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Design of a Wireless Pulse Oximeter for use in a Clinical Diagnostic System

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Electrical and Biomedical Engineering Design Project (4BI6)

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Electrical and Biomedical Engineering

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Electrical and Biomedical Engineering Design Project Report

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ABSTRACT

For patients at risk of respiratory failure, it is important to monitor the blood oxygen saturation of such individuals to ensure proper perfusion of blood in their system. Preferably this information should be received on a continuous basis. Both of these objectives can be reached via the non−invasive method of pulse oximetry. This is currently used in hospital/clinical settings, however uses wires which in effect bound an individual to an area. The purpose is to create a clinical diagnostic system which takes a few physiologically relevant signals and transmits them wirelessly to a base station. This allows an individual in a clinical or research setting not to be bound to a specific area. This project specifically deals with the design of a wireless pulse oximeter for this system. The oxygen carrying molecule of blood is hemoglobin, which can be either oxygenated or reduced. By using the principle of differential light absorption and the assumption that the transmission of light through the arterial bed is influenced only by the relative concentrations of oxygenated and reduced hemoglobin and their absorption coefficients at the two wavelengths, light intensity will decrease logarithmically according to Beer−Lambert's law. Using light emitting diodes and photodetectors at two separate wavelengths (one at Infrared, another at red) and electronic circuitry (current-to-voltage converter, filters and amplifiers) we are able to obtain a pulsatile signal which we can post process to obtain an oxygen saturation reading. The theory behind our device, hardware design and the experimental results of the system are presented.

Key words: Pulse oximeter, hemoglobin, light emitting diodes, photodetectors, oxygen saturation, reduced hemoglobin, oxygenated hemoglobin, Beer-Lambert's law

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Hamzah Qureshi

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Nomenclature

Here is a list of key words that have been used throughout this report, and there definitions, given in alphabetical order.

Arterial Bed: A network of blood vessels that deliver oxygenated blood to the body tissues.

Beer-Lambert's Law: A physical law that states the relationship between the transmittance of light through a material and the property of that material.

Capillary: smallest network of blood vessels.

DAQ: Acronym which stands for the data acquisition system used in order to acquire the signal before processing.

Hemoglobin: protein that is the oxygen carrying molecule of the blood.

LED: Acronym which stands for Light Emitting Diode.

MATLAB: Mathematical software program.

Oxygenated Hemoglobin: Hemoglobin which is bound to oxygen.

Oxygen Saturation: The amount of oxygenated hemoglobin to the total amount of hemoglobin.

Photodetector: A semiconductor (electronic) device which acts as a sensor to detect light and convert this incident light into an electrical signal (current).

Pulse Oximeter: A system that uses the principles of light transmittance in order to calculate oxygen saturation.

Quick Doc: Term that refers to the whole group project: a clinical diagnostic system that takes a few physiologic measurements and transmits them wirelessly to a base station for processing and display.

Reduced Hemoglobin: Hemoglobin which is not bound to oxygen.

R_x: Short form to indicate the receiver of a transmitter-receiver system.

Transmittance/Transmission: Refers to the passing through of light (or anything) through an object or space.

T_x: Short form to indicate the transmitter of a transmitter-receiver system.

SNR: Acronym which stands for Signal to Noise Ratio, which is the ratio of the signal power to noise power.

Venous Blood: Blood which is deoxygenated and returning to the heart.

Chapter 1

Introduction

1.1 Background

Health care is one of the most important aspects of one's life. Without it many would say your quality of life would be poor. Fortunately, in Canada we have a very well established universal health care system. Our universal health care is something envied by many. However although we are able to provide this service, there are many criticisms that exist of this system.

It is no mystery that flaws in our health care system exist. The CBC (Canadian Broadcasting Corporation) reports that in 2004, a number of organizations including: The College of Family Physicians, the Canadian Medical Association, and the Royal College of Physicians and Surgeons, all collaborated on a National Physicians Survey which found the follow startling facts[1]:

- 117 is the average number of patients per week a family physician would see.
- If you include on-call hours, a family physician works 70-80 hours per week! Approximately more than 70 per cent of family doctors provide some type of on-call service.
- About 60 per cent of doctors say they do not regularly accept new patients.
- 18.2 per cent said they are not accepting any new patients
- Only 20.2 per cent of physicians said that their practices were accepting new patients without any restrictions.

Also the CFP (Canadian Family Physician) organization reports that, in a research poll performed by the College of Family Physicians of Canada in September of 2006, it shows "that 17% of Canadians do not have family physician which amounts to 5 million Canadians that have no family doctor. Of these 5 million, nearly 2 million have looked for a doctor but cannot find one."[2][Bailey, 2007] It can be clearly seen from the above

statistics that we are in dire need of either more health care professionals, and/or ways to ease their work load. One solution is to look towards improving/developing better medical instrumentation/devices which in the past have done just that for the world of biomedicine.

Instrumentation devices have become a staple in the medical world, both in research laboratories and clinical settings. They have become so relied upon that physicians, nurses, occupational therapists, physical therapists and other health care professionals cannot carry on their work suitably without them. From ECG's to EMG's, EEG's and pulse oximeters, the list continues. These devices have not only revolutionized the field of medicine with their rich technology, but have also increased the quality of medical care that patients receive.

The purpose of these devices is to provide vital information, usually on a continuous basis, to clinicians and other health care professionals in order so that they may be able to set a course of action, make decisions or plan the next steps. Whether these are on treatment options, monitoring options etc... However, like any system or device, there is always room for improvements and advancements.

When undertaking an engineering project, we must first ask the question, "Why should we do this?" Answering this question establishes a vision, goals, and an action plan (or plan of action). Also, answering this question provides a driving force and constant motivation towards completion of the project at hand. As engineers we are expected to undertake projects that will bring benefit to society. As biomedical engineers we hope to bring benefit to society through our engineering innovations in the field of biomedicine. Then the main fundamental basis of our project is to benefit society via our underlying objectives of the project.

