRO. It is this fact, despite the slightly larger dimensions and weight of the HI-PRO [21] that make it the programmer of choice for this system.

Table 3.3: Modern hearing aid programmers

Programmer	NOAH Link [25]	HI-PRO [21]
Price	≈ R12 000	≈ R5 500
Wired/ Wireless	Wireless	Wired
Power Supply	Rechargeable battery	USB
Dimensions	91x100x31mm	137x114x37mm
Weight	141g	230g
Programming Speed	Medium	Fast
Binaural fitting	Yes	

<sup>4</sup>Prices based on Rand Dollar exchange rate as of May 2011 (R7.18/\$)

The HI-PRO makes use of two DIN 6 pin connectors (one for each hearing aid) with standard 4 pin hearing aid connectors on the other end which connect the cables to the hearing aid. These are purchased separately.

It should be noted that from a design point of view the choice of programmer is irrelevant. The system is sufficiently decoupled to allow any programmer which is compatible with the computer's operating system and DSP to work seamlessly. This section is included only from the point of view of providing a complete system for commercial use.

Considering the internal complexity of hearing aid programmers there is little reason for the excessive cost of the programmers. These costs can only be explained by the apparent stranglehold that the large hearing aid manufacturers have on the industry. The standardisation of hearing aid programming equipment does simplify the technical aspects of the audiology profession, however it has also provided the means for an apparent collusion between the major manufacturers and effectively limited the number of people who have access to hearing aids.

#### **3.3.4 Hearing Aid Programmer Drivers**

The hearing aid programming drivers are responsible for establishing a communication protocol and language which allows the computer to communicate with the hearing aid programming box. The choice of drivers go hand in hand with the choice of programmer (see Section 3.3.3). The selection of the HI-PRO programmer as the preferred programmer for the system requires that ADROCOM3 HI-PRO USB drivers published by Dynamic Hearing are used in conjunction with the programmer. These drivers are supplied with the purchase of a HI-PRO.

These drivers are compatible with Microsoft Windows XP, Vista, and 7 operating systems and the chosen hearing aid Programming Interface (see Section 3.3.5).

#### **3.3.5 Hearing Aid Programming Interface**

This interface provides the means for the user to control how the hearing aid programmer customises the hearing aid. It is one of two major interfaces which will be in use during fitting sessions. Therefore, the interface must also be intuitive and easy to use and set up.

The requirements of this software are that it is compatible with the HI-PRO USB hearing aid programmer, a large range of low end hearing aid DSPs, and run on the Microsoft Windows XP, Vista or 7 operating systems.

The particular software which has been chosen is Soundfit. It satisfies all the requirements for the system's hearing aid programming interface. It has a patient database management system (DMS) stored locally on the computer for its own use. Soundfit supports a plug-in architecture whereby the functionality of Soundfit can be expanded by adding a plug-in for new DSPs. The software is pre-packaged with a multitude of plug-ins for common DSPs.

It also allows the user to interact with a graphical equaliser which supports an automated fitting procedure according to the provided audiograms. Compression ratios, feedback cancellation, and multiple programs are also supported should a particular DSP plug-in support the respective features.

The use of Soundfit requires that DSPs be pre-programmed by additional software. This software, Interactive Data Sheet (IDS), is available as part of the ARKBase package [50]. It provides a more extensive and technical interface that the majority of audiologists do not require access to. Each hearing aid need only be pre-programmed with IDS once during its lifetime. This pre-programming should be factory programmed as part of the hearing aid manufacturing process.

### 3.3.6 Digital Signal Processor Interface

This software is transparent to the user as it provides the communication protocol and language for communicating with the chosen hearing aid's DSP via the hearing aid programming box. The plug-in is specific to the DSP type chosen for use in each hearing aid.

Soundfit, the hearing aid programming interface chosen, provides an extensive library of DSP plug-ins for a range of DSPs manufactured by ON Semiconductor. While only the GA2006 and the Rhythm SB3231 plug-ins have been tested within the system, theoretically any plug-in compatible with Soundfit is compatible with the system.

### **3.3.7 Audiometer**

This is the device which provides the means to detect hearing loss. On instruction from the controller (modern systems use a computer [12, p52-53]) the audiometer presents sounds and the patient responds such that the audiologist can verify that the patient has perceived the sound correctly. The audiometer can only detect the presence and severity of hearing loss, not the cause of the hearing loss. Additional tools, not included as part of the Audiflector system, such as an otoscope and tympanometer perform this function [53, p33-34] [16, p1].

The Kuduwave 5000 clinical audiometer [19] was chosen in this case. It can perform binaural fitting and uses double occlusion through the use of both noise cancelling headphones and foam inserts. This allows the fitting to be conducted outside of a booth. Stereo microphones monitor background noise and pause the diagnosis process until the noise has subsided. This ensures the validity of the clinical data. The decision to use this audiometer is largely based upon its software rather than the device itself (see Section 3.3.8). The requirements for the audiometer were only that it is portable and relatively low cost.

The Kuduwave is by far the most expensive component of the system even though it is considerably lower in cost than the alternatives. A similar situation to that of the hearing aid programmers exists in that portable audiometers are needlessly expensive. The excessive costs can be attributed to the low adoption rate of new technologies in the field of Audiology and the development costs associated with new technologies.

### **3.3.8 Audiometer Interface and Drivers**

This software enables communication between the computer and the audiometer. It also provides the interface for the user to manipulate the audiometer. This software is the second of three major interfaces which are used during fitting sessions. Thus, the interface must also be intuitive and easy to use and set up.

The choice of audiometer software, eMOYO 500 [19], was largely based upon its compatibility with the system. It has several important features: eMOYO has a built-in patient DMS, can perform both pure tone and speech audiometry tests, and can support external

program integration.

### 3.3.9 File Hosting Service

As discussed in Section 3.1.2, the need for database redundancy is an important issue. Publicly accessible file storage servers allow users to create an account and then upload data to a secure server when connected to the internet.

- **Secure Access:** Any files stored on the server must be accessible only through a verified user account.
- **Security:** All data must be transferred over a secure channel and stored in an encrypted format.
- **Cost:** The system aims to provide a low cost hearing aid fitting system. This can only be done if all costs are minimised where possible.
- **Complexity:** The installation and use of the chosen software should be as simple and intuitive as possible.

This backup service has a number of requirements all of which must be fulfilled. Table 3.4 shows a comparison of all file hosting services which meet these requirements.

Table 3.4: File hosting services

Service	Free Storage Size	Update Client	Security
Amazon S3 [66]	Unlimited	Paid account only	SSE/ SSL
Dropbox [14]	2 GB	Free	256 bit HTTPS/ AES
FileSonic [17]	Unlimited	None	Undisclosed
Google Docs [22]	1 GB	None	Undisclosed
Live Mesh [45]	5 GB	Free	TLS/ SSL
SkyDrive [43]	25 GB	None	TLS/ SSL
Ubuntu One [9]	5 GB	None	HTTPS/ SSL

Based upon the summarised results of this table the best file hosting service for this system is Dropbox [14]. Dropbox has an intuitive setup process that involves installing the client

program on the computer and registering for the online service (see Section 3.4.4). Use of the software once the service has been set up is completely transparent to the user as the background service automatically synchronises the database with the online server.

### 3.3.10 Data Transfer Software

Any program which makes extensive use of data generally makes use of a database in one form or another. When two programs, each of which maintain their own database, need to share the same data, these databases, or at least a part thereof, need to be synchronised.

Many programs which could be used to provide the hearing loss diagnosis and hearing aid programming components for this system are available only as two separate programs. As is the case with the use of the eMOYO - Soundfit combination. This software was custom designed specifically for the transfer of data between eMOYO and Soundfit. The plug-in is written in Delphi version 6 as it allows the creation of ActiveX forms and can control Client Dataset databases [10].

This is the only component of the system which had to be coded. The program functions as a plug-in in the eMOYO framework and as such had strict requirements which had to be filled: The plug-in is principally an ActiveX form. The resulting .ocx ActiveX file is uniquely identified by a plug-in Object CLSID. This and other information is provided to the eMOYO program on start-up in the form of an .xml file. eMOYO uses these .xml files to identify and classify all available plug-ins.

The plug-in is required to fetch data pertaining to a particular patient from eMOYO, convert the data into a usable format, and make the data available to Soundfit. In the interest of maintaining data integrity, only one database, the eMOYO database, is used by the system to store patient information.

#### *Usage*

When the eMOYO user chooses a session, eMOYO makes all the session information available to all plug-ins through a number of API (Application Programming Interface) requests. This information is then parsed. The Soundfit database is emptied and new records are inserted such that only one patient with one fitting session exists in the Sound-

fit database. On successful insertion (synchronous insertion) a Windows shell command is then executed to automate the start-up of Soundfit. A callback signal notifies the plug-in that Soundfit has closed on successful termination of Soundfit. Finally, the plug-in notifies eMOYO of its intention to terminate.

### *Design*

The ICONIX process was again used in the design of this software. However, all its design steps (with the exception of the class diagram) have been excluded as it is beyond the requirements of this analysis.

In keeping with the spirit of the system which has been created, where a component can be replaced with little or no disruption to the rest of the existing system, the code makes provision for the replacement of both the audiometer and hearing aid programming software. This is done by the creation of three separate classes (eMOYOinterface, Soundfitinterface, and eMOYODataTransferInterface). The eMOYOinterface and Soundfitinterface classes inherit requirements for their parent classes (AudiometerSoftware and HearingAidProgrammer classes respectively) as seen in Figure 3.7. The two additional classes (PatientData, and SessionData) are used as containers for the transportation and organisation of data.

The hearing aid fitting software, Soundfit, has a proprietary database purpose designed for Soundfit by H.I.M.Tech [28]. The schema for this database is shown in Figure 3.8. Patient details are stored in “newclient\_cds” and their clinical data is stored in “clientdata\_cds”. The data transfer software transfers information for one patient with one set of clinical data.

#### 3.3.11 Modem

As the field computer requires a means to communicate with the audiologist’s computer it is assumed that the audiologist’s computer has a suitable internet connection for the audiologist in terms of mobility and bandwidth.

As mentioned previously in Section 3.2.4 some locations may provide suitable internet connectivity. However, this design assumes no such facilities are available and makes

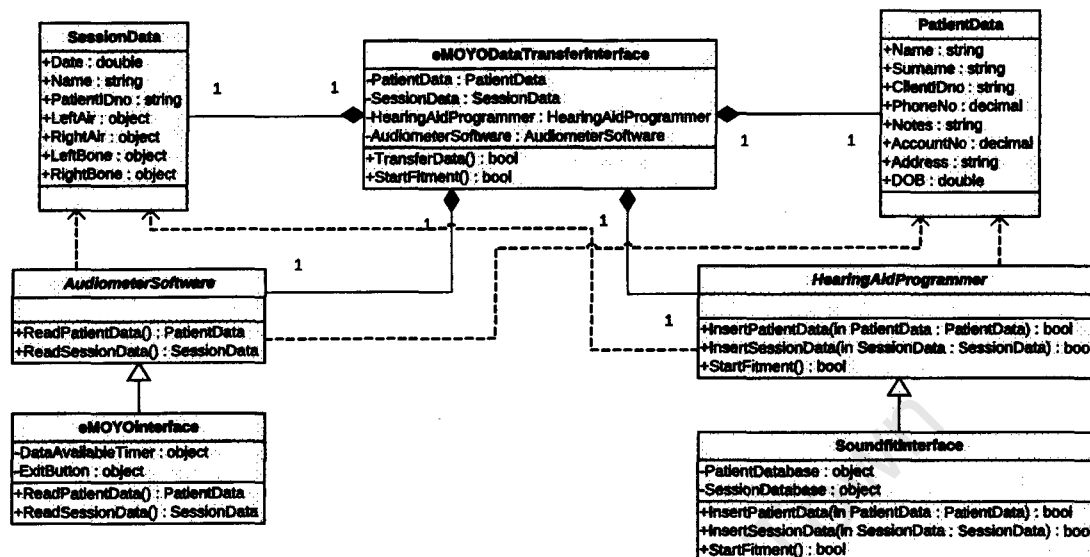


Figure 3.7: Data transfer software class diagram  
(Created with Microsoft Office Visio 2007)

provision for the lack of such facilities.

High speed portable internet connectivity is provided by means of the national cell tower network. A mobile network card functions as the modem and connects the field computer to the cell tower network. This internet connectivity means was chosen solely based on the fact that it realises unparalleled portability as there is very little area of South Africa which does not have cell tower coverage [90, p267-269]. Bandwidth is highly dependant on location. Coverage and bandwidth is constantly being improved on at a rapid rate by network operators.

One critical aspect which the cellular company must make provision for is the use of an unrestricted Access Point Name (APN). Unrestricted APN access provides the user with a public IP address which is not situated behind a network address translator (NAT) system [81]. NAT systems map one public IP address to many private IP addresses by directing each private IP's traffic through a particular port on the public IP. While this does not affect the majority of users who mainly use HTTP traffic, it does provide a source of problematic internet connections for this system.

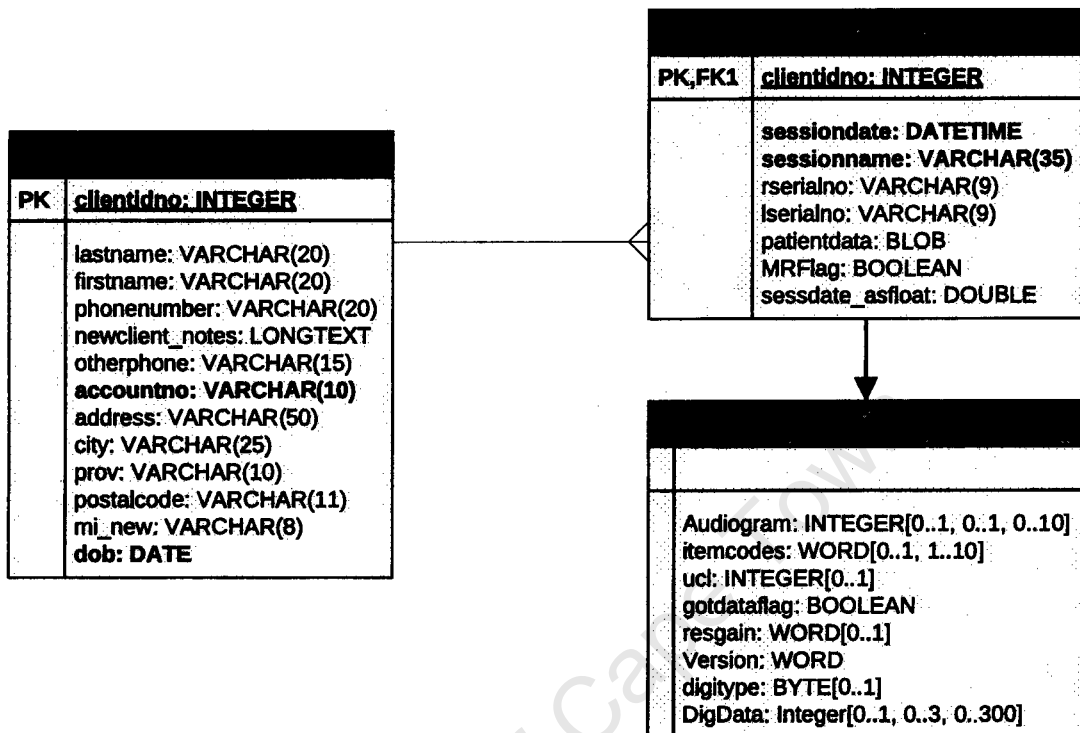


Figure 3.8: Soundfit database schema  
(Created with Microsoft Office Visio 2007)

Currently, South Africa has four cellular network operators [72]. Critically however, only two of these (Vodacom and MTN) have the ability to provide an unrestricted APN. Of these two service providers, Vodacom has the widest coverage and it is for this reason that Vodacom was chosen. Network coverage and respective bandwidths for the Vodacom network are available from <http://spatial.vodacom.co.za/coverage/>[82].

The actual modem which was chosen was a Huawei Technologies E220 HSDPA (High Speed Downlink Packet Access) USB modem provided by Vodacom.

### 3.3.12 Modem drivers and Interface

This software provides the communication protocol and language to allow the modem to communicate with the computer. It also presents an interface allowing the user to connect to the internet, query credit remaining, and monitor network strength. This software is

installed automatically on insertion of the modem into a USB port.

### 3.3.13 Conference Software

As with remote desktop applications, conference software systems are numerous and highly varied. However, specific requirements need to be met for the software to be usable within the system:

- Client capable of running on Microsoft Windows XP, Vista and 7
- Support encryption
- Support video, voice and text based chat
- Intuitive and easy to use interface and simple set up procedure
- Must not require exclusive control of the soundcard as both the audiometer software and conferencing software require simultaneous use of it.

Currently, there are four conferencing services which meet these requirements and are compared in Table 3.5.

Table 3.5: Chat clients comparison

Chat Client	Skype [69]	Windows Messenger [87]	VSee [83]	Yahoo [91]
Encryption	256 bit AES	None	256 bit AES	None
Price	Free	Free	Free	Free
Advertising	Small	None	None	Large
Bandwidth Usage	High	Medium	Low	Medium

Skype requires exclusive use of the Sound card when conducting video or voice chat sessions which makes it unacceptable for using it while conducting hearing loss testing. Windows Live Messenger is not compatible with Windows XP. Yahoo is a free service which is paid for by advertising which has quite a heavy presence on the interface. VSee uses 256 bit encryption, is free for commercial use, has no advertising, and has a relatively

low bandwidth requirement even with the use of video [83]. Hence, VSee was chosen as the conferencing software of choice. VSee operates its protocol over UDP. This is ideally suited for video conferencing software as it has little effect on video or sound streams if a few bytes of data are lost. Video and sound can continue streaming no matter how lossy the communication is.

#### 3.3.14 Remote Application Execution Software

Remote desktop software has long been used by IT professionals to provide technical support to troubled users by taking control of their computer from a remote location [61, p226]. While this is the most common use of the software, it is by no means the only use and it is actually central to the use of this system.

A slight variation of remote desktop software is a category of software best described as remote application execution software. This allows the software to be executed on a remote computer but with the interface presented on the local computer. This is different from remote desktop software in that the remote computer does not have access to the interface and the local computer does not have access to the entire remote desktop.

Winflexor [88] has been chosen for use as the remote application execution component. The Winflexor server, a background service, allows a user to choose applications which can be remotely accessed and executed. User access is granted by use of the active Windows login credentials. Alternatively, the Winflexor server can maintain a private purpose built database of users and their credentials. Winflexor operates over TCP as the server ideally wishes to receive every keyboard and mouse event which is sent from the client computer. TCP provides the best attempt at delivering this service.