The project that was undertaken by our group was a wireless clinical diagnostic system. The objective of this project was to design a system that will take a few physiologically relevant signals from the user and wirelessly transmit them to a

processing station. For this system the physiologic signals that will be incorporated into our project are: 1) An electrocardiogram (ECG) 2) A blood pressure monitor and 3) A blood oxygen concentration monitor. The system as a whole was named Quick Doc, and will be referred to this name for the remainder of the report. Other members of the group consisted of: Kundan Thind who would be working on integrating and post processing all the physiologic signals and getting them wirelessly transmitted, Ashwin Ayyaswamy who would be working on the ECG component, and Doralice Ferreira who would be working on the blood pressure monitor component. There are two objectives to this project, one is to simplify the environment of patients while in a clinical setting, so that vital measurements can be taken through a wireless system. The other is to implement a system that will incorporate more than one physiological signal. My contribution to this project is to implement a wireless pulse oximeter for this system.

For patients at risk of respiratory failure, it is important to monitor the blood oxygen content of such individuals to ensure proper perfusion of blood in their system. This is important as our body tissues require a constant supply of oxygen, and without it can only survive for a very short period of time. Preferably this information should be received on a continuous basis. Both of these objectives can be reached via the non−invasive method of pulse oximetry. The technique is now well established and is in regular clinical use. The purpose of including a pulse oximeter in the Quick Doc system is to be able to monitors the user's blood oxygen content in order to ensure that they are receiving adequate perfusion.

1.2 Objectives and Scope of the Project

In times of doctor shortages and ever increasing wait times in hospitals and clinics (as described earlier), we hope to implement a system that will be able to decrease both the wait times of a patient and the work load of a physician. Our group plans on accomplishing this with our first objective, which is to establish an instrumentation system that will be able to incorporate several physiological signals. Quick Doc is a system that will take a 3 physiologically relevant measurements including: ECG, blood oxygen content and blood pressure. We believe these 3 signals are very crucial when vital

measurements are needed in a clinical or research setting. With a system that integrates these 3 useful signals into one system that can be used to display all the necessary and pertinent information, we believe that it may be easier and faster for a clinician to spot an abnormality or make a diagnosis. The vision is that this would be the type of system may be implemented in a clinical setting, such as a walk in clinic, where a patient/user can put it on (wearable device) and then the information delivered to a base station (the nurse's station). This can allow better organization of vital signals, and can allow clinicians to determine quantitatively who the most high risk patients are.

Also, we believe that the wireless aspect of this project allows us to further its scope as well as accomplish our objectives. In almost all clinical settings, patients are likely to be literally hooked up to diagnostic instruments which measure their vital signs. These instruments are necessary in order to monitor their health. However, due to the nature of their attachment, they make it very difficult for patients to become mobile. In a hospital or clinical setting, many patients become either uncomfortable or even just simply bored staying in a room, or being bound to an area (such as their bedside). This makes it more difficult for the patient to get through their already difficult ordeal. We believe that instrumentation devices in a clinical setting should transmit signals wirelessly in order to help increase the care/comfort a patient is provided. We believe that the Quick Doc system will accomplish this objective. Quick Doc will allow for mobility of these patients who are restricted to their bedside by transmitting the vital physiologic signals wirelessly to a base station. This will allow a patient/user to be mobile while using this system.

As a result of this, Quick Doc could also theoretically be implemented in training and physical therapy. Again, many times in these settings patients are hooked up to many electrodes monitoring their activity. In such an environment it creates difficultly for the user and clinician alike to try and engage in certain exercises/activities without disconnecting or disabling their systems. We believe due to the objectives of our system we will be able to avoid this problem. With our wireless system we would be able to not only monitor their activity, but also allow for greater range of activities in effect increasing the effectiveness of their training/therapy.

Our Quick Doc system has the underlying theme to create ease for the user, by incorporating a wireless component. We also hope to help the clinical world by incorporating 3 different vital signals. With the ability to measure more than one physiological signal and the ability to transmit these signals wirelessly to our instrument/device makes this project unique.

1.3 Methodology

As with any engineering project, our group has divided the whole project into 4 sub-projects, due to the complexity and many different subsystems involved. The 4 sub-projects consist of: an ECG device, pulse oximeter device, blood pressure device, and transmission/post processing (base station). The whole Quick Doc system can be diagrammatically shown using an engineering block diagram in which each block represents a certain system. This is shown in Figure 1.

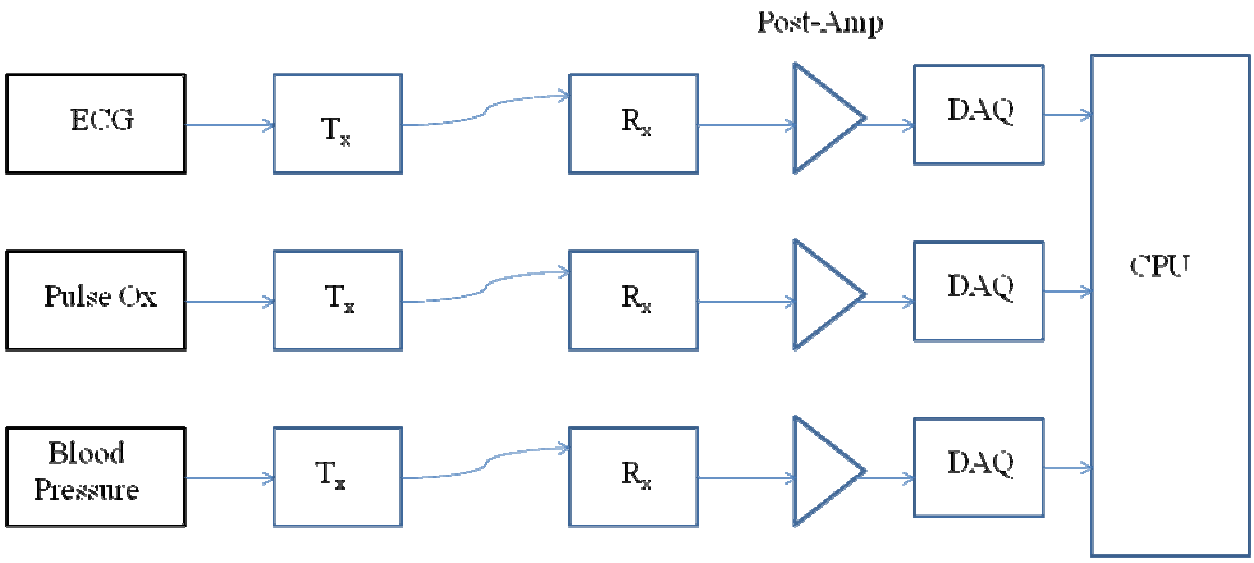

Figure 1 Depiction of the whole Quick Doc system T_x represents the transmitter, R_x represents the receiver and DAQ is the data acquisition unit, is the processing unit (or computer/laptop)

The methodology for implementation for a pulse oximeter must be carefully considered. Firstly, research must be done in order to properly understand how one can use electronic principles in order to obtain a physiological signal such as blood oxygen content. The implementation for a pulse oximeter consists of both a hardware and software component (see chapter 3 and appendix B). The hardware component consists of electronic circuitry in order to obtain the signal, while the software component consists of extracting the necessary information from this signal which will then be used to calculate the blood oxygen saturation (for both hardware and software components please see chapter 3 and appendix B on details of how this implementation is possible). For this portion of the project, only the hardware implementation will be considered in order to obtain the physiologic signal. For the post processing (e.g. software component) please refer to the report by Kundan Thind. The objective of this project is therefore to obtain the pulsatile signal that consists of the necessary information in order to obtain the blood oxygen saturation. If we can obtain this signal, then it can be shown that we can wirelessly transmit such a signal to a post processing station and obtain a value for the blood oxygen saturation which can then be incorporated into the Quick Doc system.

1.4 Brief History of Pulse Oximeters

The first "pulse oximeter" to measure oxygen content in humans was built in the 1930's. However, these devices were not able to distinguish between the different types of blood within the finger including: arterial, venous and capillary blood. It was also then realized that the light transmitted through the finger is attenuated by the arterial blood, but also by venous and capillary blood, skin (whose absorption properties will vary from person to person, due to different pigmentations) and by other tissues (such as muscle and bone). In the 1970's Hewlett−Packard created a device which tried to combat this problem by transmitting light at more than two wavelengths. They had developed a multi component model of the ear, and it was composed of up to 8 light absorbing substances (such as Hb and HbO_2, skin, other tissues etc...). However, due to the high cost of the instrumentation along with the need for measurements at many (eight) different wavelengths caused it be very impractical and it never found regular clinical use. However it was later realized that a device that only needed to transmit light at two

different wavelengths could measure the blood oxygen saturation, without much computational power. These devices are now a staple in every hospital bedroom and monitor the patient's blood oxygen content and are known as pulse oximeters.

1.5 Conclusion/Summary

In summary, our group objective is to design a clinical diagnostic system that transmits 3 physiologically relevant signals wirelessly to its base station. This allows for two objectives to be accomplished, one which is to obtain multiple physiologic signals, and second to allow for user mobility (via wireless acquisition). The signals to be acquired are: ECG, blood oxygen content and blood pressure. This project will be considering hardware implementation of a blood oxygen content system or better known as pulse oximeter.

Chapter 2

Literature

2.1 Introduction

This following chapter reviews pertinent papers and journal articles on work in the area of pulse oximetry. We will consider a few papers and articles not to overwhelm the reader into the vastness of the field. As an overview, pulse oximetry (described in more detail in chapter 3) uses the principles of light transmittance and absorbance in order to obtain an electrical signal which contains the necessary information to calculate the blood oxygen saturation. This measurement is important in order to ensure proper perfusion of body tissues, as tissues cannot survive long without oxygen. This is a very diverse field and requires an understanding of physiology, electronics and electrical signal processing.

2.2 Overview on Pulse Oximetry and its Developments

The first journal article we will be discussing is from the journal CHEST (which is the official publication of the American Chest Physicians)[6]. This article gives a nice introduction and broad overview of the topic of pulse oximetry from a more physiologic stand point. It begins by giving a broad overview behind the theoretical basis of the pulse oximeter, and then goes into the history behind the device in terms of its implementation in world war two. The article then goes on to discuss the development of the device. It stated that, it took many years to properly produce the technology due to its practical limitations. The article then discusses its uses in a clinical setting and sources of problems that cause errors in its readings. According to the article, "the two most bothersome problems are light and motion artifacts"[6][Tremper, 1989], stating that due to the use of photodiodes in transmitting and detecting the light, surrounding light sources cause an issue in this regard, and that the motion of the individual causes errors in the waveform generated which is necessary to calculate the oxygen saturation. Both of these issues were also discovered in our implementation of the pulse oximeter project. After

reading this article the reader is suggested to refer to this article if they feel they need a brief and meaningful introduction to the field.

2.3 Optimization of Pulse Oximeter Hardware

The next article to be considered looks more to the optimization of the hardware system involved in the pulse oximeter unit. This article titled *Direct Digital Capture of Pulse Oximetry Waveform*[7] was published by researchers from the University of South Florida. This article describes the current electronics involved in capturing the pulse oximetry waveforms, which briefly are described in the following order (by the article): "a sensor photodiode generates a current proportional to the intensity of the red and IR waveforms. The photocurrent is amplified by a current-to-voltage convertor for further analog processing. The voltage signal is then filtered in the analog domain and then digitized by an A/D convertor for further processing..."[7][Scharf and Athan, 1993] This accurately describes (briefly with no major details) the processed involved in obtaining a physiologic signal by pulse oximetry. The article then goes on to discuss a possible optimization by the use of Texas Instruments TSL220 light to frequency photodiode. This electronic device combines a photodiode, current-to-frequency convertor and an amplifier all in one small package. The results produced from the use of this device match those of regular pulse oximeter readings and the fidelity of the waveforms were considered "excellent". Due to this compact combination, it allows for a small footprint, low cost, and low power consumption, which the articles states is ideal for the use in pulse oximetry applications.