The resulting system is one where the audiologist controls the software which is being executed on the field computer. The controlling interfaces (audiometer software (Section 3.3.8) and hearing aid programming software (Section 3.3.5)) remain hidden from the patient.

The result is that the remote program appears and functions similarly to a local program. There are three distinct advantages to using such a system:

- The absence of the remote desktop windows simplifies the execution of remote programs
- Displaying only a single program instead of a remote desktop window uses less bandwidth
- Allows the entire field computer's screen to be devoted to displaying video and/or text conferencing systems

The software has simple requirements in that it only requires that both computers be networked and that the server have a publicly accessible IP address.

Winflexor offers seamless Windows integration by allowing the creation of shortcuts for remote applications, essentially rendering Winflexor a background service which is completely transparent to all users. Winflexor also supports 256 bit AES encryption, uses very little bandwidth, and provides a free for commercial use limited version. The disadvantage of the free version is that it only allows for the simultaneous execution of two remote programs. Currently however, only a maximum of two programs ever need to be simultaneously remotely executed. Should the need for the maximum number of programs which can be remotely executed increase, Winflexor is still a viable option. A single user licence currently costs \$ 70.00 [88].

Creation of remote program shortcuts allows the audiologist to launch remote programs, aimed at a particular server, as if they were locally run programs. However, for this to occur, the server address must remain constant. This is only possible with the use of the DynDNS service.

### **3.3.15 DNS Update Software**

Due to the sheer number of devices connecting to the internet, and the limited number of IP addresses, modern operating systems make use of the Dynamic Host Configuration Protocol (DHCP) Service to assign an IP address to the network interface card (NIC) on internet connection initiation [13]. This allows devices to connect to the internet on an ad-hoc basis and results in a highly dynamic network. One of the major disadvantages to

this system is the dynamic assignment of IP addresses for publicly accessible servers as it is possible that the server IP address will change every time it is connected to the network.

Domain names provide an address which is both easier to remember and static (e.g.: `www.uct.ac.za`). The problem remains of translation from a static domain to a dynamic IP address. Servers can employ a background service which constantly update DNS servers with their latest IP address.

The service chosen for use in this system is that of Dyn Standard DNS [15]. The service currently provides a single domain name for free. The choice of name is arbitrary and unrestricted within a choice of several domains so long as it is unique. The name chosen for a system server is unique in that it identifies a particular server but arbitrary as the service is, generally, completely transparent to both the audiologist and hearing assistant.

The service also provides a background client called Dyn Updater which runs transparently on the server. At set intervals this client updates the DNS servers with the latest IP address of the server. DynDNS runs on Microsoft Windows XP, Vista, and 7 operating systems, is completely transparent to the user, and requires an insignificant amount of bandwidth in comparison to the remote application execution software (see Section 5.1).

The addition of the DynDNS service simplifies the logging of a user into the Winflector component. Winflector, as a stand alone service, requires an address (normally a dynamic IP address), username, and password. With the inclusion of the DynDNS service in the software stack, the address for a particular field computer becomes constant.

### 3.4 FINAL SYSTEM

Figure 3.9 shows the various components which the system is comprised of and how they all interact with each other, the three users, and the hearing aid. Some components have been omitted in Figure 3.9 for clarity reasons.

The system has been designed with extensibility in mind: Technological change is fast paced both in software and hardware. It is hoped that many future developments in the field of audiology can be incorporated into the system with little or no change to the existing system.

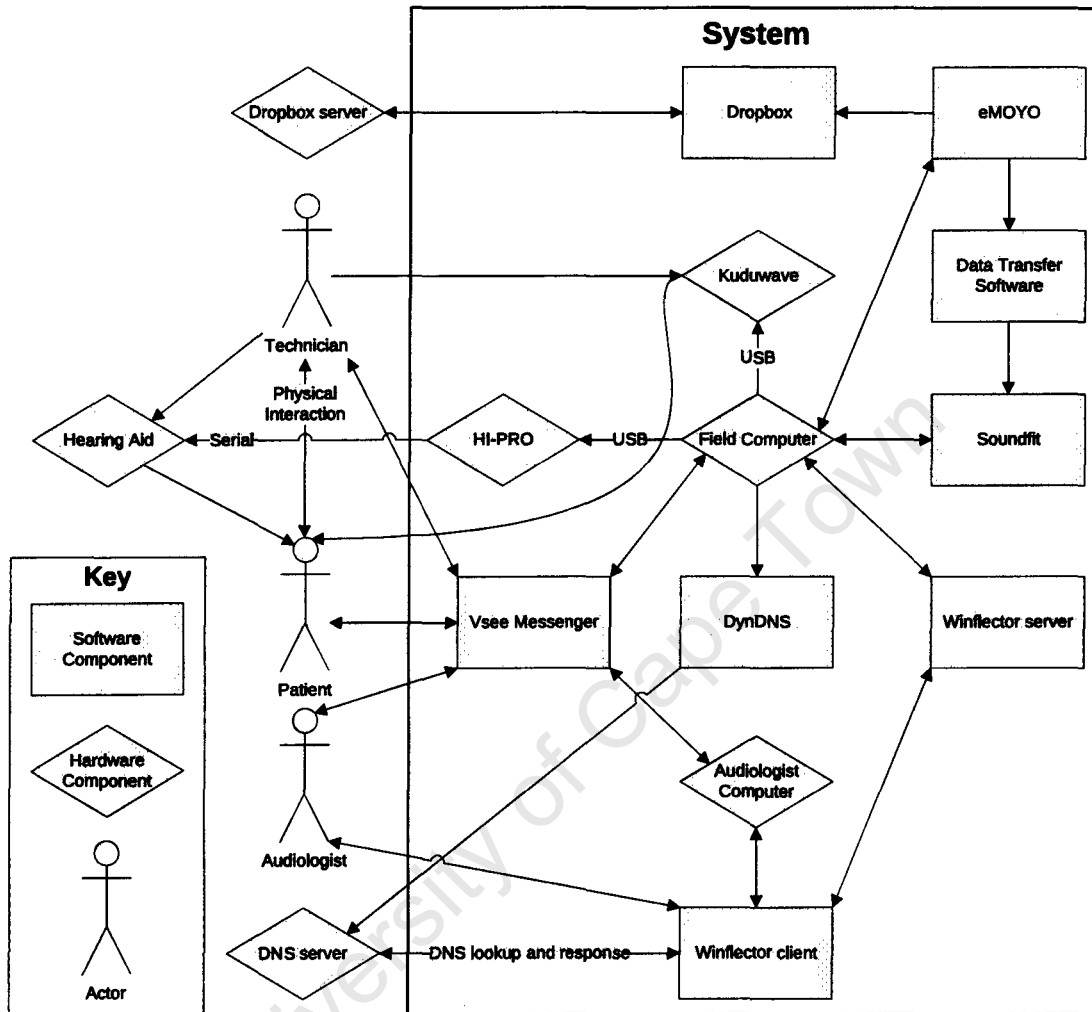


Figure 3.9: System overview  
(Created with Microsoft Office Visio 2007)

The aim of this chapter was to design a commercially viable system and therefore the system requires a name. The name “Audiflector” was chosen and is comprised of two distinct parts. “Audi” comes from audiologist, and “flector” from the word reflector owing to the remote nature of the system. The name is also partially derived from one of the core software components: Winflector.

A Readme (see Appendix B) is compiled as part of the system. It provides a summary of core issues such as system requirements, components, installation, usage, and mainte-

nance. It is not meant to provide an exhaustive instruction set, but simply supplement any training which audiologists and hearing assistants may receive in the use of this system, audiometers, and hearing aid programmers.

#### 3.4.1 Ear Moulds

Section 2.2.3 briefly discussed the range of options available for ear moulds. Given this information and the relative simplicity of open-fit hearing aids, the open-fit approach is the one which will be used. It should be noted that the discussion on open-fit hearing aids [37] does also mention that only certain hearing loss patterns can benefit from open-fit approaches.

#### 3.4.2 Packaging

The requirement that the system be portable and robust dictates that the system hardware be transportable. Packaging must therefore be investigated. The Kuduwave 5000 clinical audiometer currently comes pre-packaged in a hard plastic carrying case. Laptop carrying bags are widely available and provide the laptop with limited shock protection. The HI-PRO, with its relatively small dimensions, can easily be fitted into a laptop carrying bag along with all other required cabling. Finally, the packaging of hearing aids, as received from the manufacturer, will provide a limited degree of protection for the hearing aids themselves.

#### 3.4.3 Licensing

The purpose of this system is to provide a complete system to audiologists which they can use to benefit society. The system is envisaged to be freely available and the only costs involved are those associated with acquiring the hardware. All the software which forms part of the system is free for commercial use. Currently, the system does not have any licensing associated with it, however, it is the intellectual property of the University of Cape Town.

### 3.4.4 Services and Accounts

Due to the nature of the system, a number of services are required. These services are secure and as such require accounts to be created. These are listed in Table 3.6 below:

Table 3.6: Online services

Service	Website	Purpose
ON Semiconductor	sounddes.com	Soundfit registration
VSee (Audiologist's Computer)	vsee.com	Chat service registration
VSee (Field Computer)		
DynDNS	dyn.com	DNS service registration
Dropbox	dropbox.com	File hosting service registration
eMOYO	info@geoaxon.com	eMOYO activation

With the exception of eMOYO, all these accounts need to be created prior to system installation to make the system easier to install. eMOYO activation allows the use of eMOYO software once it has been installed.

### 3.4.5 Software Distribution and Installation

A user friendly means of enabling the audiologist to set up the system must be provided to reduce set up time. The following two subsections detail the various means of distributing and installing the software which is freely available. The hardware components must all be purchased separately.

#### *Field Computer*

The system software can be distributed in two ways:

The first choice is to have the software pre-installed on the portable computer with automated start up sequences enabled on boot. This is the preferable means as it reduces the chance of set up error occurring and simplifies the set up. However, this option can only be considered if an administrator has access to the computer before it becomes the property of the audiologist. Additionally, all accounts must be set up and account details

must be transferred to the audiologist.

The second choice is to provide the software on removable media. This method can be used if an audiologist requires that the software be installed by their own means. Most modern portable computers do not have optical drives but do have USB ports. Thus the preferred medium of software distribution would be via a flash memory unit. The flash drive will contain an automated start-up script and install script. The start-up script specifies what action must take place when the flash drive is inserted into a USB port, and several properties such as the flash drive icon and name. In this case the action which will take place on insertion is the execution of the installation script.

The install script will open up the computer's default browser and proceed to download all the installation wizards. All default install options must be used. When login details are requested, the user must provide the details which were used when registering for the specific service.

Two more tasks are required before the field computer setup is complete. First, the Winflector server must be configured. A user must be set up and remote access to both eMOYO and Soundfit must be allowed. The DynDNS client must be configured by registering the client with the chosen URL. Finally, the VSee contact of the audiologist must be added to the field computer's VSee account.

### ***Audiologist Computer***

Two applications need to be installed on the audiologist's computer. The first is the Winflector client. Once this is installed the audiologist may choose to create shortcuts to both remote programs (eMOYO and Soundfit). This allows the audiologist to start-up the remote programs as if they were locally run programs. Additionally, the audiologist may select optional extras which reduce bandwidth usage.

### **3.4.6 System Use**

Conventional hearing aid fitting is already a fairly complex process, hence the need for audiologists. The addition of the remote element only serves to increase the complexity of the process. Ideally, neither the audiologist, nor the patient should be able to discriminate

between the conventional and remote means of hearing aid fitting. Currently however, this is not possible. This means the system must try to minimise both the added complexity of the system and the disruption caused by the remote element.

The diagram in Figure 3.10 shows the various steps involved in conducting a single fitting session along with the required signals exchanged between the audiologist and the hearing assistant.

The following two subsections explain how the system should be used by both the audiologist and the hearing assistant. This assumes that all the installation steps have been followed correctly. A more user orientated approach is taken in describing these steps in the Readme in Appendix B.

### ***Audiologist***

During the time in which the hearing assistant is setting up the equipment, the audiologist can set up and check the equipment on their side. This would include checking the web cam, speaker, microphone configuration, and internet connectivity. The audiologist can signal their readiness by logging into the chat service and checking that their chat presence setting is visible.

The hearing assistant will initiate either a text, voice, or video chat session when all the equipment is set up. The fitting process can now begin. Start the remote eMOYO application, and verify that all the eMOYO details are correct. Open an existing patient or create a new patient and fill in their details as is applicable. Create a new clinical note and select "puretone audiometry". All defaults such as tone duration and selected frequencies are generally considered the norm in the audiology profession. However, settings such as the selection of manual or automatic threshold testing and single or warble tones are at the prerogative of the audiologist. Once all settings have been checked, use the next screen to explain to the patient what they are required to do and check the audibility of the tones. The testing may now begin.

When the testing is finished save and close the clinical note. Let the hearing assistant know that they can unplug the audiometer and set up the hearing aid programmer and

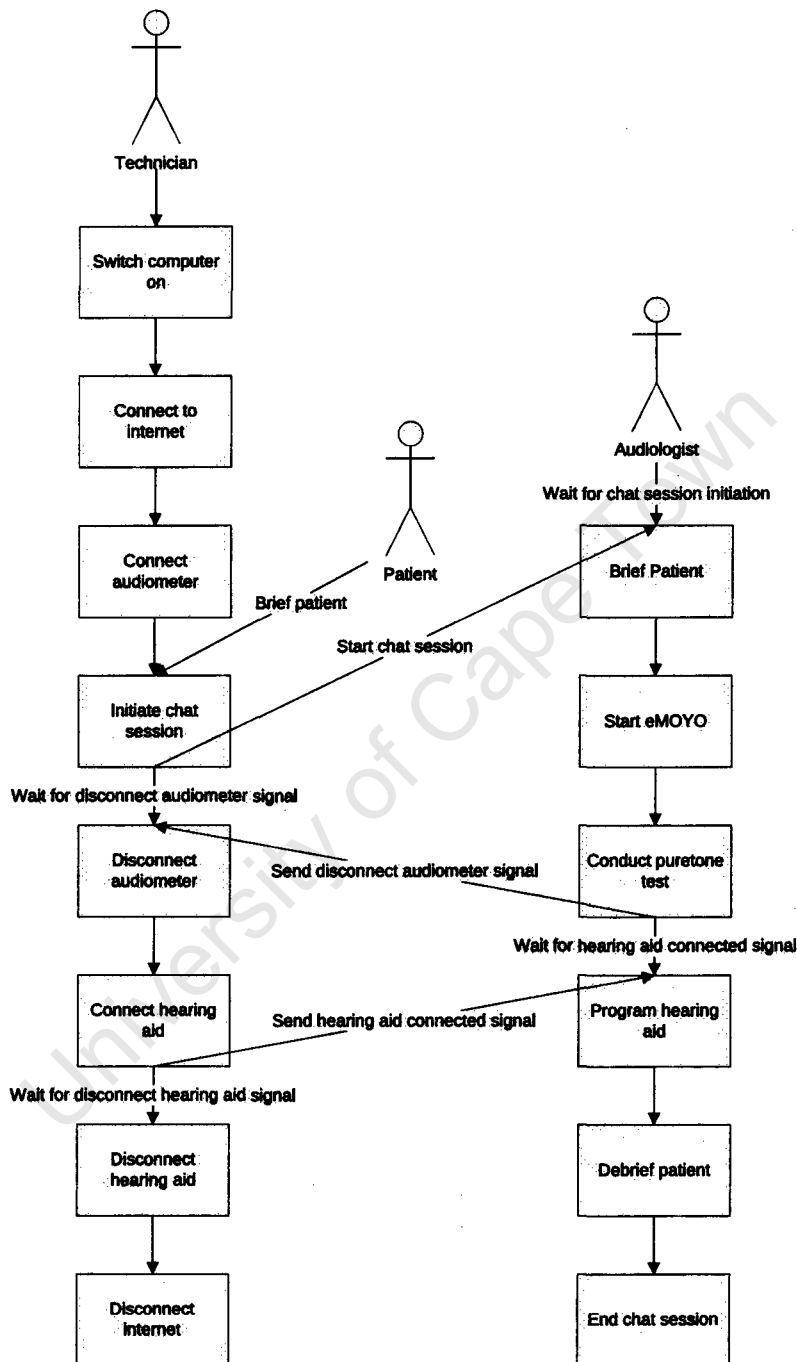


Figure 3.10: Fitting steps and signals  
(Created with Microsoft Office Visio 2007)

hearing aid. Start Soundfit and transfer the data by adding a new clinical note and selecting “program hearing aid”. The topmost clinical note is also the most recent and will be selected by default.

When Soundfit has started select the only entry in the table. Detect the types of hearing aid(s) connected by advancing the Soundfit screen. When the hearing aid has been correctly detected advance Soundfit on to the programming window and execute the auto fit procedure. This programs the hearing aid to compensate for the loss detected in the audiogram. The next stage is adapting the hearing aid to better suit the patient. This is a highly variable and subjective process as each patient has their own preferences and the number of customisations which can be made is large and dependant on the particular hearing aid chosen. When the patient is happy with the hearing aid, exit Soundfit and let the hearing assistant know that the hearing aid and its programmer can be disconnected.

As part of the debrief session the audiologist may choose to set up a subsequent session for the purposes of fine tuning the hearing aid based on the patient’s experience of wearing the hearing aid in everyday life. For the purposes of remote audiology specifically, this process could be automated by allowing the patient to contact a post fitting care service themselves, as required.

### *Hearing assistant*

The hearing assistant, or field assistant’s purpose is to carry out tasks that an audiologist in a conventional setup would do that a remote audiologist is unable to do. It is the hearing assistant who will be on location, travelling around to various clinics and/or houses with the equipment. When the hearing assistant reaches the location for the fitting to take place and they have found the patient they can start the process.

Switch the computer on and connect the modem to the computer. When the modem interface appears connect to the internet. Attach foam inserts on to the tubes of the audiometer. Connect the audiometer to the computer and the response button to the audiometer. When the patient is ready, initiate a chat session with the audiologist.

The audiologist will take over the interaction with the patient from this point. However,

the audiologist will still issue instructions for tasks which cannot be carried out remotely. These instructions will comprise of placing the audiometer on the patient, removing and disconnecting the audiometer, connecting the hearing aid programmer and placing the hearing aid on the patient's ear, disconnecting the hearing aid, and finally packing up the system. All these tasks must only be completed when the audiologist provides the appropriate signal.