The next article also deals with optimization of the pulse oximeter system by using a new implementation technique. The article is a publication by undergraduate students from the University of North Carolina. This paper looks specifically at eliminating the use of two LED circuits in order to measure the pulse oximetry waveform, and instead use a different approach, using a blue LED and a red ruby. The article first describes the usual theory behind pulse oximetry and then goes into the details into their new implementation idea, which is to use a blue LED and a red ruby. They believe that this approach will simplify the circuitry involved and make it simpler to

calibrate. The article then presents the theory behind this new idea, which is to use the blue light excitation from the ruby which causes a “doublet” emission, which is then transmitted and detected using the usual principles of pulse oximetry. Using both the blue light and the created doublet, they were able to create and reconstruct a pulse oximeter waveform signal and extract the necessary information for the oxygen saturation. This article concludes (from their results and discussion) that, “It is possible to use a blue LED and a Ruby to implement transmission oximetry. Using a blue LED and a Ruby saves on the additional circuitry needed to calibrate the light intensity from different light sources. The transmission rate of blue light through blood can be detected using a highly sensitive color sensor.” This article is a good example of possible further developments in the field of pulse oximetry and how the optimization of these systems is important both clinically and in research environments.

Chapter 3

Statement of Problem and Methodology of Solution

3.1 Statement of Problem

The problem as defined by our group is to try and implement a subsystem that measures a person's blood oxygen content, so that we can incorporate this vital signal in our clinical diagnostic system. This signal it is important to monitor the efficiency of gas exchange in the lungs, which indicates how well the arterial blood is oxygenated. Poor gas exchange may indicate respiratory failure. It has been realized that this information can be available via the non-invasive technique of pulse oximetry, which is now a well established technique in clinical settings. Both the theoretical principles and methodology of solution are presented in this chapter

3.2 Theoretical Background

There are many theoretical principles that are fundamental to understand how we can use pulse oximetry in order to obtain a signal relevant to physiological function. However, due to the many different fields involved, we will limit this discussion to only the pertinent details that are necessary in order to understand pulse oximetry. If the reader feels they need a more detailed description please refer to appendix B, which presents the theory in more detail.

Hemoglobin is the oxygen carrying molecule of the blood and blood consists of millions of these molecules. It can also exist in two forms: oxidized (or oxygenated) Hemoglobin denoted HbO_2 and reduced hemoglobin denoted Hb. Approximately 99% of oxygen is bound to hemoglobin in red blood cells. Oxygen saturation denoted SaO_2 refers to the ratio of oxygenated hemoglobin to the total concentration of hemoglobin, or simply:

$$SaO_2 = [HbO_2] / [\text{total concentration of hemoglobin}]$$

Equation 1

This SaO_2 is normally given as a percentage, and for a healthy individual is > 91% (on average however is around > 97%).

Due to the optical properties of both HbO_2 and Hb at 500nm-1000nm it is possible to measure oxygen saturation. We do this by measuring transmitted light (through the tissue, normally finger or earlobe) at two different wavelengths. Making the assumption that the transmission of light through the arterial bed is influenced only by the relative concentrations of oxygenated and reduced hemoglobin and their absorption coefficients at the two wavelengths, light intensity will decrease logarithmically according to Beer−Lambert's law (for a more detailed description on Beer-Lambert's law refer to appendix B). Using these principles we can obtain an expression for the ratio of the intensity of light transmitted at two different wavelengths given by:

$$R = \log_{10}(I_1) / \log_{10}(I_2)$$

Equation 2

Where I_1 is the intensity of light at λ_1 (wavelength 1) and I_2 is the intensity of light at λ_2 (wavelength 2). Once we know the absorbance coefficients of HbO_2 and Hb at the two wavelengths, we can find the oxygen saturation via the following formula:

$$SaO_2 = (\alpha_{r2}R - \alpha_{r1}) / [(\alpha_{r2} - \alpha_{o2})R - (\alpha_{r1} - \alpha_{o1})]$$

Equation 3

Where:

- α_{r1} is the absorption coefficient of Hb at wavelength 1
- α_{r2} is the absorption coefficient of Hb at wavelength 2
- α_{o1} is the absorption coefficient of HbO_2 at wavelength 1
- α_{o2} is the absorption coefficient of HbO_2 at wavelength 2
- R is the ratio from equation 2

The wavelengths of transmitted light through the tissue, is chosen to be at 660nm (red light) and 940nm (Infrared light). These are the most practically used values, due to the fact that light at this wavelength is least attenuated by body tissues (tissue and pigmentation absorb blue, green and yellow light).

3.3 The Signal

In pulse oximetry, only the part of the signal which is related to the inflow of arterial blood at that segment is used for the calculation of oxygen saturation. When light at these wavelengths (IR and red) is transmitted through the tissue it gives a pulsatile signal as shown in figure 2. This signal varies with time in relation to the heart beat. Therefore the heart rate of an individual can be extracted from this signal, (heart rate = frequency of signal). This is also useful when designing our system, as it gives us an idea of the frequency content of our signal.

Figure 2 Pulsatile signal obtained when IR or red light is transmitted through the finger. Figure taken from *Medical Electronics*, Dr. Neil Townsend.

As you can see from figure 2 the signal is a pulsating one, whose frequency is related to the individual's heart rate. From this we can extract the necessary information, which in our case will be the voltage measurements at any given time from this outputted signal. This voltage measurement relates to the intensity of the transmitted light and can be implemented into equation 2 and 3 in order to find our oxygen saturation reading. The signal in figure 2 however is just one example of a pulsating signal we can obtain. Different individuals produce small differences in the outputted signal (as will be seen in the results and discussion section of this report).