### 3.4.7 System Cost

Despite the effort to keep costs to a minimum the system still has significant costs associated with it. Table 3.7 tabulates those costs<sup>5</sup> which are independent of the number of fitting sessions which occur. Table 3.8 lists those costs<sup>6</sup> which are dependant on the number of fitting sessions which are held. For the purposes of cost calculations a typical cellular data bundle package such as the Vodacom-MyGig 1 Standard package is proposed for use [26]. This provides 1000 MB for R 249.00 which works out to R 0.249/MB.

Table 3.7: Set costs

Item	Quantity	Unit Price [R]	Price [R]
Hearing Aid Programmer	1	5 500	5 500
Hearing Aid Programmer Connecting Wires	2	120	240
Audiometer	1	53 000	53 000
Field Computer	1	2 500	2 500
<b>Total</b>			<b>61 240</b>

Table 3.8: Variable costs

Item	Quantity	Unit Price [R]	Price [R]
Audiometer Foam Inserts	2	5	10
Modem	63.5 MB	0.249	15.81
<b>Total</b>			<b>25.81</b>

The cost<sup>5</sup> of the system is then defined in terms of the number of binaural hearing aid fittings (x) which are done without replacement of any non-consumable components in

<sup>5</sup>Prices based on Rand Dollar exchange rate as of May 2011 (R7.18/\$)

<sup>6</sup>estimated data usage as calculated in Section 5.1.5

Equation 3.1 below. The costs do not include hearing aids, transportation, wages, etc.

$$\text{Total Cost} = 25.81x + 61240 \quad (3.1)$$

This means the Audiflector system requires an initial outlay of R 61 240 and an additional R 25.81 per fitting session.

The task of cost comparison between remote and local hearing aid fitting is not a trivial one as it is dependant on many unknown variables. The major unknown variables which have been identified are: The audiologist's hourly rate and the hearing assistant's hourly rate.

The majority of the above known costs are common to the fitting system regardless of whether the fitting is completed remotely or not. What is of interest in addition to these costs, is whether remote fitting does result in a significantly cheaper fitting process than a local fitting process. If the assumption that the audiologist's hourly rate is considerably greater than the hearing assistant's hourly rate holds true then, generally speaking, the remote fitting process will be less expensive than the local fitting process. A more accurate assessment of relative costs can only be completed when field trials are conducted.

### **3.5 SUMMARY**

The design of a remote hearing aid fitting system has been completed. All required components have been chosen and issues such as the use and installation of the system have been discussed along with an analysis of the system costs. This system can provide a test bed to ascertain whether the system is reliable, usable, and commercially viable.



# TESTING

The objective of testing is to check how well the system executes its function. This involves gauging how well the system interacts with users and itself and how many errors occur. Four distinct testing platforms were designed to fully test the system. Testing scenarios involving test subjects were designed to emulate the envisioned commercial use while simultaneously maintaining control over the issues being tested. Each test is fully described in the following sections with the results and their analysis presented in Chapter 5.

The process of fitting a hearing aid varies due to many factors. Some of these factors are too variable to predict but others can be predicted within tolerances by conducting sets of tests. The factors which have been identified as major sources of variability are listed below:

- **Limited field computer resources:** Resources shared not only by the Audiflector system's processes but by all the computer's processes
  - Battery usage:** Power consumption by the field computer and all peripherals
  - CPU activity:** Arithmetic operations which the CPU performs
  - Memory usage:** Data required to be immediately accessible by the CPU
  - Disk activity:** Data which is read from and written to the hard drive
  - Network activity:** The rate at which data is transferred by the network between the field and audiologist's computers

- **Human variances:** Personal preferences and ability in the interaction of a person with another person and with a computer

**Audiologist variances:** Level of computer literacy, familiarity with digital audiometry software and remote fitting processes, efficiency of interaction with patients and hearing assistants

**Hearing assistant variances:** Level of computer literacy, familiarity with digital audiometry equipment and remote fitting processes, efficiency of interaction with patients and audiologists

**Patient variances:** Level of hearing loss, familiarity with remote fitting processes, efficiency of interaction with audiologists and hearing assistants

- **Environmental disturbances:** Disturbances external to the system which affect the fitting process

**Background noise:** Background noise hinders the patient's ability to hear the tones presented

**Network connectivity loss:** Loss of communication between the field and the audiologist

**Process disturbances:** People interrupting the process in person, by cellphone, etc.

The impact these variables have on the use of the system are analysed in the two sections which follow (Section 4.1 Resource Testing and Section 4.2 User Acceptance Testing). They address the issues of limited field computer resources and human variances respectively.

Two computers (the field computer and the audiologist's computer) are used for testing. The technical specifications of the field computer are listed in Section 3.3.2 and the specifications of the audiologist's computer (a Fujitsu Siemens AMILO M1450G laptop) are listed below:

- 1.7 GHz Intel Centrino Processor

- Microsoft Windows 7 Home Basic operating system
- 512 MB RAM
- Built in speakers and microphone
- ZIXA USB webcam

## 4.1 RESOURCE TESTING

Each of the processes which the Audiflector system incorporates, uses its own resources. The summation of these resources provide insight into the system requirements. Resources monitored over time will allow conclusions to be drawn as to when resource usage peaks and how resource usage can be flattened.

### 4.1.1 Objective

To quantify the usage of system resources by the Audiflector system when using video conferencing on the field computer with a wired network connection. These are physical resources which are limited and quantifiable. The resources of interest are battery usage, CPU usage, memory usage, disk activity, and network loading.

### 4.1.2 Apparatus

The very act of measurement disturbs the system when measuring a computer's system resources. This is due to measurement tools themselves requiring a share of the limited resources. Thus, the measurement has been conducted such that the system disturbance due to measurement is minimised. Microsoft Performance Monitor [40] (version 6.1.7600) was used for the monitoring of the CPU, memory, and hard disk drive. Total network statistics were also monitored using the Performance Monitor. Microsoft Network Monitor [41] was used to monitor network specifics. These two performance monitoring tools were chosen as they both have low resource footprints, are widely used in industry and have a large community support base. Together, these two applications provide all the performance monitoring information required for resource usage analysis of the Audiflector system.

Microsoft Performance Monitor allows the creation of Data Collector Sets which can be started and stopped as needed. Each set contains multiple Data Collectors which write data in a two dimensional matrix in a chosen file format. Each Data Collector can monitor a number of different performance counters. The “Audiflector Server” Data Collector Set is arranged as follows:

- CPU

- Process(Dropbox)\% Processor Time
- Process(DynDNS)\% Processor Time
- Process(eMOYO)\% Processor Time
- Process(Soundfit)\% Processor Time
- Process(VSee)\% Processor Time
- Process(Winflector)\% Processor Time

- Disk

- Process(Dropbox)\IO Data Bytes/sec
- Process(DynDNS)\IO Data Bytes/sec
- Process(eMOYO)\IO Data Bytes/sec
- Process(Soundfit)\IO Data Bytes/sec
- Process(VSee)\IO Data Bytes/sec
- Process(Winflector)\IO Data Bytes/sec

- Memory

- Process(Dropbox)\Working Set
- Process(DynDNS)\Working Set
- Process(eMOYO)\Working Set
- Process(Soundfit)\Working Set
- Process(VSee)\Working Set
- Process(Winflector)\Working Set

- Overall

Memory\Committed Bytes

Network Interface(Ethernet Adapter)\Bytes Total/sec <sup>1</sup>

Processor(Total)\% Processor Time

Physical Disk(Total)\Disk Bytes/sec

Each Data Collector Set creates a new folder named according to the date and time the test started. These folders each contain a comma delimited file for each Data Collector. These are imported into Matlab and organised into two dimensional matrices for manipulation.

All resources are monitored and recorded against time. Testing time lines have been categorised into four major phases as depicted in Figure 4.1 each of which encompass their own distinct events. These phases have been identified for the purposes of providing key points on the time line to assist in results analysis. Each test will have different corresponding phase durations which, if not taken into account will distort statistics. This is rectified by “stretching” time for each test such that the duration of all identical phases are identical for all tests. Data is then scaled as needed for graphical representation.

Phase one is devoted to the establishment of a communication channel and the briefing of the patient on the process by the audiologist. Phase two is characterised by the puretone testing and the setup of the puretone test. Phase three is devoted to the programming of the hearing aid and its fine tuning according to the patient’s needs. Phase four is characterised by the debriefing of the patient and the termination of the connection channel.

The final list of apparatus required for this testing is listed below:

- Audiflector system including all hardware and software except the 3G card and its software
- Wired internet connection for the field computer
- Microsoft Performance Monitor Software

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<sup>1</sup>Ethernet used in preference to 3G card to provide best possible network connection for resource testing

Event	Phase			
Communication channel established				
Introduction				
eMOTO opened				
Patient details captured/ Patient chosen				
Puretone Test setup				
Puretone Test				
Soundfit opened				
Soundfit closed				
Conclusion				
Communication channel destroyed				
Phase	1	2	3	4

Figure 4.1: Phase-event relationship  
(Created with Microsoft Excel 2007)

- Microsoft Network Monitor Software
- Remote audiologist’s computer with internet access

#### 4.1.3 Monitored Resources

Five tests were conducted while the usage of all resources of interest were monitored. Individual process resource usage is monitored to understand how the needs of each process change with time during the process of fitting a hearing aid. Total resource usage is also monitored to ascertain the system requirements for the field computer. For each monitored resource Equation 4.1 is true for two reasons:

$$\sum_{\text{Audifactor Processes}} \text{Resource}_{\text{Process}} < \sum_{\text{Computer Processes}} \text{Resource}_{\text{Process}} \quad (4.1)$$

1. The computer’s operating system uses its own resources
2. All other background services (anti-virus programs, printer spooler, etc.) use their own resources<sup>2</sup>

<sup>2</sup>The Resource Monitor and Network Monitor applications also use their own resources but as discussed

It is therefore necessary to monitor resource usage per process as well as overall. These resources are now discussed:

### *Battery Usage*

When the field computer is not connected to a mains power supply, the portable computer battery is the source of power not just for the computer, but also for the audiometer, hearing aid programmer, and 3G card. Additionally, processing intensive programs, such as eMOYO and video conferencing software, will reduce the expected lifespan of a single battery charge. Naturally then, it would be expected that the field computer manufacturer's estimated usage time on battery would be greater than the system's estimated usage time. Thus, testing is carried out to determine how long the battery can power the system. The battery provided with the Gigabyte Q2005 portable computer is a lithium ion 4400 mAh 6-cell battery. Gigabyte claims the battery will last for six hours under normal usage.

The Resource Monitor counter which monitors the rate of discharge of the battery is supposedly "DischargeRate" [40]. However, it was found that this counter was not compatible with the field computer's battery controller and therefore did not correctly monitor the discharge rate of the battery. No counters exist for quantifying the battery usage due to a particular process either. However, qualitative results are still provided.

### *CPU Usage*

CPU usage is quantified by analysing the time which the processor spends executing instructions. Two Resource Monitor counters were used to monitor CPU usage. "Process (% Processor Time)" is the percentage of elapsed time that all the threads of a particular process used the processor to execute instructions [40]. "Processor (% Processor Time)" is the percentage of elapsed time that all threads of all non-idle processes used the processor to execute instructions [40].

The actual number of operations a processor can complete per second is an issue of debate

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in Section 4.1.2 these programs were chosen as they had a small resource usage footprint and for the purposes of this testing this usage is ignored

which has not yet been settled [27, p40-41]. The performance of a CPU is not only dependant on how many floating point operations it can complete per second but also the complexity of the operations, idle time waiting for data to be fetched, number of processors, etc. As such, an accurate system requirement of the CPU type cannot be determined as it is beyond the scope of this text. Instead, an estimation is provided based on results.

### *Memory Usage*

Memory usage is quantified by analysing the amount of RAM currently storing data. Two Resource Monitor counters were used to monitor memory usage. "Process(Working Set)" is the set of memory pages, in bytes, touched recently by the threads in the process<sup>3</sup> [40]. Memory(Committed Bytes) is the amount of physical memory which has space reserved on the disk paging file [40].

### *Physical Disk Activity*

Disk activity is analysed by monitoring the amount of data which is transferred to and from the hard disk drive. Two Resource Monitor counters were used to monitor disk activity. "Process(IO Data Bytes/sec) is the rate at which the process is reading and writing bytes in input and output operations to the physical disk drive [40]. "Physical Disk(Disk Bytes/sec)" is the rate at which bytes are transferred to or from the disk during read and write operations [40].

### *Network Usage*

Network usage is concerned with the measurement of sent and received network traffic which is handled by the computer. The Microsoft Network Monitor was used to monitor traffic and the Windows Parser Profile which uses the Open Protocol Specifications Parser Library, was used to interpret and divide up the traffic according to process name. Network traffic generated by each process is comprised of all the packets which are either directed at the process or are sent by the process. Total network traffic for the field computer was monitored using the Performance Monitor counter "Network(Bytes/sec)".

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<sup>3</sup>This figure includes shared memory

This is the rate at which bytes are sent and received over a particular network adapter and includes framing characters [40].

Microsoft Network Monitor records packet against packet number which provides an easy approach to analysing packet sizes. However, this information is not useful when considering bandwidth requirements. For this reason packets are divided, according to their time (offset from the beginning of the capture), into bins each one second in duration. The summation of all packet sizes in each bin then represent the rate at which data was transmitted and received.

#### **4.1.4 Subjects**

Five subjects (one for each test) were used in the role of patients. None of the test subjects who were used in the position of patients had ever had their hearing tested but did not appear to suffer from any noticeable hearing loss. Additionally, they were all unfamiliar with the process of hearing aid fitting and the Audiflector system.

The author played the role of the audiologist as he was both familiar with the process of hearing aid fitting and with the Audiflector system. The hearing assistant was given a brief training session in the use of the Audiflector system from the point of view of the hearing assistant.

#### **4.1.5 Scenario**

Two computers, located in adjoining rooms such that the audiologist cannot interact with the patient or hearing assistant physically, were set up. The field equipment consisted of the entire Audiflector system as described in Section 3.3 but without the 3G modem providing internet access. The audiologist's computer was setup as listed in the introduction to this chapter. Both computers had no foreground programs running other than the Audiflector components, Microsoft Network Monitor, and Microsoft Performance Monitor on the field computer. The field computer was powered using a mains supply. The performance monitoring software were set to run as transparent background services such that the test subjects are unaware of their presence.

A wired Ethernet local area network was used to provide direct communication between

the computers while minimising the effects of network latency and maximising network bandwidth. This Ethernet connection also provided high speed internet connectivity to enable the use of the VSee video conferencing service. The network connections' performance criteria were tested before every test. Table C.1 and Table C.2 in Appendix C show these performance criteria.

The wired Ethernet connection was used on the field computer side in preference to the 3G modem to give the system the best network access available. This was done to use a network with characteristics as close as possible to ideal for determining the requirements of a network. It then follows that the 3G network card was not attached at the time of testing and the 3G network card drivers were not running, hence the drivers' resource usage is not monitored. However, it has been observed that the 3G network card driver's usage of all resources as negligible when compared to the resource usage of the other processes.

The default settings were used in all settings for all components except where specified. Video conferencing was used in preference to voice and text based chat so as to ascertain the maximum system requirements. 2 channel, 16 bit 44,1 kHz audio was recorded and transmitted from both computers and both computers played this audio through 24 bit 48 kHz stereo soundcard outputs. Video quality was set to 30 fps with a resolution of 480 x 480 pixels. As shown in Section 4.1.6, the network and resource monitoring was only started once all programs were started and all users were ready. eMOYO puretone test settings were set to automatic threshold testing, while testing only air conduction for both ears at 250, 500, 1000, 2000, 4000, and 8000 Hz. External noise was constantly monitored during the hearing loss diagnosis stage. Soundfit programmed a custom built hearing aid featuring a Rhythm SB3231 DSP. This was programmed automatically according to the audiogram constructed in eMOYO using the autofit function. Additionally, ten random parameters were customised to simulate the process of fine tuning the hearing aid.

#### 4.1.6 Procedure

Using the setup and settings specified in Section 4.1.5, the list below describes the testing procedure:

1. Set up Audiflector system
2. Connect field computer to internet
3. Start Performance Monitor
4. Start Network Monitor
5. Prepare the audiologist's computer
6. Audiologist, hearing assistant and patient test subjects briefed
7. Start capture of network interface card connecting field computer to the internet
8. Start the server test data collector set
9. Complete the fitting process
10. Stop the network capture
11. Stop the server test data collector set
12. Save the network capture

#### **4.1.7 Summary**

Resource testing attempts to quantify the usage of the Audiflector's limited resources. Overall usage and usage due to each component was monitored for CPU, memory, disk, and network usage. The exact testing conditions have been documented by identifying the subjects, scenario, and procedure used during the test. The results and their interpretation are located in Section 5.1.

## **4.2 USER ACCEPTANCE TESTING**

This test suite was designed to qualitatively investigate the level of user satisfaction the Audiflector system offers. A sample set of users are asked to use the system for its intended purpose. Feedback is obtained by questioning the users after use of the system. The testing investigated several aspects of the system which are quantified by assigning values to particular ratings (from worst to best). These results are then averaged out and presented in Section 5.2.

#### 4.2.1 Subjects

The system was simultaneously controlled by two people in distinctly different roles (an audiologist and a hearing assistant) while testing mock patients. All subjects were briefed before the start of the tests and were provided with a tutorial on how to operate the system before testing began. None of the mock test subjects who were used in the position of patients had ever had their hearing tested but did not appear to suffer from any noticeable hearing loss. Additionally, they were all unfamiliar with the process of hearing aid fitting and the Audiflector system.

Two 4<sup>th</sup> year Audiology students from the University of Cape Town were used in the roles of the audiologist and hearing assistant for each test with a total of four students. These students were all familiar with the general principle of hearing loss diagnosis and hearing aid fitting. All of the students were also familiar with the use of the Kuduwave 5000 and eMOYO 500 as the software for hearing loss diagnosis but none had previously used Soundfit as the software for programming hearing aids.

#### 4.2.2 Scenario

The testing scenario for user acceptance testing was largely identical to that of resource testing (see Section 4.1.5). However, user acceptance testing does not require the use of the Microsoft Performance Monitor or Microsoft Network Monitor applications but did require the use of the 3G network card and its software. Questionnaires, designed specifically for the testing of the Audiflector system, were used to gauge system usability and level of technical expertise required according to the test subjects in the roles of audiologists and hearing assistants. This questionnaire is included in Appendix D.

#### 4.2.3 Procedure

Using the setup and settings specified in Section 4.2.2, the list below describes the testing procedure:

1. Set up Audiflector system
2. Connect field computer to internet

3. Ready the audiologist's computer
4. Audiologist, hearing assistant and patient test subjects briefed
5. Complete the fitting process
6. Allow the test subjects in the roles of audiologist and hearing assistant to fill in questionnaires

#### **4.2.4 Summary**

User acceptance testing attempts to investigate the level of user satisfaction the Audiflector system offers. Questionnaires were used to gauge the level of satisfaction the test subjects felt with the use of the system. The exact testing conditions have been documented by identifying the subjects, scenario, and procedure used during the test. The results and their interpretation are located in Section 5.2.

### **4.3 UNIT TESTING**

Unit testing involves the use of a script which automates tests on various areas where

- the testing framework can automate the execution of sections of code
- outputs are predictably based on inputs

The only part of the system for which both these conditions hold true is the data transfer software (see Section 3.3.10). This software was written in the Delphi programming language.

Test adequacy criteria determine the stopping condition for unit testing. Closely linked to testing adequacy criteria is the testing techniques chosen. Software testing is heuristic in nature in that it lacks a theoretical base. For this reason an adequacy criteria can, at best, be specified in terms of vague parameters. A number of unit testing techniques exist, each of which have their own strengths and particular purpose. Two of the more common testing techniques are now briefly discussed:

Error seeding involves the substitution of input data with data which is outside of the accepted input domain (pikes). This testing involves not only checking the success rate of these pikes being caught by the software but also how the software handles the unexpected input. Mutation testing involves comparing the output of function  $f$  with the output of function  $f'$  given the same input.  $f'$  is identical to  $f$  except for the substitution of a single constant or operator.

Since the software was designed purely to fetch data presented to it by a program and store it in an existing database, the most useful testing technique in this case is error seeding. This involves checking if the program correctly accepts or rejects boundary condition inputs. The stopping condition was defined as the 100 % success rate of successfully storing acceptable data and rejecting pikes.

The hearing aid fitting software, Soundfit, has a propriety database purpose designed for Soundfit. The schema for this database is shown in Figure 3.8. This schema shows there are 28 variables which can contain data. All 28 of these variables were tested.

The first test battery tested a number of different conditions to check that acceptable boundary data is captured correctly and unacceptable boundary data is not captured and that exceptions are thrown. This includes the insertion of data into mismatched field types (e.g.: integer data inserted into date fields) as shown in Figure 4.2 for a general "Date-Time" variable. Some data types are partially acceptable (e.g.: DateTime instances on or before the current date time) and are validated based upon their value.

The second battery tested the maintenance of the foreign key in the clinical data table (clientdata\_cds) by establishing under what conditions the foreign key did not correctly relate the patient information entry (in the newclient\_cds table) to the clinical data entry (in the clientdata\_cds table).

#### 4.3.1 Objective

To reduce the number of errors which exist in the code and thereby increase the reliability of the code. Unit testing also provides an automated way for the basic code structure to be tested as it is maintained.

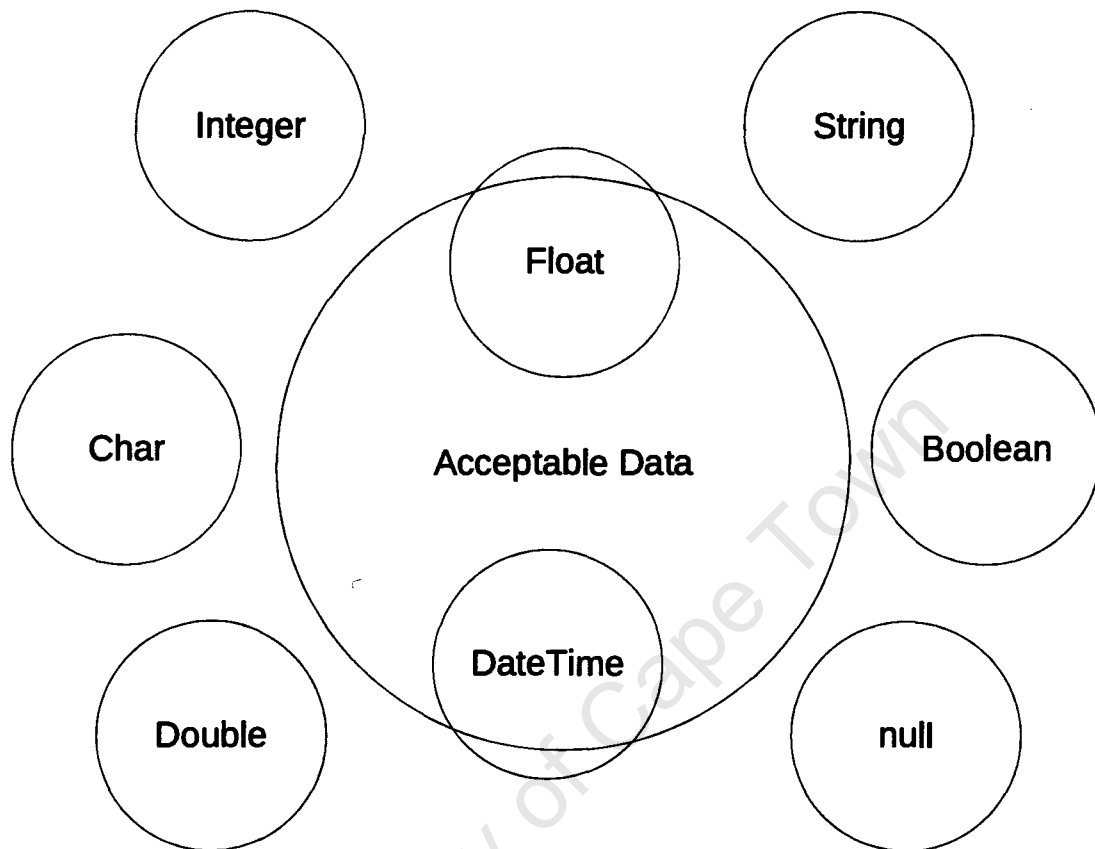


Figure 4.2: General datetime variable data Venn diagram  
(Created with Microsoft Office Visio 2007)

#### 4.3.2 Apparatus

The Integrated Development Environment (IDE) chosen for the compilation of the Data Transfer Software was Delphi 6 (see Section 3.3.10). The DUnit unit testing framework is one package which allows the automated testing of Delphi classes. It integrates seamlessly with the Delphi 6 IDE and can perform all the required testing procedures. It is for these reasons that the DUnit unit testing framework has been chosen for use in unit testing.

The final list of apparatus required for this testing is listed below:

- Computer

- Delphi 6 (IDE)
- DUnit unit testing framework
- Data Transfer Software

### 4.3.3 Procedure

Unit testing differs from other testing types in that it does not require user interaction or even the use of any system components (excepting the Data Transfer Software). Each time the data transfer software unit is built from its source code the unit testing procedure can be executed. Results from each test battery are presented when the test has completed. The source code can then be changed as needed to improve the source code to the point that it reaches the stopping condition of 100 % acceptance of true data and rejection of pikes.

### 4.3.4 Summary

Unit testing has provided the means for testing code and providing an automated means for the code to be error tested each time the software is built from its source code. The apparatus and testing procedure have been documented with all the required detail for reconstructing the testing. Section 5.3 contains the results of the testing.

## 4.4 COMPARATIVE TESTING

Phase one, three, and four as shown in Figure 4.1 involve large amounts of patient-audiologist interaction and as such are subject to many of the uncontrolled sources of variability listed in Section 4. Phase three is unique in that a large part of the process is controlled by an automated algorithm which determines a patient's hearing threshold. This is only subject to the variability caused by the patient's level of hearing loss. Additionally, the outcome of phase three provides quantifiable results through the resulting audiogram. It is for these reasons that phase three is the only phase which will yield any meaningful comparative testing results. The resulting situation is that while the entire hearing aid fitting process is tested during comparative testing (for the purposes of comparing event durations) only the audiogram produced in phase two is used for comparison

of results.

The design of the Audiflector system is one where the execution of the hearing loss diagnosis application (eMOYO) is run locally on the field computer with only the interface being transferred to the audiologist's computer. Ideally then, remote testing should yield not only identical results but also testing durations should be identical, when compared to local testing. These two aspects are the subjects of investigation in this set of testing. Local tests were conducted using eMOYO over one computer as per the conventional method of conducting hearing loss diagnosis. Remote tests were conducted using the hearing loss diagnosis component of the Audiflector system (i.e.: the eMOYO interface is accessed on the audiologist's computer and communication is done by means of VSee video conferencing).

Theoretically, the standard deviation and mean in remote test results should be precisely the same when compared to the standard deviation and mean of local test results, given a large enough sample. If this is not the case the cause and magnitude of the differences must be identified. Ideally remote and local testing durations should be equal but realistically this is unlikely to be achieved with current technology. Testing durations are compared to increase the insight into whether remote fitting does indeed reduce the reliance on audiologists. Recommendations can then be made for further work on the system.

#### **4.4.1 Objective**

To investigate how hearing loss diagnosis results are affected by remote execution in comparison to those of local testing results.

#### **4.4.2 Apparatus**

The final list of apparatus required for this testing is listed below:

- Audiflector system including all hardware and software
- Field computer with wired internet connection
- Online Stopwatch application

- Remote audiologist's computer with internet access

#### 4.4.3 Subjects

Five subjects (one for each test) were used in the role of patients. None of the test subjects who were used in the position of patients had ever had their hearing tested but did not appear to suffer from any noticeable hearing loss. Additionally, they were all unfamiliar with the process of hearing aid fitting and the Audiflector system.

The author played the role of the audiologist as he was both familiar with the process of hearing aid fitting and with the Audiflector system. The hearing assistant was given a brief training session in the use of the Audiflector system from the point of view of the hearing assistant.

#### 4.4.4 Scenario

The testing scenario for comparative testing was largely identical to that of resource testing (see Section 4.1.5). Comparative testing does not require the use of the Microsoft Performance Monitor or Microsoft Network Monitor applications but does make use of a stopwatch. The stopwatch application chosen for use is a flash based online application called Online Stopwatch [51].

#### 4.4.5 Procedure

Using the setup and settings specified in Section 4.1.5, the list below describes the testing procedure:

1. Audiflector system set up
2. Connect field computer to internet
3. Ready the audiologist's computer
4. Test subject is briefed
5. Start timer

6. Remote testing procedure started
7. Note split times at the end of each event
8. Stop timer
9. Start timer
10. Local testing procedure started
11. Note split times at the end of each event
12. Stop timer
13. Repeat last four steps

Each patient was tested three times: Two local tests were used to create control results. These control results show the mean and standard deviation experienced by eMOYO for each test patient when tested locally. The mean of these two results were then used as a standard against which the remote testing results could be compared to.

#### **4.4.6 Summary**

Comparative testing attempts to quantify the difference in results and testing duration when remote testing is compared to local testing. Puretone audiometry results and the duration of each event in the fitting process was recorded. The exact testing conditions have been documented by identifying the subjects, scenario, and procedure used during the test. The results and their interpretation are located in Section 5.4.

#### **4.5 SUMMARY**

Four distinctly different testing suites have been created each with the purpose of assessing a particular issue: Resource testing quantifies how each component uses the field computer's resources and what the field computer's system requirements are. User acceptance testing gauges the user friendliness and interface intuitiveness of the system from the point of view of the audiologist and hearing assistant. Unit testing provides an automated means for testing and maintaining the source code. Finally, comparative testing

compares the reliability and usability of remote fitting sessions in comparison to local fitting sessions by analysing their results and durations.

The results of these four tests will provide valuable insight into the performance of the Audiflector system and remote hearing aid fitting in general.

University of Cape Town

## RESULTS AND INTERPRETATION

The purpose of this chapter is to present the results obtained from the testing procedures documented in the previous chapter. Each test suite presented in the previous chapter has a dedicated section which presents the results from the test suite with noteworthy points highlighted. Conclusions are drawn based on these results. The test suites covered in this chapter are resource testing, user acceptance testing, unit testing, and comparative testing. Appendix C provides an overview of the network which the computers were connected to in an attempt to provide a reproducible testing environment.

### 5.1 RESOURCE TESTING

This section presents the results of the testing procedure which were documented in Section 4.1. All subsections follow a common pattern: Firstly, the usage of the resource in question is analysed on an individual process level. The total usage of the resource is then analysed for system requirements. Finally, conclusions and recommendations are made based on the evidence presented for each resource.

#### 5.1.1 Battery Usage

As discussed in Section 4.1.3, battery usage could not be monitored using resource counters in Microsoft Performance Monitor. However, the test field computer was tested with only the field computer's battery supplying power to the entire system. It was found that the test field computer did not have adequate system resources when using the Audiflector system to conduct a video based fitting session without cripplingly lengthy delays both in

the video conferencing software and the presentation of the remotely executed audiometer software. However, when the system only used voice or text means of communication, it was found that the field computer did have adequate system resources.

The Microsoft Windows 7 starter operating system default power management settings adjust the maximum permissible usage of system resources in an attempt to enhance the life of the field computer's battery on one charge. If it were possible to override the default power management settings theoretically it would be possible to run the system with the field computer's battery as the only power supply, albeit for an expectedly short duration. The actual number of fittings which could be completed on one charge is beyond the scope of this text as it does not involve the use of video as the communication means.

### 5.1.2 CPU Usage

Figure 5.1 shows the proportion of processing time for each process as a percentage. Processor time is the percentage of elapsed time that all the threads of a particular process used a particular processor to execute instructions [40]. The test field computer has two parallel hyper threaded processors resulting in a theoretical limit of 400 % for each process [42].

By a margin of 136 % (on average) VSee uses the most processing time of all the processes. The second most processing intensive program was eMOYO with an average of 34.3 % processor usage. eMOYO functions as the audiometer driver, sends and receives signals to and from the audiometer, and builds the patient's audiogram. Not surprisingly then, processor usage due to eMOYO is significant. The point at which eMOYO is started is easily identified as phase two begins when eMOYO is started. Processor usage also shows how eMOYO is then initialised and is relatively idle while patient information is captured. Processor usage then remains high while the hearing loss diagnosis and hearing aid programming processes run.

The three minor processes, Dropbox, DynDNS, and Winflexor remain consistently small, averaging at a total of 1.13 % processor usage over the entire procedure. Dropbox is responsible for establishing a secure connection to the Dropbox server, and uploading the changes in the eMOYO database which, while frequent, are small and therefore require

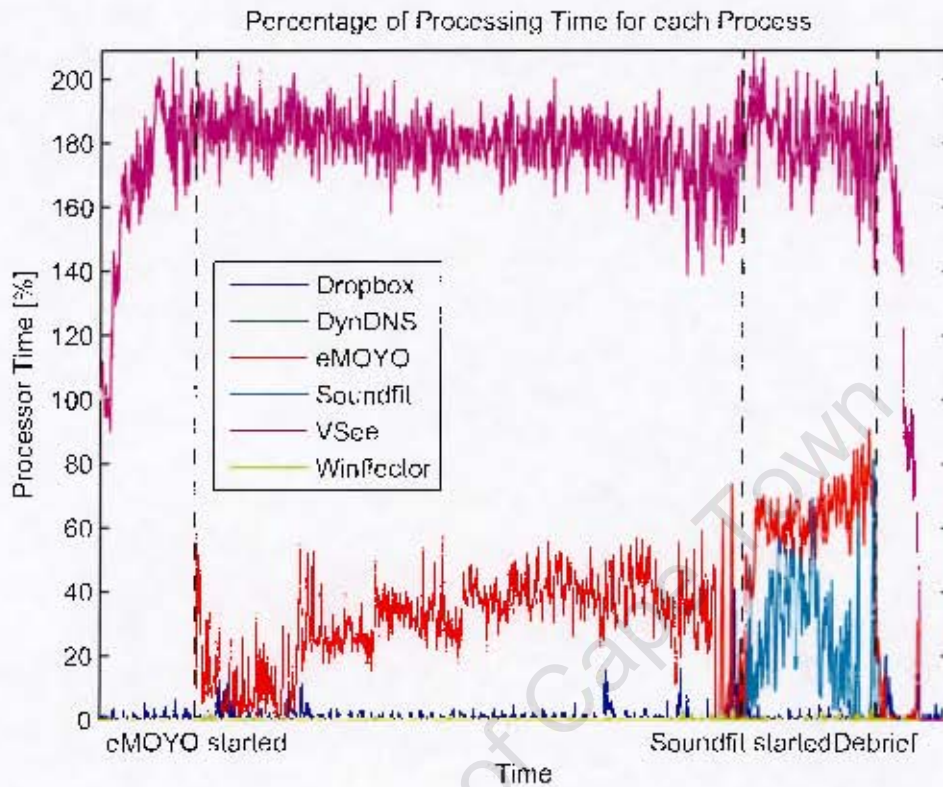


Figure 5.1: CPU usage of individual processes  
(Created with MathWorks Matlab 7.11.0)

very little processing. The WinFector process is responsible for only running the server which involves authenticating user access, passing mouse and keyboard events to eMOYO and Soundfit, and updating the WinFector client (running on the audiologist's computer) with changes in the graphical user interfaces of eMOYO and Soundfit. These are small tasks requiring very little processing power. Finally, DynDNS, the DNS update client is responsible for periodically checking the field computer's IP address and sending a notification to the DNS servers in the event of any IP address change. This process requires very little processing and not surprisingly, requires the least amount of processing power.

Total processor usage is calculated as follows:

$$\text{Processor Usage} = \frac{1}{\text{processor no.}} \sum^{\text{processors}} (100 - \text{idle time \%}_{\text{processor}}) \quad (5.1)$$

Using this formula Figure 5.2 is created and shows the total processor usage divided by the number of processors (4 in this case) of the field computer over the entire fitting session. The region of highest CPU usage occurred predominantly during the hearing aid programming which suggests the third phase is the most processing intensive phase. This can be attributed to the fact that phase three is the only phase in which all six processes are being executed. If eMOYO were to be closed once it had transferred data to Soundfit, processing power requirements could be reduced. However, the reduction would be insignificant as phase two has similar processing requirements and these are established almost entirely by the requirements of eMOYO.