3.4 Methodology of Solution

Now that we have an understanding of the theoretical aspect of the pulse oximeter, and how we can get an electrical signal that relates to physiologic function, we must now design a system/device that can be used in obtaining this signal. The following is a brief description of implementation parameters of the pulse oximeter, to give an idea of how we can implement it directly from our theoretical understanding that has been established. In the next chapter we will present a much more detailed description of the implementation both on a large "big picture" scale (description of the whole system) and on a smaller "micro" (individual block) scale.

Since we are using the principles of light transmittance/absorbance through an arterial bed, we need a light source in order to transmit the light through a small area (such as the finger). We also need a detector that can convert the transmitted light into an electrical signal which would be our desired signal. Due to the fact that we are operating in a small area, we need small light sources and detectors. This can be accomplished via LED's and small photodetectors. These photodetectors are known as either photodiodes or phototransistors, which are optoelectronic devices that work off the principle of detection of incident light which is then converted into an electrical signal. This electrical signal is a current. Since in electrical systems we wish to work with voltages (due to many factors, for example: ease of use, voltages are easier to manipulate etc...) Therefore we need a system to convert this electrical signal into one we desire to work with. Also, since we wish to implement this system wirelessly, we need to be able to acquire it and transmit it with high fidelity so that we can ensure a proper oxygen saturation reading. On the receiving side of the process, we need to post process the signal and manipulate it (using equations 2 and 3) in order for us to obtain an oxygen saturation reading. As you can see both a hardware implementation (in order to acquire the signal) and software implementation (in order to post process it) are required. This report deals with acquiring and transmitting the signal, while the post processing was done by my colleague Kundan Thind (for a detailed account on the software component please refers to Kundan Thind's report).

This has been a brief introduction to the theoretical aspects of the pulse oximeter and how we can use this theoretical background, along with our known knowledge of electrical instrumentation and electrical systems in order to design a device that will be able to give us an oxygen saturation reading. However the methodology of implementation that has been presented in this chapter has been a gross oversimplification of the overall pulse oximeter system. The following chapter (chapter 4) will deal in detail with how this system was implemented starting from the simplest design to a more robust one.

Chapter 4

Experimental or Design Procedures

4.1 Introduction

In this chapter there will be a discussion on the design of the pulse oximeter system, starting from initial implementations, to further refinements. No results of the implementations will be presented in this chapter, but will be presented in the following chapter (chapter 5) where both the results and a detailed discussion will be presented. This section of the report will deal with first explaining the initial design overview, then the details of implementation of each section (block).

The whole system of the pulse oximeter can be shown as a single block from the whole Quick Doc system as shown in the figure below (and previously in chapter 1). The pulse oximeter block is the one we wish to implement and describe in this chapter.

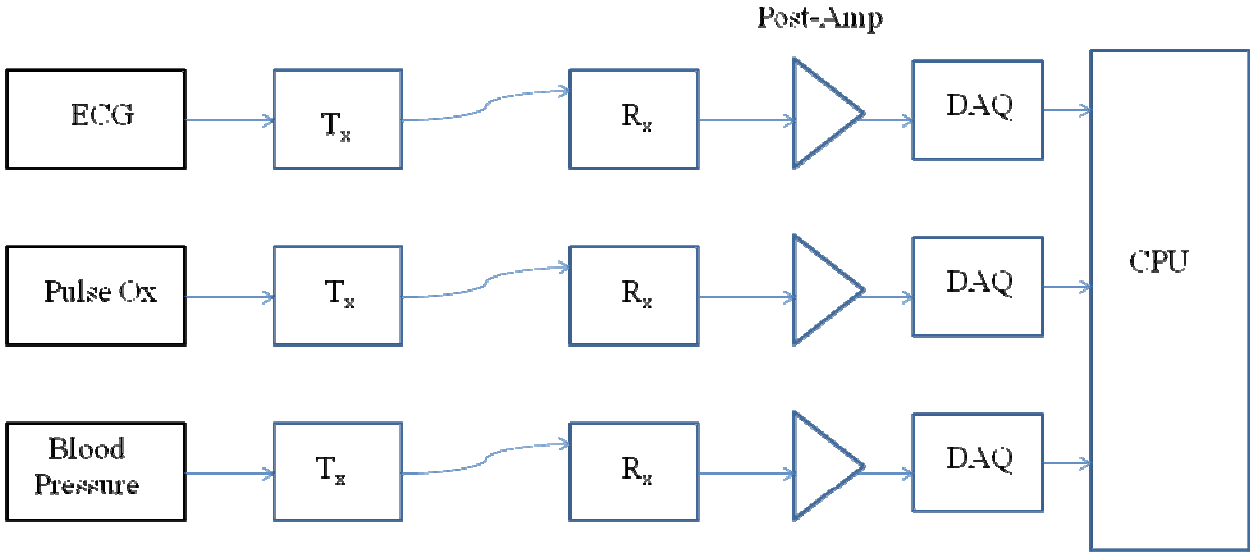

Figure 3: Depiction of the whole Quick Doc system, the pulse oximeter is the block that we wish to implement

4.2 Initial Design

As described earlier (chapter 3) pulse oximetry works on the principles of light transmittance/absorbance, therefore we need a photo emitter (LED circuitry) to emit light through the area of interest (finger) and a photodetector (phototransistor/photodiode) in order to convert this transmitted incident light into an electrical signal. Also it was discussed earlier that this electrical signal will be a current that corresponds to light intensity (the higher value of current the greater the light intensity). However, since we wish to work with voltages as opposed to currents (as described in chapter 3), we will need to convert this current into a corresponding voltage. This can be easily accomplished via a current-to-voltage convertor. This design can then give us an output signal that corresponds to a pulsatile signal which we can use to extract the oxygen saturation reading.

This system described above can be depicted via the following block diagram, which shows the LED circuitry, photodetector circuitry, and the current-to-voltage convertor, each represented by a block, (note that there are two of these systems, one for the red LED and one for the IR LED):

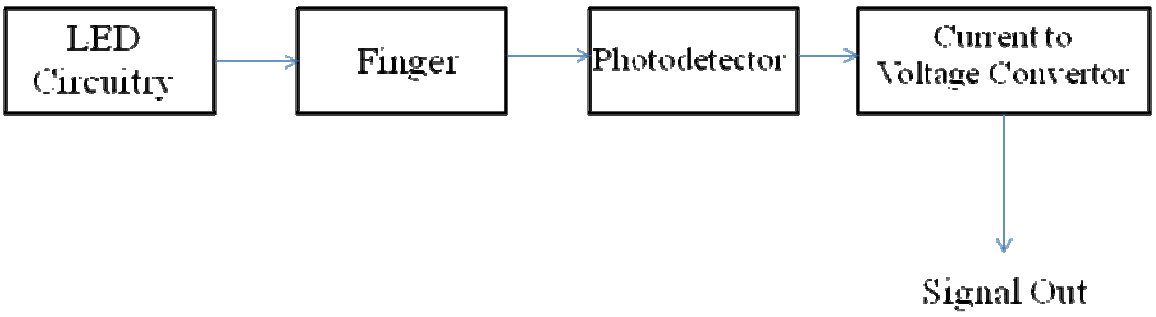

Figure 4: Initial design of the pulse oximeter

Now we will present schematic diagrams of each block that can be implemented as shown in the following figures. Note that first each block will be presented separately, and then the whole (initial) pulse oximeter system will be presented.

The following below is a schematic diagram of the LED circuitry involved in transmitting light through the finger, note that there would be two of these circuitry's one for each red LED and IR LED. The 5 V power supply causes a current flow through the resistor and LED, powering the LED and producing light. The purpose of the 100 Ω resistor is to regulate the current across the LED so that it does not burn out. The approximate current through this system is 50 mA (assuming the LED resistance is negligible).

Figure 5: Schematic for the LED circuitry, each Red and IR LED would have a separate circuitry associated with it

On the following page is a schematic diagram of both the photodetector (represented by a photodiode) and current-to-voltage convertor which is involved in detecting the transmitted light through the finger and converting that current into a voltage (note that there would be two of these circuitry's one for each red LED and IR LED). The incident light transmitted through the finger strikes the photodiode causing current to flow. This current then flows up through the 2MΩ resistor and creates a voltage at the output port of the operational amplifier which is our desired signal of interest.

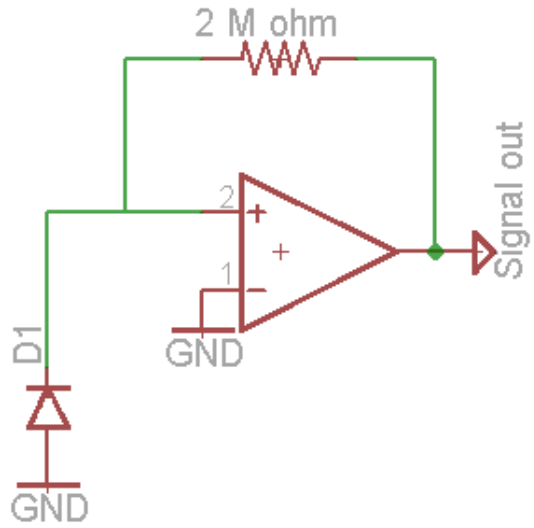

Figure 6: Schematic for the photodiode and the current-to-voltage convertor

Together the system can be represented with the following schematic, showing both "blocks" together (again this would be for implementing one LED):

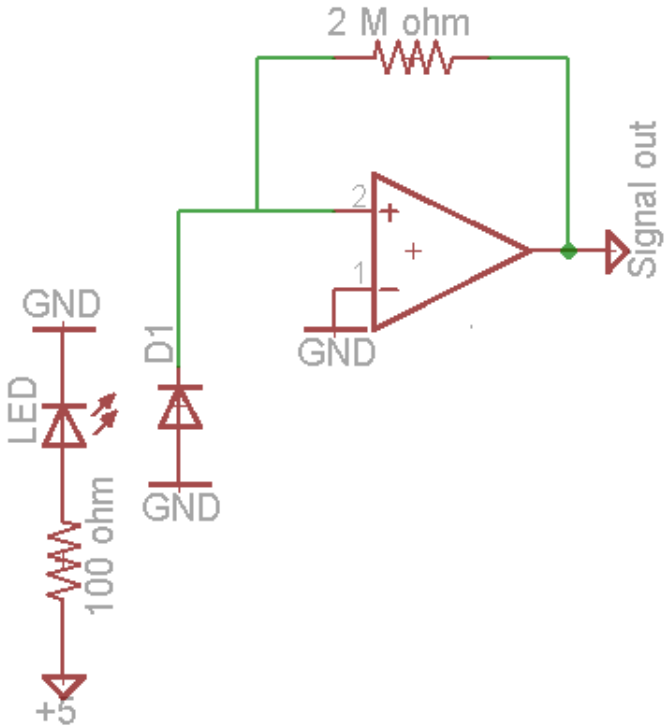

Figure 7: Schematic for the whole pulse oximeter (note this is the initial design)

4.3 Further Refinement

Although this system is very simple to implement and does produce a pulsatile signal (see results section), but due to a number of issues we wish to implement a further refined/robust system. The issues pertaining to the signal are due to the ability to transmit the signal with high fidelity. What this means is due to these issues (large DC offset, corruption by noise, low signal amplitude), we are unable to properly send/recover a signal from this simplistic system (for a more detailed discussion please see the results/discussion chapter). Realization of this allows us to implement a refined system that will deal with these issues and allow us to transmit/recover the signal with high fidelity. This involves some "pre-post-processing" in order so that we can properly send and recover a signal at the receiver (for a more detailed description of the issues, how they cause a problem, and how we deal with them please see chapter 5 results/discussions).