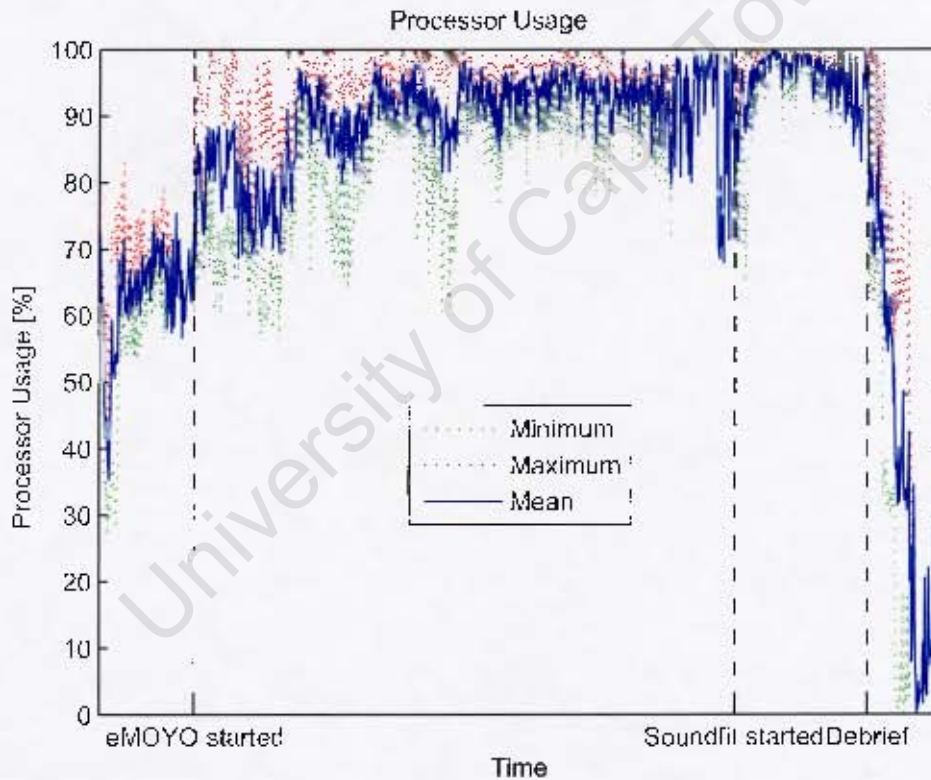


Figure 5.2: Overall CPU usage  
(Created with MathWorks Matlab 7.11.0)

The maximum of the sum of processor time percentages for all Audiflector processes is 301 % (75 % average processor time). This suggests that the operating system and all

other background processes require an additional 25 % processing power over and above what is needed by the Audiflector processes.

Based on the results shown in Figure 5.2, the conclusion that can be drawn is that the Audiflector system can work satisfactorily when using the field computer's processor. If a slower processor were to be used or one with less parallel processors, the system would simply run slower to the point that the system is unusable.

### 5.1.3 Memory Usage

Figure 5.3 shows the physical memory used by each Audiflector process. The usage of physical memory is determined by measuring the set of memory pages, in bytes, recently read or written to or from by the threads in the process and includes memory shared with other processes [40].

Again VSee is the largest user of this particular resource with a mean of 85.7 MB. Drop-box is the next highest consumer process with an average of 40.2 MB. Memory usage by eMOYO is a lot more erratic as eMOYO requires more memory during hearing loss diagnosis and hearing aid programming than while the patient's details are being captured and eMOYO is idle. All other processes (DynDNS, Soundfit, and Winflector) contribute a mean total of 16.1 MB.

Figure 5.4 shows the physical committed memory which has space reserved on the disk paging file [40]. This is a summation of the usage of physical memory by all processes including those of the Audiflector system and the operating system.

The maximum memory usage of all Audiflector processes combined is 180 MB. This is in contrast to the maximum memory usage of all computer processes at 1334 MB. This leads to the conclusion that the Audiflector processes themselves actually require very little physical memory in comparison to that of the operating system and its background processes.

Based on the results shown in Figure 5.4 we can draw the conclusion that the field computer's physical memory requirement is to have at least 1334 MB of RAM (Random Access Memory).

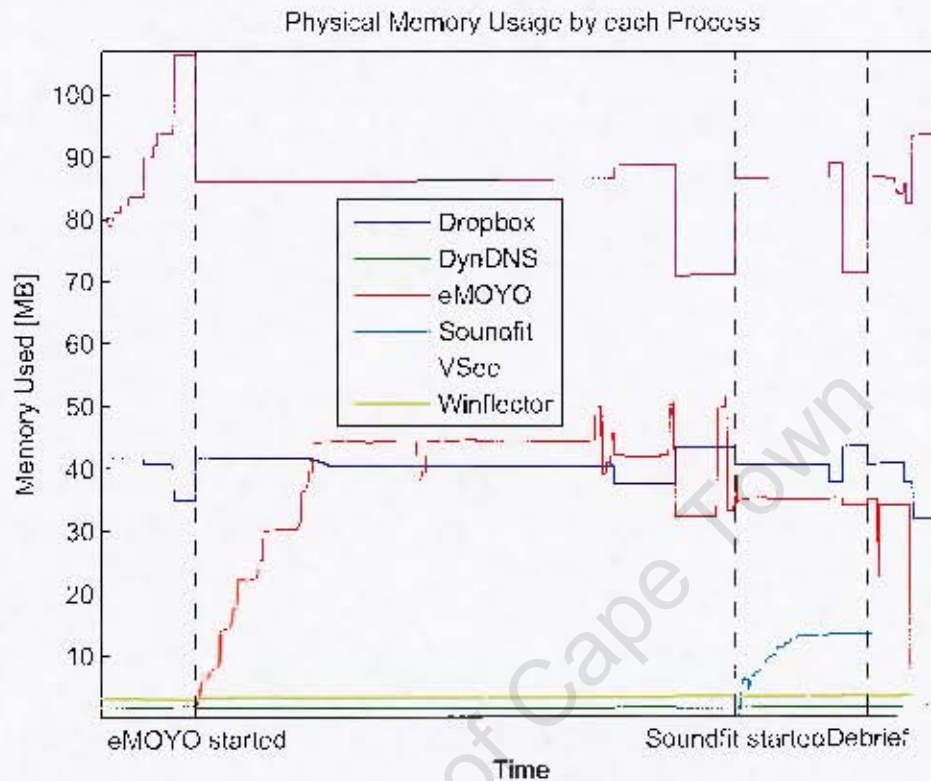


Figure 5.3: Memory usage of individual processes  
(Created with MathWorks Matlab 7.11.0)

#### 5.1.4 Physical Disk Activity

Figure 5.5 shows the hard disk activity due to each Audiflector process. The hard disk activity shown is the rate at which each process is reading and writing bytes in input and output operations to the physical disk drive [40].

Dropbox is by far the largest user of the hard disk with a mean transfer rate of 5.01 kB/s. The event which is identifiable from Figure 5.5 with the rise of the transfer rate due to the Dropbox process is the conclusion of eMOYO writing data to the database and Dropbox then reading the disk and updating the server with the new contents of the database. This is the period with the highest disk usage by the Audiflector processes combined with a transfer rate of 216 kB/s.

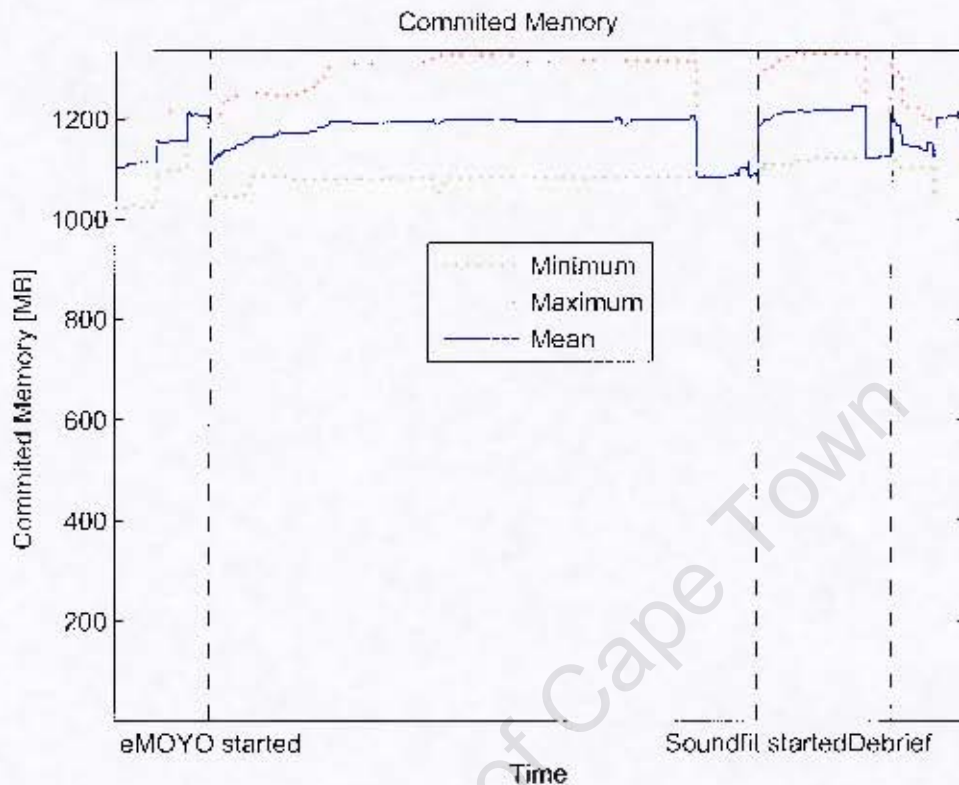


Figure 5.4: Overall memory usage  
(Created with MathWorks Matlab 7.11.0)

Figure 5.6 shows the hard disk activity due to all processes running on the field computer. It is the rate at which bytes are transferred to or from the hard disk during read and write operations [40]. The mean disk transfer rate was very low (195 kB/s) compared to the various bursts. However, at 5.02 kB/s the sum of mean disk activity due to all the Audiflector processes is a mere 2.57 % of the overall disk usage.

Figure 5.6 shows a number of significant spikes well above the mean (the maximum transfer rate recorded was 30.5 MB/s). However, even at this rate, no special high speed physical disks are required for the field computer as most modern hard disks can handle disk transfer rates in excess of 300 MB/s [4].

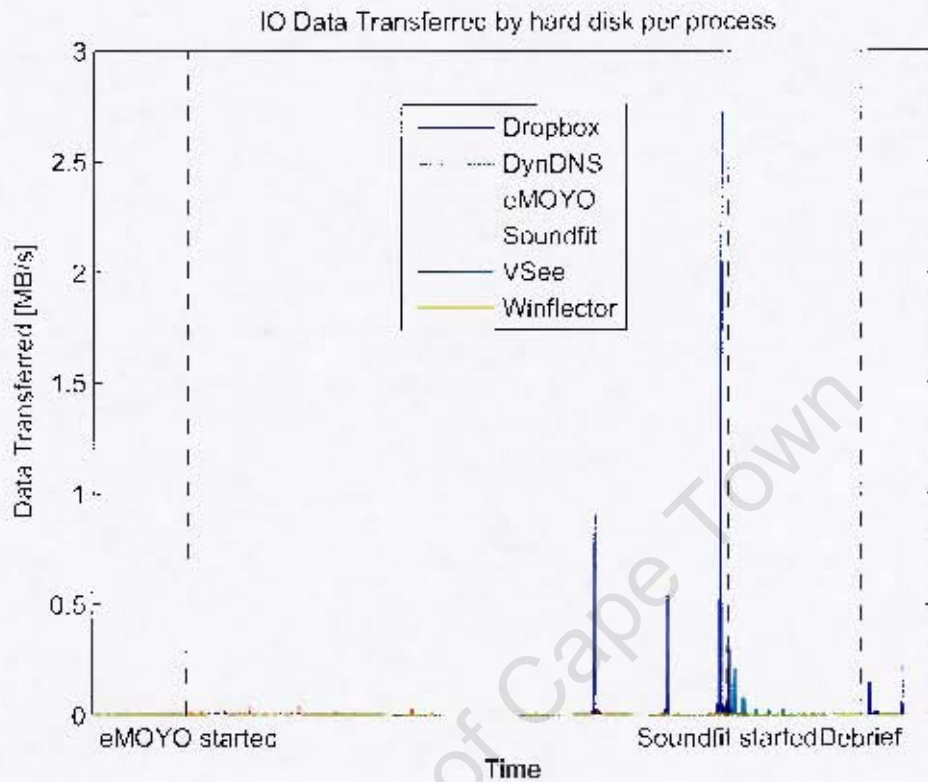


Figure 5.5: Physical disk usage of individual processes  
(Created with MathWorks Matlab 7.11.0)

### 5.1.5 Network Activity

Network traffic generated by each process is comprised of all the packets which are either directed at the process or are sent by the process. Packets have been binned in one second intervals and the summation of all packet sizes in each bin is that bin's size. Figure 5.7 shows the network transfer rate due to each process by plotting bin against bin size.

Out of the six Audiflector processes which were monitored during testing, only four processes opened network ports for data transmission. While the two processes eMOYO and Soundfit are accessed remotely from the audiologist's computer it is not eMOYO and Soundfit themselves which are creating this link. This is done by Winflector.

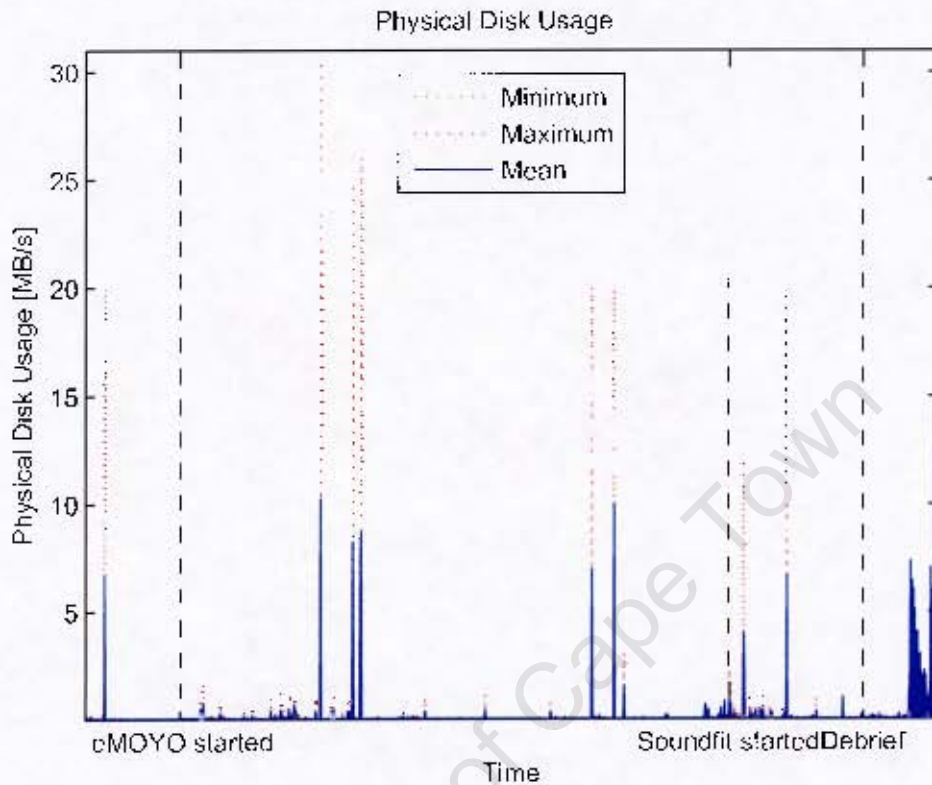


Figure 5.6: Overall physical disk usage  
(Created with MathWorks Matlab 7.11.0)

Once again VSee is responsible for the majority of the network traffic with a mean transfer rate of 50.3 kB/s. Winflexor has a comparatively small usage of the network with a mean transfer rate of 2.01 kB/s. Dropbox and DynDNS processes contribute a comparatively insignificant flow of data with a mean transfer rate of 226 B/s and 2.00 B/s respectively.

Figure 5.8 shows the computer's total network activity due to all processes running on the field computer. This is the rate at which bytes are sent and received over a particular network adapter and includes framing characters [40]. The mean network transfer rate for all traffic was 51.6 kB/s. The mean of the sum of all network traffic due to Audiflector processes was 50.8 kB/s which represents 98.4 % of the mean level of network traffic. The last 819 B/s are accounted for by the Microsoft Windows background processes "svchost" and "System" and unrecognised processes (according to the Open Protocol Specifications

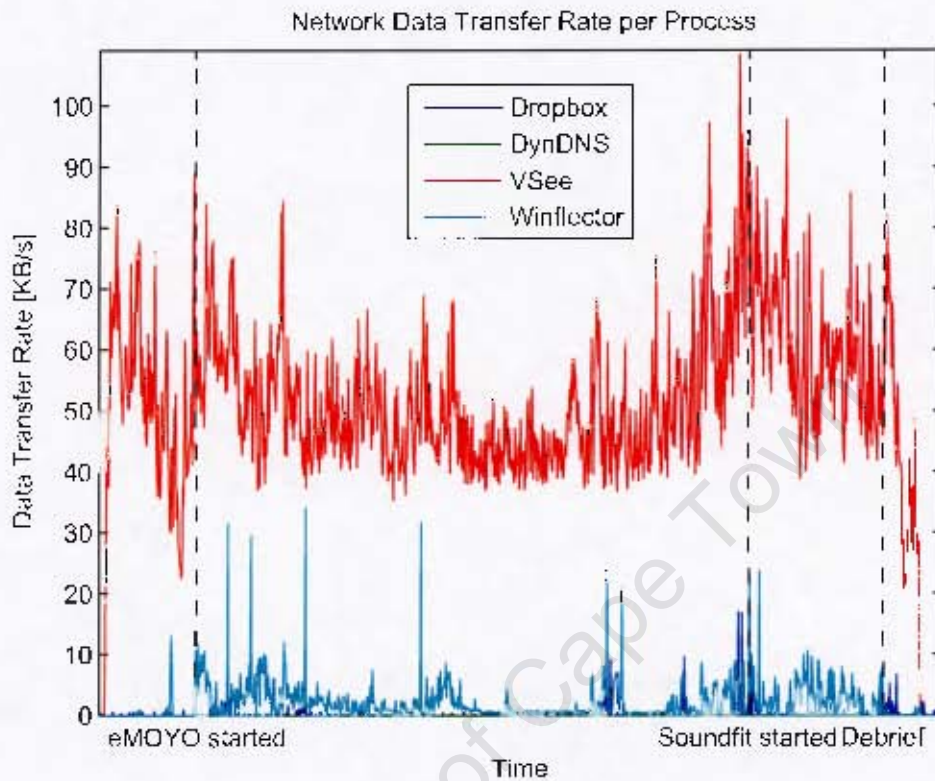


Figure 5.7: Network data transfer rate of individual processes  
(Created with MathWorks Matlab 7.11.0)

Parser Library).