The following below is the block diagram for the refined system. It includes some post processing in order to deal with the numerous issues involved in transmission and recovering a RF signal. Also note again that there are two of these systems, one for the red LED and one for the IR LED:

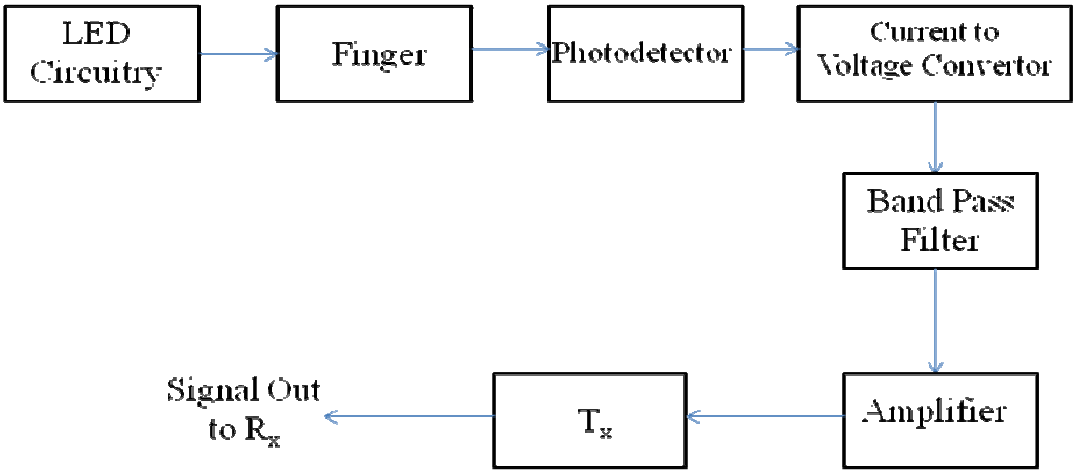

Figure 8: New design for pulse oximeter system, note that after the current to voltage convertor we have a filter and amplifier that does some post processing of the signal before transmission

Each of the first 3 blocks (LED Circuitry, photodetector, current-to-voltage convertor) can be implemented as shown before. The band pass filter and the amplifier implementation can be shown by the following schematic diagrams:

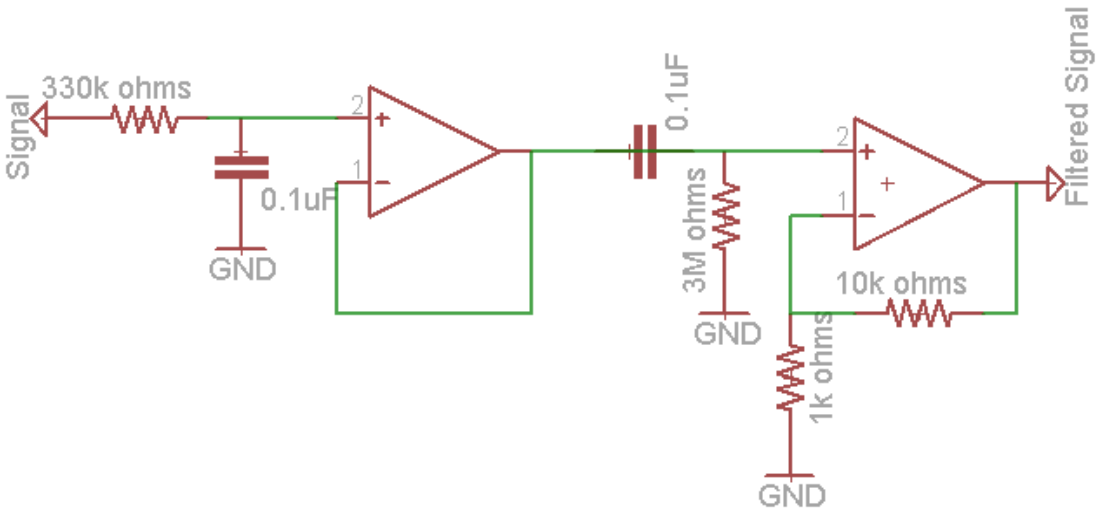

Figure 9: Schematic diagram for the Band pass filter with a small pre-amplification gain

The amplification stage can be represented by the following schematic:

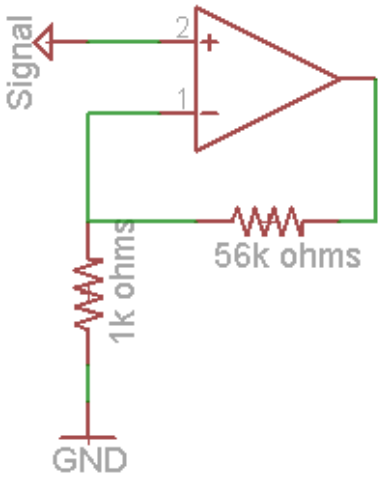

Figure 10: Schematic diagram for amplification stage

The purpose of the filter is to keep any frequency content between 0-5Hz and eliminate above and below this range (for a detailed discussion on this please refer to chapter 5). This has been implemented with the band pass filter shown in figure 1.4.7.

The low pass cut-off of this band pass filter is ~ 5Hz, which is accomplished via the combination of the 330kΩ resistor and the 0.1μF capacitor. The high pass cut-off of this filter is ~ 0.5 Hz and is accomplished via the combination of the 3MΩ and the 0.1μF capacitor. Also this filter has a pre-amplification via the 10kΩ and 1kΩ resistor combination at the inverting input of the operational amplifier. This combination gives us 11x amplification prior to sending it to the amplification stage, so that we get a larger signal amplitude.

The purpose of the amplification stage is to amplify the remaining signal as close to 5V as possible (so we still have a detectable signal at the receiver, see chapter 5 for more detail). This is accomplished by using a non-inverting amplifier with the combination of a 56kΩ resistor and a 1kΩ resistor. This gives us a gain of approximately 57x amplification.

The new design for the whole pulse oximeter can be depicted via the following schematic diagram on the following page.