Appendix C provides an overview of the network statistics which the field computer was connected to. As the test network characteristics were far in excess of the system's requirements, it can be assumed that the network traffic generated was far less than the network can be expected to handle. The critical figure in determining the required network bandwidth is the maximum network transfer rate experienced by the network due to all processes. This number is 187 kB/s. Theoretically then, the system should work with sufficiently good quality video and sound (see Section 4.1.5 for exact figures), and provide remote application execution with imperceptible delay when the network connection has a bandwidth of 187 kB/s or greater. However, due to the nature of networks, as discussed in Section 2.3.3 this is not the case. The reasons behind this are beyond the

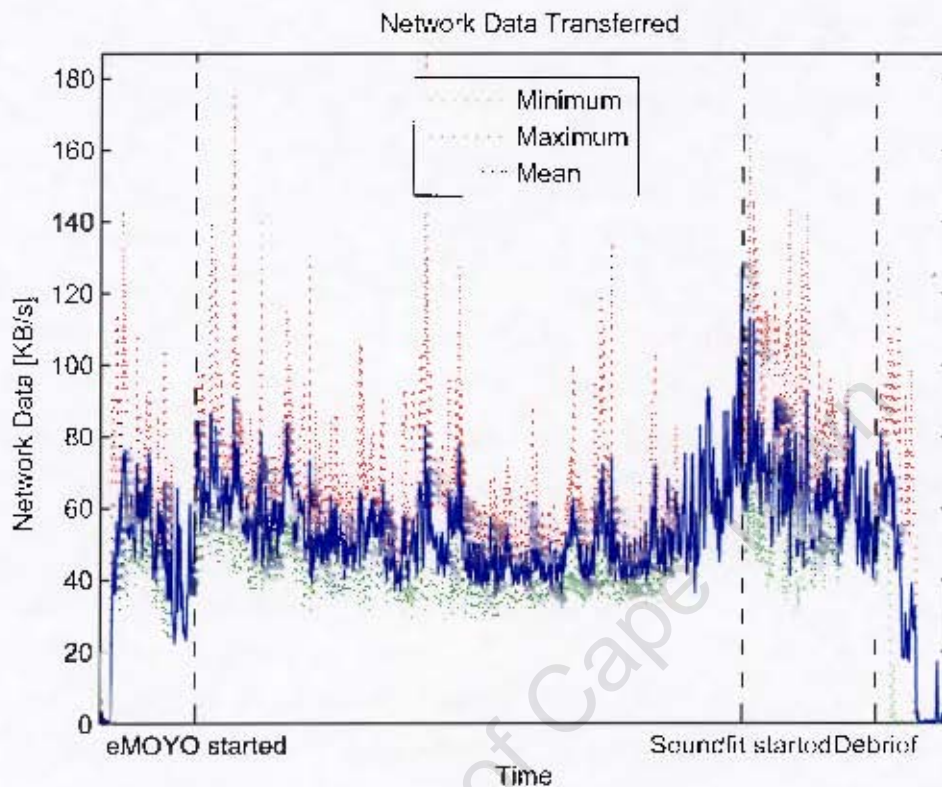


Figure 5.8: Overall network data transfer rate  
(Created with MathWorks Matlab 7.11.0)

scope of this text. What can be said is that the Huawei HSDPA E220 modem provided by Vodacom should have adequate bandwidth for using the Audiflector system with video conferencing when in an area with 3G coverage. This is stated as 3G promises data speeds of 14 Mbps [38, p579-580] which is far greater than the requirement of 120 % of 187 kB/s (1.80 Mbps).

Total network usage averaged at 63.5 MB. If network access is provided by a clinic's wired network or the like, this number is fairly insignificant. However, if network access is provided through the use of the system's 3G modem the number becomes more significant. The final data cost is then dependant on the data package chosen for use.

### 5.1.6 Summary

Video conferencing is a graphic processing intensive application type [33, p110-111] and therefore requires a large amount of processing time, memory, and of course network bandwidth to send the data. Should it be decided that the preferred means of communication is voice, it is assumed, based on the fact that video chat is a combination of both video and voice and that video is resource intensive, that resource usage will decrease significantly. Should text communication be chosen, VSee's resource requirements would fall even further, possibly to levels around that of Dropbox's resource requirements, and allow the field computer to run without a mains power supply. The margin by which the requirements would be reduced is beyond the scope of this text.

The Dropbox process is not an essential process to the working of the Audiflector system. It is used simply to maintain a remotely accessible database and provide an online backup service. If text based chat were used in preference to video conferencing it is possible that network usage due to Dropbox will become significant when compared to network utilisation by the other processes. If network bandwidth is restricted the Dropbox service could be run after the completion of the hearing aid fitting process. If data costs are excessive, this feature could be removed completely but with the drawback of vulnerable data which is also not remotely accessible.

The system requirements for the field computer have been discussed in each section. The results are that the field computer has the following minimum resource requirements if the intended means of communication is video:

- Atom 1.50 GHz dual core 32 bit processor (suggested)
- 1334 MB RAM
- Hard disk drive with I/O data transfer rate of 195 KB/s
- Mobile modem and network with actual bandwidth of 1.8 Mbps

This list of tested resources is by no means an exhaustive one. It is meant as a guide for the approximate system requirements of the field computer for the Audiflector system.

## 5.2 USER ACCEPTANCE TESTING

This section presents the results of the testing procedure which was documented in Section 4.2. This testing was designed to qualitatively investigate the level of user satisfaction the Audiflector system offers.

Tables 5.1 and 5.2 show the average results for the ratings given by test subjects, from both the audiologist and hearing assistant roles. The scale used is from 1 (worst) to 5 (best) for each aspect respectively.

Table 5.1: Audiologists' user acceptance ratings

Aspect	Rating
Interface Simplicity	5
Interface Intuitiveness	3
Video Call Quality	4
Video Call Delay	4
Technical Expertise Required	3

Interface simplicity was rated as being extremely simple yet the interface's intuitiveness was rated as average. This suggests that while the system is simple enough to use from the audiologist's point of view, the overall opinion is that the interface needs a more guiding approach. While this could and probably would be rectified by additional training, steps could be taken to ensure a more "obvious" flow of tasks which the audiologist is required to execute.

Video call quality was rated as being good. This simply means the VSee video chat client makes excellent use of available bandwidth when a high speed network is available. This quality rating will degrade proportionally to the network latency and bandwidth restrictions.

The last aspect which was investigated was that of the technical expertise required to operate the Audiflector system. This aspect was given 3/5 which suggests the level of technical expertise required is not menial. This was largely caused by the need for specialist technical knowledge not normally required in audiology (e.g.: the computer's microphone,

speakers, and webcam all need to be correctly connected for the system to work). However, with current technological limitations this is unavoidable.

Table 5.2: Hearing assistants' user acceptance ratings

Aspect	Rating
Interface Simplicity	2
Interface Intuitiveness	2
Video Call Quality	4
Video Call Delay	4
Technical Expertise Required	5

Interface simplicity and intuitiveness was given a low average rating. This was likely caused by the sheer number of hardware components which is required for the system to work correctly. The set up of these components are not trivial either. Given current technological limitations, only small changes can be made to simplify this situation.

Again video call quality was rated as being good. This means that it is likely both the audiologist and the hearing assistant were experiencing the same video quality, as would be expected.

Finally, the level of technical expertise required to operate the system from the hearing assistant's point of view was rated as excellent. The resulting situation is that while the field technologist's setup and use of the system is not intuitive, it does not require a high level of technical expertise. This is a critical requirement of the Audiflector system: A hearing assistant who does not require complex technical training in the use of computers or in the field of Audiology.

### 5.3 UNIT TESTING

Section 4.3 discussed the means of unit testing for the data transfer software. Two test batteries were designed with the objective of obtaining a 100 % success rate of successfully storing acceptable data and rejecting pikes.

A total of 35 tests comprising of 98 comparisons formed the two test batteries. A full

set of tests (both batteries) ran over an average duration of 32 seconds on the computer described as the audiologist's computer in Section 4.

As mentioned in Section 4.3, software testing is highly heuristic in nature and test adequacy criteria is no better. However, in an attempt to provide a quantifiable standard of testing, the stopping condition of a 100 % success rate was implemented. This stopping condition was attained.

In total, all tests covered an estimated 17 % of the code. Such low code coverage is attributed to the large amount of existing code automatically created on creation of an ActiveX project. Additionally, a large portion of the code is devoted to the customisation of the user interface and how the audiometer software graphically interfaces with the hearing aid programming software.

#### 5.4 COMPARATIVE TESTING

This section presents the results of the testing procedure which was documented in Section 4.4. This testing investigated two distinct areas of interest and are discussed separately. First is the comparison of the variability of results between local and remote testing. Second is the comparison of testing duration between local and remote tests.

##### 5.4.1 Puretone Testing Result Variability

Figure 5.9 shows the variability in puretone testing results experienced by both local and remote tests<sup>1</sup>.

Average standard deviation for local tests came to 1.96. Average standard deviation of remote test results from their corresponding local test results was 1.97. The result is that remote tests had a standard deviation of 0.598 % greater than that of local tests. This shows a 99.4 % similarity in the overall standard deviation between results.

It was noted that as the number of tests increased the standard deviation at each recorded

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<sup>1</sup>Local test results are included to provide a reference. This reference shows the variability which can be expected under normal test conditions when using the Kuduwave 5000 clinical audiometer and the eMOYO 500 health operating system.

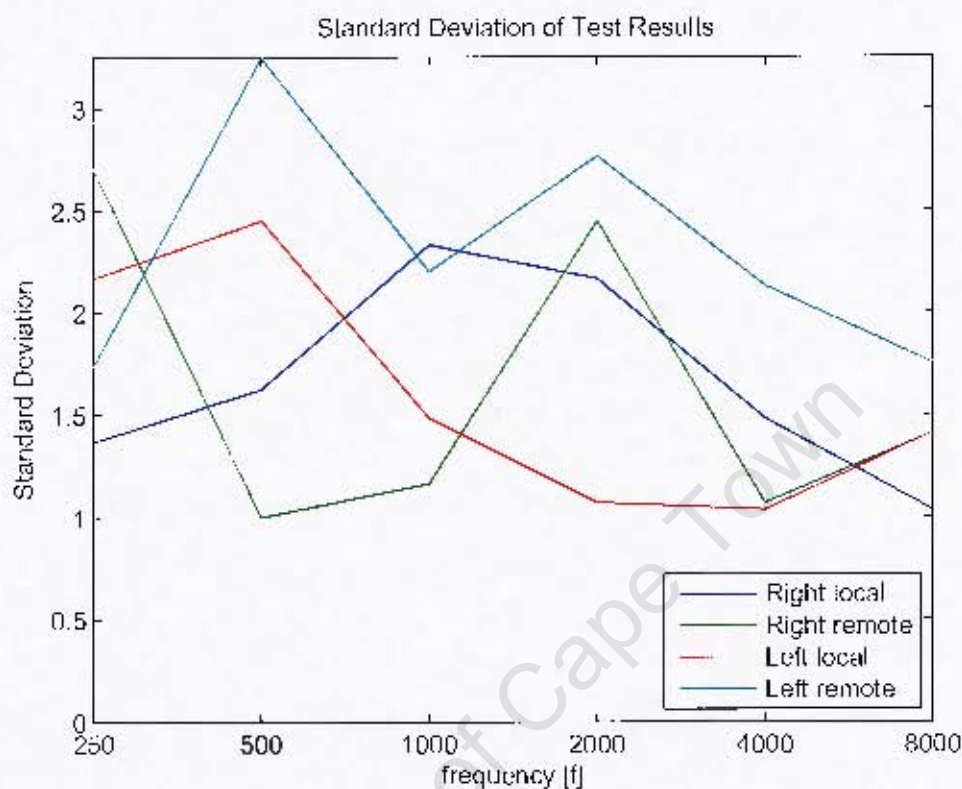


Figure 5.9: Local and remote hearing loss diagnosis result variability  
(Created with MathWorks Matlab 7.11.0)

frequency dropped. This is expected as a greater number of tests will reduce the importance of spikes in variability due to patient error. The limited number of tests which have been conducted do not provide sufficient data to establish a reliable source of information for variability in hearing loss diagnosis test results. However, what can be determined from the results is that the addition of the remote element in hearing loss diagnosis does not cause any significant difference in patient hearing loss results.

#### 5.4.2 Result Duration

Figure 5.10 shows the cumulative duration of each event located in Figure 4.1. For a large majority of the event durations the gradient of the remote tests are steeper than that of the local tests. This implies that the duration of the majority of events involved in hearing aid

fitting take longer when carried out remotely than in person. Each event is isolated and those that contribute to this difference are discussed.

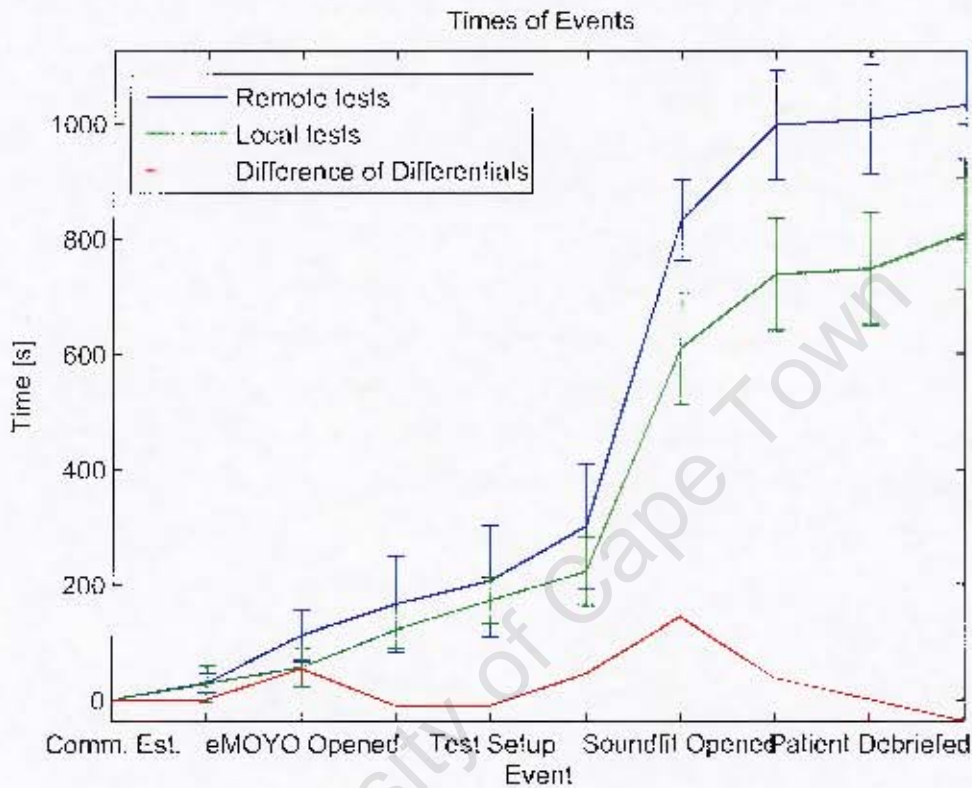


Figure 5.10: Cumulative test durations showing significant events  
(Created with MathWorks Matlab 7.11.0)

With current technology it must be accepted that increased durations will affect remote hearing aid fitting. However, it is possible that training in the field of remote hearing aid fitting and in particular the Audiflector system could reduce the percentage increase in duration caused by remote fitting over local fitting.

The line marked as “Difference of Differentials” shows the magnitude of duration difference for each event. Essentially this shows where the remote test fittings lose time over the local test fittings. The event which contributes the highest duration difference is that of puretone testing. Remote usage of eMOYO is, on average, 143 s slower than eMOYO controlled locally due to the latency and bandwidth restrictions of the network. The sec-

ond largest contributing event to duration difference is the process of capturing patient information with a mean difference of 54.3 s. This can be attributed to the extra layer in the communication stack (visual and audio-computer-visual and audio instead of visual and audio-visual and audio). The mean duration difference of 44.7 s from the test setup event can be explained using the same explanation as that of the puretone testing-network latency and bandwidth restrictions. The last event which causes a major time difference (mean of 37.3 s) is that of programming the hearing aid (situated between the Soundfit opened and Soundfit closed events). Overall, remote fitting had an average duration of 223 s or 27.6 % longer than local fitting. Even with this extended duration the face time the patient requires with the audiologist is still significantly lower than the face time required during local hearing aid fitting. Given that hearing aid fitting costs are directly related to face time with the audiologist, this proves that the remote element can significantly reduce the reliance on the audiologist and therefore the cost of fitting a hearing aid.

#### 5.4.3 Summary

The effects on hearing loss diagnosis and its results were investigated by comparing them to that of local hearing loss diagnosis. It was found that the level of variability experienced when conducting remote hearing loss diagnosis is comparable to that of the variability experienced when conducting local hearing loss diagnosis. This was tested by comparing results of local and remote tests conducted under identical conditions on the same patients. The conclusion that can be drawn from this testing is that the remote element does not affect the results of hearing loss diagnosis by a significant margin.

The relative duration of remote hearing aid fitting was tested and compared to results for that of local hearing aid fitting. The findings are that the duration of fitting a hearing aid remotely is significantly longer than the duration of fitting a hearing aid locally. This was tested by recording times at which significant milestones were reached while the process of fitting a hearing aid was carried out both remotely and locally under identical conditions on the same patients. The process of remote fitting is an average of 27.6 % longer than local fitting. The reasons for this extended duration were identified. Despite this extended duration, the reliance on the audiologist is reduced and therefore the costs

related to audiologist reliance are also reduced.

## **5.5 SUMMARY**

This chapter has presented the results obtained from the testing procedures documented in the previous chapter. Each test suite presented in the previous chapter had a dedicated section which presented the results from the test suite with noteworthy points highlighted.

The interpretation of the resource testing results have provided insight into how the field computer's system requirements can be reduced. This can either be done by delaying or abandoning the use of the Dropbox service. Alternatively, voice or text communication can be used in preference to video to drastically reduce the system requirements. The system requirements of the field computer have also been established based on the test results.

User acceptance testing results showed that while the system is usable, both on the side of the audiologist and the hearing assistant, improvements can be made which make the system more intuitive and easier to use. Training in the field of remote hearing aid fitting, and with the Audiflector system in particular, would make a significant difference to the users in terms of ease of use.

Unit testing results proved that an estimated 17 % of the Data Transfer Software source code can be automatically tested using the DUnit unit testing framework.

Comparative testing showed that the addition of the remote element does not affect the results of hearing loss diagnosis by any significant margin. The remote element does however, significantly extend the duration of the entire fitting process by an average of 27.6 %. However, the face time with the audiologist and hence the reliance on audiologists is also reduced.

Overall, the four testing suites have shown that while significant improvements can be made to the Audiflector system, the system is usable in its current form for its intended purpose: That of commercial remote hearing aid fitting.



## CONCLUSION

This chapter has three major sections: Firstly, it presents a summary of the dissertation in its entirety along with all major conclusions which were previously discussed. Secondly, recommendations for future work based on the conclusions previously discussed are expanded upon. Finally, closing findings are discussed by addressing the issues of research aims and objectives and whether they have been achieved or not.

### 6.1 SUMMARY AND CONCLUSIONS

This dissertation has addressed the issue of the high costs associated with hearing aids and the fitting thereof. The high costs have been attributed to four distinctly separate causes as discussed in Chapter 1:

- **Hearing aid cost:** For cosmetic purposes the hearing aid as a whole must be as small as possible and therefore each component has to be as small as possible. The battery has to be small but it must still power the entire device for extended periods. All components therefore need to consume as little power as possible. This miniaturisation and reduced power usage come at great cost when modern day advanced amplification and signal processing techniques are used.
- **Equipment cost:** Hardware used to program hearing aids are specialised medical equipment and command high prices.
- **Audiologist reliance:** All hearing aids must be fitted by a qualified audiologist for

the patient to receive maximum benefit from a hearing aid. Audiologists are highly qualified personnel who are able to charge for their time accordingly.

- **Large travelling distances:** The majority of registered audiologists in South Africa are in densely populated areas such as Gauteng and Cape Town. People who do not have easy access to transport will find it difficult to get to these audiologists. The poorer and more rural regions of the country have a sparser audiologist population and so patients must travel even further and wider in order to receive help.

The suggested solution in Chapter 1 addressed each of the four major causes by providing counter measures:

- **Hearing aid cost:** Hearing aids were constructed with very cost effective components while still producing good quality hearing aids.
- **Equipment cost:** These hearing aids were designed such that they could be programmed with a low cost hearing aid programmer.
- **Audiologist reliance:** There is no reason for the audiologist to be involved in the entire fitting process. It is their skill and training that is required to operate advanced software and make judgement calls. A large part of the hearing aid fitting process is routine. A hearing assistant can carry out the routine parts of the fitting process and reduce the time each patient requires with the audiologist. This has allowed an audiologist to assist from a remote location.
- **Large travelling distances:** With the hearing assistant providing the means for the audiologist to interact with patients remotely, the audiologist can conduct hearing aid fitting sessions in more locations without having to spend time travelling. Patients are then required to travel shorter distances as the audiologist has extended their field of influence.

Using these four counter measures, hearing aids and their fitting can have their costs significantly reduced.

The final output of this research project was:

*A commercially viable remote hearing aid fitting system.*

The testing of this system has preliminary answers of Yes for all three questions that this project originally set out to answer:

1. Can a hearing aid fitting session be conducted remotely?
2. Will the system significantly reduce costs?
3. Will patients and audiologists accept this method as preferential to traditional fitting methods when cost and accessibility are considered major factors?

The answers are preliminary in that the controlled tests which have been conducted do not accurately reconstruct the exact conditions under which this system will be used commercially. This can only truly be tested during field trials which have not been conducted yet.

### **6.1.1 Literature Review**

The purpose of this chapter was to provide the relevant background knowledge to create a basis from which a remote hearing aid fitting system could be created. Four core concepts on which this project is based were covered to enlighten the reader on the concept of “remote hearing aid fitting”.

Hearing aids are comprised of many components which work together to produce a signal which allows the hearing aid wearer to perceive sounds from the surrounding environment better than they could without the hearing aid. All the essential components of a general hearing aid have been briefly discussed and the concept of customising the hearing aid has been included. General constraints which all hearing aids are subject to are also identified to show the upper limits of certain resources.

It is generally accepted that the preferred method of hearing aid fitting is the conventional approach discussed in Section 2.2. This is as a result of the process using features which work well and contribute towards the satisfaction of the patient. These successful features are identified as:

- **Personal Interaction:** The value of one on one personal interaction between a patient and the audiologist cannot be overestimated. The removal of a physically present audiologist in favour of a remote audiologist deems this feature fundamentally impossible. A suitable means for the patient and audiologist to interact must be found.
- **Feedback Mechanism:** The patient can attend supplementary fitting sessions with the audiologist after a few weeks. This allows the audiologist to fine tune the hearing aid customisation settings based upon the patient's real world experience with the hearing aid.
- **Hearing Loss Model:** Modelling the hearing loss in a patient allows the audiologist to use a scientific approach rather than educated guesswork and subsequent correction. The audiogram models the hearing loss in such a way that the audiologist can quantitatively understand the loss and directly use the model to customise the hearing aid.

The remote hearing aid fitting system requires the use of a network to transmit data between end user systems. This network will suffer from the non-ideal characteristics which have been identified. These characteristics are exacerbated by high demands such as long distances between end user systems, large amounts of data, and additional data external to the system. A brief study of network performance criteria and network traffic was also included at this point to provide sufficient background knowledge for network testing of the envisaged system.

This section has investigated all existing systems which are unique in some respect and offered suggestions for improving the envisaged system. The design and purpose of five separate systems have been discussed and brief evaluations of the designs and their testing are covered to highlight the shortcomings and advantages of each system.

Telephonic systems provide a high degree of accessibility and a system which has the potential to be automated and has a simple interface. However, when compared to computer based systems, telephonic systems are restrictive and can be expensive due to current telephone land line rates. Online home testing systems suffered from a lack of stan-

standardised and calibrated hardware but did show the flexibility and availability of online computer based systems. Section 2.4.3 showed the viability of both testing for hearing loss and fitting hearing aids remotely. This section also showed that the use of local hearing assistants have significant advantages but these are likely to be outweighed by their disadvantages when used commercially. The use of a client-server based architecture is a costly choice unless the system will be used on a large scale due to the increased expenses of a web server. Finally, Section 2.4.5 has proved quantitatively that the remote hearing loss diagnosis over long distances is achievable and the associated effects are clinically insignificant. However, session durations were noticeably longer. This section also provided excellent suggestions for the design of the envisaged system and several system components.

### 6.1.2 System Design

Chapter 3 was dedicated to the design of

*A commercially viable remote hearing aid fitting system.*

The design had four distinct stages:

1. **Architecture:** The overall structure of the system was discussed by analysing databases and the means of communication.
2. **Design:** Advanced the design from a Graphical User Interface to a class diagram.
3. **Components:** The individual components, both software and hardware, which together implement the system, were chosen based on which choices were the most suitable for the system.
4. **Finalising:** Discussed seven key issues which finished off the system.

These four stages documented the design of the system along with reasoning behind all design choices.

The system made use of a peer to peer network architecture serviced by a local database with a shadow copy stored on a remote file server. This allowed the system to provide immediate access to the database while maintaining a high degree of data security by utilising a remote database copy.

The system was designed using the ICONIX process to provide a user centred system design. The process provided conceptual GUIs which were later replaced by system components. A use case model ensured the user centred approach. This, combined with a requirements review of the system, led to the creation of a sequence diagram from which a class diagram was constructed which detailed all the major responsibilities of each component.

Software and hardware components were then used to replace the conceptual objects instantiated in the class diagram. Five hardware components, the field computer, audiologist's computer, hearing aid programmer, audiometer, and 3G modem, made use of the eleven software components to form a single working system which fulfilled the requirements set out in Section 3.2.4. The two specialist audiometry hardware components, the hearing aid programmer and the portable audiometer, are excessively expensive and contribute to a large portion of the system's cost. The Audiflector system provides the tools necessary for the detection of hearing loss and its severity but not the cause of the hearing loss as this would require additional field equipment. The software components replaced the conceptual GUIs and communicated as envisaged in the sequence diagram of the ICONIX process. Most importantly of all, the system was user orientated in that the major activities were all initiated by the audiologist while providing as simple an interface as possible from the point of view of both the audiologist and hearing assistant.

The final stage of the system design covered issues which finished off the system. Ear moulds were discussed with the recommended choice being open-fit hearing aids. Packaging covered the issue of portability and transportation of the physical system components in the field. The final packaging featured the hard plastic case of the Kuduwave, a laptop bag, and the packaging of whatever hearing aids have been chosen. Licensing was mentioned only so far as to say that currently there is none. The functioning of the system required the use of five services. These were chosen based on the software and hardware

components chosen. All five services are free but do require an account to be set-up for each service. The installation, set-up, and use of the system, both from the point of view of the audiologist and the hearing assistant, was discussed in detail and is supplemented by a Readme provided as part of the system. Hardware components are all purchased separately but the software is freely available and can be easily distributed. Finally, an analysis of the costs associated with the system was presented. A brief comparison to that of the costs associated with an equivalent local fitting session was also provided. It was concluded that, under normal conditions, the remote hearing aid fitting process will be significantly cheaper than that of the local process.

The resulting system provided a test bed from which tests could be conducted. This was used to analyse if the system does indeed provide a service which can give reliable results and is viable within a commercial environment.

### **6.1.3 Testing and Results Interpretation**

Chapters 4 and 5 are closely linked in that Chapter 5 presents and interprets the results of each round of testing as presented and discussed in Chapter 4. As such Chapter 5 mirrors Chapter 4 in that it is divided into four distinct sections each concerned with a specific issue being tested.

Resource testing quantified the usage of the Audiflector's field computer's resources. The exact testing conditions were documented by identifying the subjects, scenario, and procedure used during the test. It was found that the video conferencing software component used the majority of the field computer's resources as video conferencing is a graphic processing intensive application type. If voice or text conferencing were used over video, it is assumed the system requirements of the video conferencing component would decrease significantly and possibly allow the process to be conducted without a mains power supply. This statement is a purely speculative one as all testing was concerned with the system while using video conferencing. The delayed usage of the remote file hosting service would decrease the bandwidth requirements of the field network connection by staggering the fitting process and the altering of the database shadow copy. Alternatively, the file hosting service could be removed from the system to reduce network utilisation but with the drawback of vulnerable data. Resource testing also allowed the overall sys-

tem requirements of the field computer to be identified assuming the use of video as the preferred means of communication.

User acceptance testing investigated the level of user satisfaction the Audiflector system offers. Again, the exact testing conditions were documented by identifying the subjects, scenario, and procedure used during the test. Results from subjects in the position of the audiologist were, on the whole, good: The interface was rated as being simple but not very intuitive. VSee provided an acceptable video quality (according to the test subjects) when given a high speed network. The level of technical experience required to operate the Audiflector system was rated as more than menial and can be attributed to the additional technical knowledge required to set up and operate the system. Ratings from the test subjects acting as hearing assistants provided an overall rating of the system as average: Interface simplicity and intuitiveness were given a low rating which was attributed to the sheer number of hardware components which are required for the system to work correctly. Again, video quality was rated as being good which meant VSee provided the audiologist and hearing assistant with the same video quality. Finally, the required level of technical experience was rated as excellent which confirmed that at least one requirement of the system had been met: The hearing assistant does not require complex technical training in the use of computers or the field of audiology.

Unit testing provided the means for testing code and automating error testing each time the software is rebuilt from the source code. A total of 35 tests comprising of 98 comparisons formed the two test batteries with stopping conditions of 100 % pike detection. These stopping conditions were achieved and covered an estimated 17 % of the code. This was considered an acceptable number as a large portion of the code is automatically generated to provide the ActiveX implementation container and devoted to customising the interface.

Comparative testing investigated the difference between conducting hearing aid fitting sessions remotely and locally. Two issues were tested and discussed: That of the difference between hearing loss diagnosis results when testing is conducted remotely and locally, and the durations of the fitting process when the process is conducted both remotely and locally. The exact testing conditions have been documented by identifying the

subjects, scenario, and procedure used during the test. Results used to test the difference between hearing loss diagnosis results showed that the level of variability experienced when conducting remote hearing loss diagnosis is comparable to that of the variability experienced when conducting local hearing loss diagnosis. This meant that the remote element does not affect the results of hearing loss diagnosis by a significant margin. The second set of results, those used to test the relative durations of fitting sessions when conducted remotely vs locally, showed that the duration of fitting a hearing aid remotely is significantly longer than the duration of fitting a hearing aid locally. This was accounted for mainly by the use of video conferencing instead of communicating in person and also due to network latency between the field computer and the audiologist's computer. Despite this increased duration face time with the audiologist is reduced and therefore the reliance on the audiologist is reduced. It was concluded that due to the reduced reliance on the audiologist the costs related to audiologist reliance are also reduced.

## **6.2 RECOMMENDATIONS FOR FURTHER WORK**

Throughout chapters 3 and 5 several major conclusions were drawn both from the design of the system and its testing. For a select set of these conclusions, recommendations for further work are now discussed.

### **6.2.1 Hearing Aid Programmers and Portable Audiometers**

Sections 3.3.3 and 3.3.7 mention the issue of the unnecessarily high costs of purchasing hearing aid programmers and portable audiometers. These two objects provide the bulk of the initial cost outlay associated with the Audiflector system. Therefore, if these costs were to be significantly reduced the cost of the system would decrease drastically. The design of these items are not freely available and are considered the intellectual property of their respective companies. Given that these components require no extraordinary manufacturing techniques or components, it is the view of the author that a significant portion of the price is due to a lack of competition and development costs.

The design of these two components are not trivial and require calibration once the manufacturing process is complete. If the design of these components could be bought the components could be sold at cost price and thereby reduce the cost of the Audiflector sys-

tem. Alternatively, an “open standard” for hearing aid programmers in particular, could be developed with manufacturers only responsible for manufacturing according to the standard. Currently however, the feasibility and cost of these tasks are unknown.

### 6.2.2 Additional Field Equipment

With the current field equipment provided as part of the Audiflector system in Section 3.3 the audiologist can diagnose hearing loss and fit a hearing aid. In the field of Audiology two other frequently used tools are an otoscope and a tympanometer. An otoscope allows magnified inspection of the physical ear by illuminating the inside chamber. This can be used to inspect for foreign objects and other causes of hearing loss. A tympanometer is used to measure, amongst other things, the flexibility of the eardrum and the ability of the ear to limit its reaction to loud tones.

If versions of these tools which could be used remotely, such as a video otoscope and digital tympanometer, were included as part of the Audiflector system audiologists would be closer to being able to provide a complete remote hearing assessment and hearing aid fitting service. However, this would further increase the complexity of the system by adding additional physical components. Furthermore, it is unknown whether remote otoscopy and tympanometry would be useful services or indeed commercially and technically viable.

### 6.2.3 USB over IP Tunnelling

The remote application execution software used in the Audiflector system executes software on the field computer (which is also connected to the hardware) and presents the GUI on the audiologist’s computer. This effectively leaves all data, relatively unprotected, located on the field computer (see Section 3.1.2) and also requires the installation of component programs on the field computer. An alternative system model could feature the transmission of USB data over the network instead of the transmission of the software GUIs.

This system model would be significantly different from the system proposed in Chapter 3 and would require a similar set of tests to those described in Chapter 4. This system

would have the advantage of an inherently more secure database located on the audiologist's computer but may suffer from unacceptably slow USB communication when making use of the audiometer and the hearing aid programmer. Additionally, it may move a significant amount of processing requirements to the audiologist's computer and thereby reduce the system requirements of the field computer but increase those of the audiologist's computer.

#### **6.2.4 Improving Ease of Use**

The results from user acceptance testing in Section 5.2 showed that the test subjects thought the level of usability of the system was acceptable but could be improved upon. This was attributed to the interface requiring more of a guiding nature and the requirement of technical knowledge not normally required in the field of audiology. Additionally, installation of the Audiflector system is a five page document detailing, in point form, every step of the installation process if the system is not provided with the Audiflector system pre-installed on a portable field computer.

The system is comprised of a number of different software components each with their own interface. If software components were to be used which provided a software development kit (SDK) allowing the software components' functionality to be built into an interface purpose built for the Audiflector system, the interface intuitiveness and simplicity ratings would be likely to increase significantly. The same approach could be used for the set up and installation of the system: A single installation wizard could install all the software components while a single website could be used to register users for all the required services on both the field computer and audiologist's computer.

#### **6.2.5 3D Pinna Scanning**

Section 3.4.1 discusses the many options associated with the creation of ear moulds and the wide acceptance of open-fit hearing aids. However, it also notes that open-fit approaches only benefit certain hearing loss types and patterns. When the open-fit concept cannot be used an ear mould is required. The creation of ear moulds requires firstly that an impression of the ear is made followed by the creation of the mould itself based upon the impression. Section 2.4.3 noted this creation must be done personally by a qualified

clinician to maintain quality control.

Section 2.4.3 suggests that a solution to this problem is to use high definition scanning to create an ear mould instead of ear impressions. If the use of 3D pinna scanning alleviated the need for a qualified clinician on site this could allow the audiologist to create a ear mould remotely. Naturally the feasibility of this, both from a financial point of view and portability, need to be assessed before this can be seriously considered.

### **6.2.6 Hearing Assistant and Audiologist Training**

As mentioned in Section 5.2, a possible solution to aiding the users of the system to overcome their technical difficulties is to provide audiologists and hearing assistants with training. This would cover the issues of actual use of the system, troubleshooting technical difficulties such as webcams not functioning, and the set up and installation of the system. This training would have to be carried out by a person with in depth knowledge of the Audiflector system and vast experience in its use.

### **6.2.7 Post Fitting Care**

An issue briefly discussed in Section 3.4.6 was the issue of post fitting care. This would involve providing a means for the patient to receive training on how to maintain their hearing aid, set up subsequent fitting sessions to fine tune the hearing aid according to the patient's experience in everyday life, etc.

In the interest of providing an easy to use and widely accessible service, this post fitting care could be provided through the use of an automated query and response service. Such a service could be provided telephonically with a combination of automated and personal assistance. Additionally, a simple website could be set up with the facilities for making appointments and frequently asked questions.

## **6.3 CLOSING FINDINGS**

Overall, the testing has shown that significant improvements can be made to the system but in its current state it can provide the system which was intended:

*A commercially viable remote hearing aid fitting system.*

This text has shown that hearing aids can be fitted remotely and that the Audiflector system is one system that provides the means for this process. Remote hearing aid fitting is very likely to reduce the costs associated with hearing aid fitting and that due to this patients and audiologists can accept this method as preferential to traditional fitting methods when cost and accessibility were previously prohibitive factors.

What remains to be seen is the level of acceptance and popularity of remote hearing aid fitting and in particular the Audiflector system when used commercially. This will be judged by the number of patients who previously did not have access to hearing aids, and who are satisfied with the fitting of their hearing aids. This will be made evident from the results of the field trials which, at the time of printing, had not been conducted.



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## PROJECT MANAGEMENT

The dissertation in which this document is included is the culmination of 13 months of work. As the dissertation is only one part of the project it may not be clear how time was utilised. All additional documents associated with the Masters project are documented. All but the most menial of projects require a level of project management. It is for these reasons and the clarification of time utilisation that this chapter is included.

### A.1 ADDITIONAL DOCUMENTS

The Audiflector system and its design is accompanied by documents which supplement the dissertation and the project as a whole. Where possible these are provided in a digital format with the dissertation.

- First and foremost, a digital copy of the dissertation, provided on compact disc in both compiled .pdf format and  $\text{\LaTeX}$  source code. All diagrams are included in .eps vector image format and .vsd Visio format. All graphs are also included in .eps vector image format.
- The Audiflector system's Readme is provided as part of the system. It provides a summary of core issues such as system requirements, components, installation, usage, and maintenance. It is not meant to provide an exhaustive instruction set. It simply supplements any training which audiologists and field technicians may receive in the use of this system, audiometers, and hearing aid programmers.

- A University of Cape Town laboratory book was used to document the project during its development. It is comprised of rough designs and the thought process behind some of the design decisions made in the project.
- A signed declaration form for Masters degree candidates from the Faculty of Engineering and Built Environment at the University of Cape Town is submitted with the dissertation.
- A completed Masters Intellectual Property Assessment Form notifying the University of any public disclosure issues.
- A summary of the key aspects of the dissertation, written in the format of a paper, which has been approved by the project supervisor and is of a publishable standard.
- An ethics form signed by the Faculty of Engineering and Built Environment Ethics Committee granting the project ethics approval. It is available for viewing from the Faculty office.
- A consent form in .pdf format for use with human test subjects as required for ethics approval.
- The raw data accumulated during testing of the Audiflector system from Microsoft Network Monitor and Microsoft Performance Monitor in .csv and .cap formats as well as test times in .xlsx spreadsheet format.
- The matlab scripts and functions written specifically for graphing test data.
- The source code, register.xml file, and .ocx file for the Data Transfer Software.

## A.2 TIME MANAGEMENT

The entire project was scoped to be completed in a period of 14 months. This includes project setup time, preliminary investigations, and literature review. Figure A.1 shows a Gantt Chart with all the major sections of the project, their durations, and start dates.<sup>1</sup>

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<sup>1</sup>The durations and start dates of each task has been estimated from records kept within the Author's laboratory book.

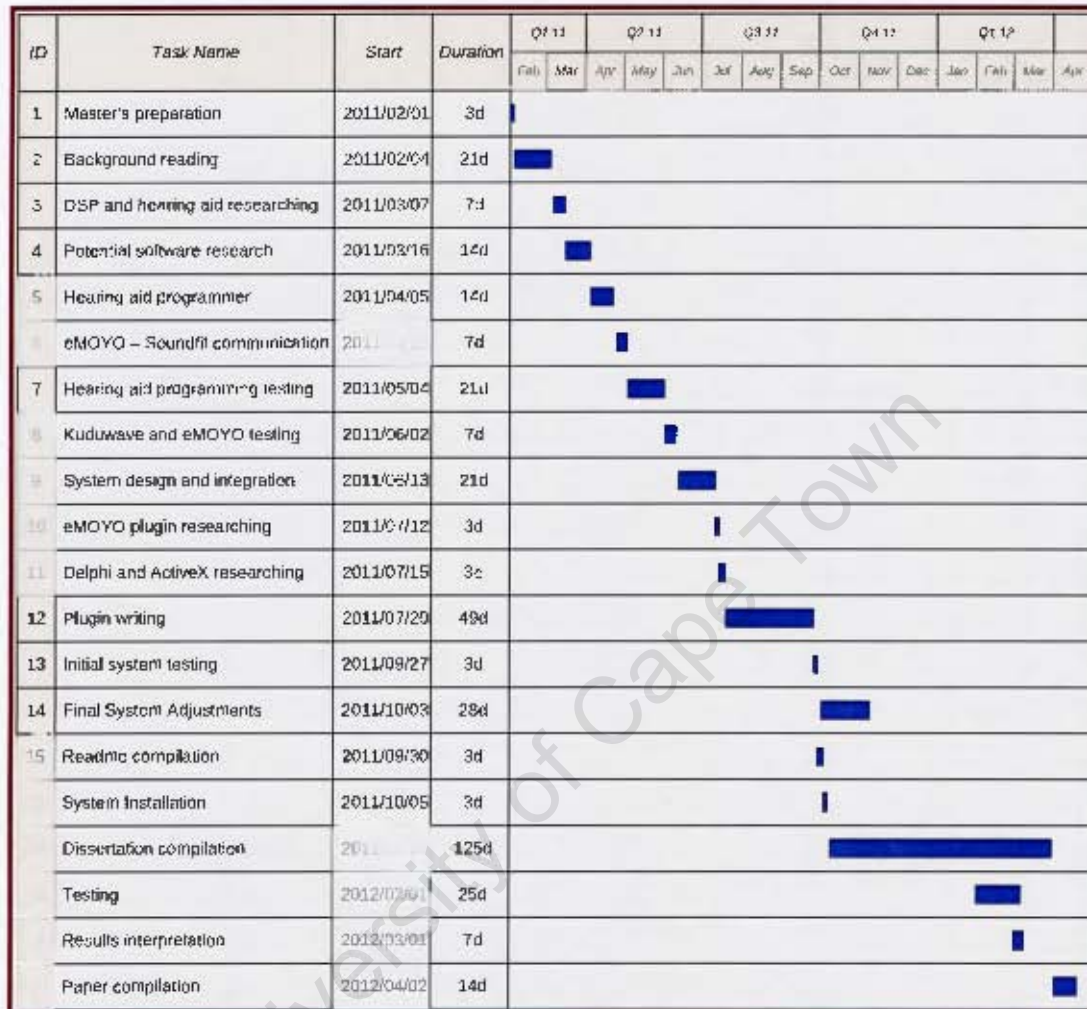


Figure A.1: Gantt Chart  
(Created with Microsoft Office Visio 2007)

A significant amount of time (21 days) was devoted to the initial investigation of literature concerned with hearing aids and the field of audiology. This was followed by an extensive audit over 61 days of software which was potentially useful in the envisaged system. The system was then designed and integrated over a period of 21 days. All aspects of the eMOYO plug-in, from the design to the testing were then completed over the next 55 days. Initial testing, designed to test absolute minimal functionality, was carried out over three days followed by a 4 week period of making final system adjustments. While these final

system adjustments were carried out, the system Readme was compiled and installation of the system was designed and implemented. Once the system installation was finished the compilation of the dissertation was started. This was carried out over an estimated period of 125 days beginning in mid October 2011. During the second half of the dissertation compilation the formal system tests were designed and executed. This was followed by a week long period of results interpretation. Finally, the compilation of the academic paper on the subject of the dissertation is envisaged to be completed two weeks into April 2012.

### **A.3 SUMMARY**

All additional documents associated with the Masters project have been documented. The clarification of time utilisation throughout this Masters degree has been included and discussed.

University of Cape Town

# README

This is the Readme for the Audiflector remote hearing aid fitting system. The purpose of this Readme is to provide a summary of core issues such as system requirements, components, installation, usage, and maintenance. It is not meant to provide an exhaustive instruction set, it simply supplements any training which audiologists and field technicians may receive in the use of this system, audiometers, and hearing aid programmers. The Readme is intended for distribution in a .pdf format and is distributed with the system's software components.

## B.1 REQUIREMENTS

- Operating System: Microsoft Windows XP, Vista, 7
- Bus Width: 32 bit or better
- RAM: 1334 MB RAM or better
- CPU: Atom 1.50 GHz dual core processor or better
- Internet access: Mobile modem and network with actual bandwidth of 187 KB/s or better
- Three free USB 1.1 (or better) ports
- Administrator privileges

## **B.2 COMPONENTS**

### **B.2.1 Hardware**

- **Kuduwave 5000 Clinical Audiometer:** Hardware used to diagnose patients' hearing loss
- **HI-PRO USB Hearing Aid Programmer:** Hardware used to interface between the computer and the hearing aid
- **Gigabyte Q2005:** Portable computer used to deploy system
- **USB 3G dongle:** Provides wireless internet access through cellphone network

### **B.2.2 Software**

- **eMOYO 500 health operating system:** Audiometric hearing data assessment software
- **Soundfit:** Hearing aid programming software
- **HI-PRO drivers:** Software allowing communication with HI-PRO USB
- **Winflexor:** Remote application deployment software
- **VSee:** Text, audio and video conferencing software
- **Dropbox:** File hosting service software
- **DynDNS Update Client:** DNS address update service

## **B.3 INSTALLATION**

**Note:** The system cannot be used immediately after installation. Each copy of eMOYO needs to be registered with GeoAxon before it can be used. Allow 3 working days for a registration request to be processed.

### **B.3.1 Field Computer Installation**

- **Insert system installation memory stick**
- **Select “field computer installation” from autostart menu. If autostart is disabled start “FieldComputerInstall.bat” from system installation memory stick root folder**
- **Run through HI-PRO setup wizard**
  - Connect USB only when prompted**
  - Select HI-PRO type as HI-PRO USB**
- **Run through Soundfit setup wizard**
- **Run through Dropbox setup wizard**
- **Run through Winflector setup wizard**
  - Select Winflector server to autostart**
  - Set Winflector to run as administrator by right clicking on shortcut, selecting properties, compatibility tab, and check “run as administrator”**
- **Start Winflector server**
  - Click “Preferences”**
  - Click “User Accounts”**
  - Under “Account:” section, fill in details as provided by the audiologist and click “Add”**
  - Click “OK”**
  - Click “Applications”**
  - Click “+Add new application”**
  - Click “[...]”**
  - Navigate to location of “Soundfit” installation**
  - Click “Soundfit.exe”**
  - Click “Add”**

Click "+Add new application"

Click "[...]"

Navigate to location of "eMOYO" installation

Click "eMOYO.exe"

Click "Add"

Click "Save and close"

Click "Options"

Check "Encrypt transmission"

Click "OK"

Click "Disconnect"

- Run through eMOYO setup wizard

- Run through eMOYO upgrade setup wizard

Set eMOYO to run as administrator by right clicking on shortcut, selecting properties, compatibility tab, and check "run as administrator"

- Start eMOYO

Fill in all required details

Send registration by clicking one of the three buttons at the bottom of the eMOYO screen

When GeoAxon sends the required unlock code, start eMOYO and copy and paste the unlock code into the unlock code field

Click ">>> "

Click "Change database folder", select Dropbox folder, click "Finish"

Press next and exit eMOYO

- Run through VSee setup wizard

Click "Create New Account"

Fill in required information

Click “Agree and Sign up”

Click the spanner button in the top right of the VSee window, go to preferences, and tick “Automatically accept calls...”

Click “add” then “add contact...”

Fill in the audiologist’s username

Click “OK”

- Go to <http://account.dyn.com/dns/dyndns-pro/trial.html>

Type in a hostname name and select a domain

Click “Your current location’s IP address is xxx.xxx.xxx.xxx”

Click “Add to cart”

Fill in required registration details

Click “Create Account”

Click “Proceed to checkout”

Fill in payment information

Fill in billing address

Click “Place order”

- Run through DynDNS update client setup wizard

Fill in username and password

Click “OK”

- Insert 3G dongle into USB port

Select install software from autostart menu. If autostart disabled start “install.exe” from 3G dongle drive

Run through 3G dongle setup wizard

### B.3.2 Audiologist's Computer Installation

- Insert system installation memory stick
- Select "Audiologist's computer installation" from autostart menu. If autostart is disabled start "AudiologistComputerInstall.bat" from system installation memory stick root folder
- Run through VSee setup wizard
- Run through Winflexor setup wizard
- Start VSee
  - Click "Create New Account"
  - Fill in required information
  - Click "Agree and Sign up"
  - Click the spanner button in the top right of the VSee window, go to preferences, and tick "Automatically accept calls..."
  - Click "add" then "add contact..."
  - Fill in the field computer's username
  - Click "OK"
- Start Winflexor client
  - Click "Add"
  - Fill in name of DynDNS URL in "Server name or IP:" field
  - Click "Add"
  - Fill in the audiologist's username in "Login:" field and Audiologist's password in "Password:" field
  - Click "Applications" tab
  - Click eMOYO icon
  - Click "Other" tab

- Click “Create”
- Click “Applications” tab
- Click Soundfit icon
- Click “Other” tab
- Click “Create”
- Click “Close”

## **B.4 USAGE**

**Note:** The steps detailed in this section only provide an overview of the steps required to use the system for its intended purpose. It does not provide details on how to use the programs themselves.

### **B.4.1 Audiologist Usage**

The documentation for the use of Soundfit is accessible from the program’s help menu while quick reference cards for the use of eMOYO are supplied with the audiometer.

Usage steps for the audiologist assumes that the audiologist’s computer has a permanent internet connection and that

- Wait for Technician to initiate chat session
- Brief patient of procedure
- Start eMOYO
- Create new patient or open existing patient
- Conduct puretone test
- Wait until puretone test finished
- Signal technician that audiometer must be disconnected and hearing aid must be connected

- Wait for hearing aid connected signal
- Select “Program hearing aid” from clinical note creation list
- Program hearing aid
- Fine tune hearing aid according to patient’s needs
- Signal hearing aid must be disconnected
- Debrief patient
- End chat session

#### **B.4.2 Field Computer Usage**

- Arrive at testing location
- Locate patient and introduce process
- Switch on the computer
- Insert 3G dongle and connect to the internet
- Connect audiometer
- Initiate chat session
- Wait for signal to put the audiometer on the patient
- Wait for signal to disconnect audiometer
- Connect hearing aid
- Put hearing aid on patient
- Wait for signal to disconnect hearing aid
- Disconnect internet

## **B.5 MAINTENANCE**

### **B.5.1 Audiometer Calibration**

Refer to GeoAxon Kuduwave certificate of calibration. Audiometer must be recalibrated annually.

## **B.6 ADDITIONAL SOURCES FOR INFORMATION AND HELP**

- Audiometer: Kuduwave 5000 Placement Quick Start Card
- Hearing Aid Programmer: HI-PRO USB installation guide booklet
- 3G Dongle: Help menu on connection interface
- Audiometer Software Interface: Kuduwave 5000 Pure Tone Audiometry Software Quick Start Card
- Hearing Aid Programming Interface: Help menu in Soundfit
- Hearing Aid Programmer firmware:  
[www.otometrics.com/fittingsystems/Fitting/Hi-Pro\\_USB.aspx](http://www.otometrics.com/fittingsystems/Fitting/Hi-Pro_USB.aspx)
- Remote Application Execution Software: Winflexor user's manual stored in application installation path
- Chat Service: Spanner menu in VSee address book window
- File Hosting Service: <http://www.dropbox.com>

## **B.7 CONTACT DETAILS**

GeoAxon

Manufacturer of the Kuduwave 5000 Audiometer and developer of the eMOYO 500 health operating system

<http://www.geoaxon.com>

**Otometrics**

Manufacturer of HI-PRO USB hearing instrument programmer and distributor of the HI-PRO firmware

<http://www.otometrics.com>

**Gigabyte**

Manufacturer of Q2005 portable computer

<http://www.gigabyte.com>

**Vodacom**

Cell internet service provider

<http://www.vodacom.co.za>

**Winflexor**

Creator of Winflexor remote application execution software

<http://www.winflector.com>

**VSee**

Creator of VSee video and text conferencing software

<http://vsee.com>

**DynDNS**

DNS account and DNS server update client

<http://www.dyndns.com>

**Sounddes**

Creator of Soundfit hearing aid programming software

<http://www.sounddes.com>

**Dropbox**

Creator of Dropbox file hosting service and software

<http://www.dropbox.com>

## **B.8 README DETAILS**

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## NETWORK STATISTICS

Network statistics are required to allow the exact testing conditions to be reproducible and recreated as needed. Two sets of network statistics are recorded for the resource testing, user acceptance testing, and comparative testing of the Audiflector system. These two sets test distinctly different network paths: The first network path is the path between the field computer and the VSee chat service server, located in Santa Clara, California, United States of America, which is used to provide the VSee service. The second network path is the path between the audiologist's computer and the field computer.

Speedtest.net and Pingtest.net, are services each hosted on multiple servers. These services allow network statistics to be measured between a computer (with a connection to the internet) and a selection of servers across the world. Both services have a server in San Francisco, California located  $58 \pm 7$  km from the VSee servers (VSee server location approximated according to IP address analysis (<http://vsee.com.w3snoop.com>)).

The overall results, as measured before each test commenced, are presented in Table C.1 below:

Table C.1: Network Statistics between computers and VSee servers

	Mean	Std. Deviation
<b>Download Speed [Mbps]</b>	8.34	1.56
<b>Upload Speed [Mbps]</b>	1.57	0.434
<b>Latency [ms]</b>	236	19.6
<b>Jitter [ms]</b>	92	6.72

Table C.2: Network Statistics between the audiologist's computer and field computer

	Mean	Std Deviation
<b>Latency [ms]</b>	8.20	1.31
<b>Jitter [ms]</b>	1.39	0.120

## C.1 SUMMARY

Network statistics were recorded to allow the exact testing conditions to be recreated if needed. Two sets of network statistics were recorded for the resource testing, user acceptance testing, and comparative testing of the Audiflector system. These two sets tested the paths between the field computer and the VSee chat server and also the path between the audiologist's computer and the field computer.

## QUESTIONNAIRE

The user acceptance testing of the Audiflector system required the use of questionnaires in an attempt to qualitatively assess the usability of the system. The testing investigates several aspects of the system which are quantified by assigning values to particular ratings (from worst to best). These results are then averaged out and presented as the test results.

The Audiologist and field technician have distinctly different roles during the process of fitting a hearing aid. Thus, it is important to obtain feedback not just from the Audiologist, but from the field technician as well. Identical questionnaires are used to question both users. This is done as the system usability aspects investigated are identical, just from different points of view. As a precursor to the rating, the test subject's practical experience in the field of Tele-Audiology and related areas, is also gauged by clarifying what concepts they are familiar with.

The questionnaire follows:

# Audiflector Questionnaire

Test Date: \_\_\_\_\_ Role (Audiologist/ Field technician): \_\_\_\_\_

Field of Study: \_\_\_\_\_ Year of study: \_\_\_\_\_

Concept	Used before (tick)
Audiometer	
Kuduwave Audiometer	
Hearing Aid Programming Software	
Soundfit	
Hearing Aid Programmer	
HI-PRO USB Hearing Aid Programmer	
Remote Desktop Software	
Winflector	
Video Chat Conferencing Software	
VSee Video Chat Conferencing Software	

Rating	1	2	3	4	5
Interface Simplicity	Worst				Best
Interface Intuitiveness	Worst				Best
Video Call Quality	Worst				Best
Video Call Delay	Worst				Best
Technical Experience Required	Most				Least

Reasons for given ratings: \_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

## **D.1 SUMMARY**

Using this questionnaire a basic idea of the usability of the system by external users can be developed. The results of this questionnaire will allow any further development of the system to take into account the strong and weak points of the system from a usability point of view.

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