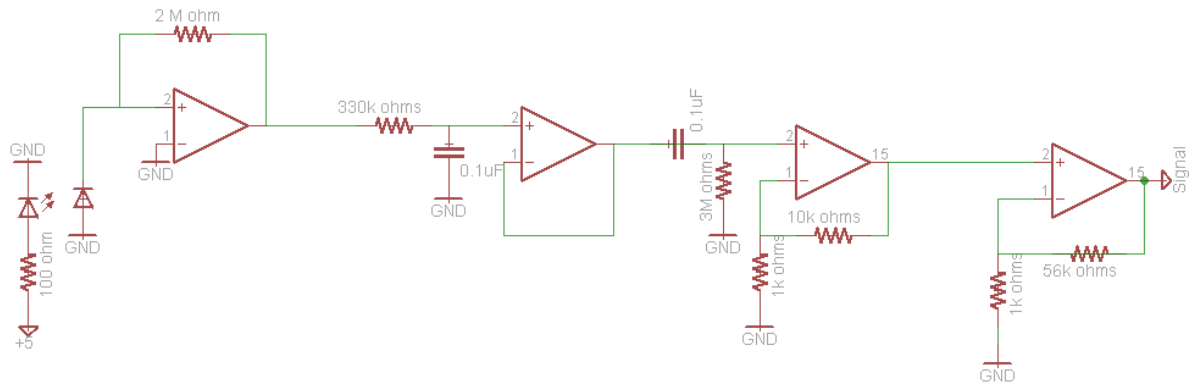

Figure 11: Schematic diagram for the whole pulse oximeter (note there would be two of these systems one for each of the red and IR LED's)

A further refinement and design were considered, however due to troubleshooting of these initial designs, constraints on funds, and time limitations, further exploration of a new and improved design was not possible. This will be discussed in a bit more detail in chapter 5.

Note that in this whole chapter we have only shown the implementation diagrams, and schematic diagrams with the use of 1 LED. However, in the actual system we use two LED's and therefore need two systems to produce a signal for both the red LED and the IR LED. To prove this concept however, we used one circuitry for both LED's (the reasoning for which will be discussed in chapter 5).

4.4 Implementation Details and Conclusion

In the actual implementation parts were ordered from the Digi-Key Corporation, and the design was implemented in the ITB 114 laboratory. The actual parts used are detailed in appendix D. The power supplies for the operational amplifiers are not shown in the above schematics and are assumed to be present. The power supply used for both the LED circuitry and the operational amplifier was from the power supply breadboards in the ITB 114 lab. To check our results and troubleshoot the circuitry, we used the oscilloscopes provided in this lab.

This has been a presentation of the experimental design procedures involved in implementation of the hardware for the pulse oximeter device that will be used in the Quick Doc system. This implementation process produced some valuable results that will be shown and discussed in the detail in the following chapter. We hope to have accomplished the goal that any individual with similar expertise and knowledge can implement such a device using our design.

Chapter 5

Results and Discussion

5.1 Introduction

This chapter of the report will deal with the results obtained from our experimental design, and a detailed discussion about them. Each design's results will be presented individually followed directly by a discussion on their merits, problems and solutions. A short description and discussion will be presented on the further refinement that was not implemented, but will not be the focus of this chapter.

5.2 Results and Discussion of Initial and Final Designs

The following was the block diagram for the initial design that was proposed to implement the pulse oximeter for the Quick Doc wireless system:

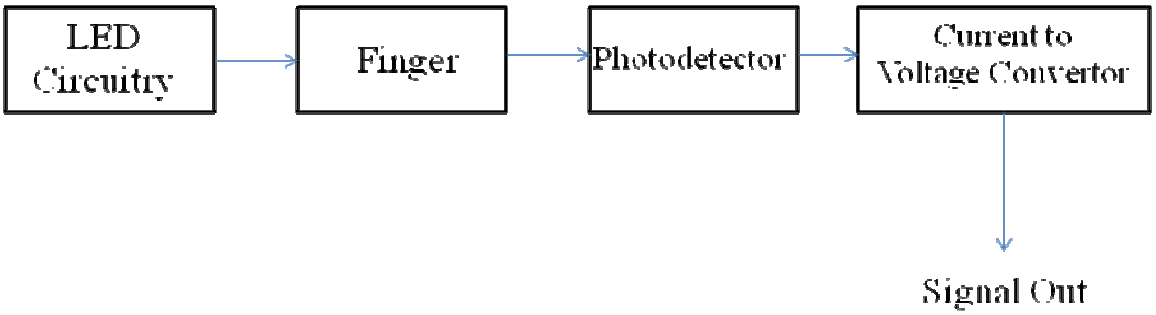

Figure 12: Initial design of the pulse oximeter

Its corresponding schematic was presented in chapter 4 by the following on the next page:

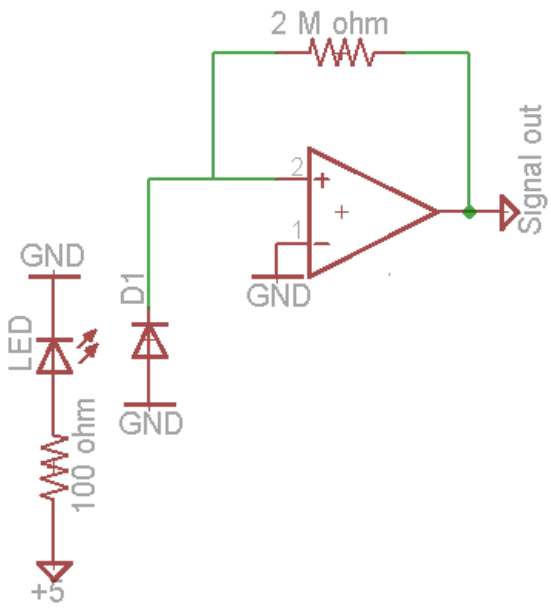

Figure 13: Schematic for the whole pulse oximeter (initial design)

The signal out would be measured by the oscilloscope, while the finger is between the LED and the photodetector (photodiode). The following signal results from the oscilloscope were obtained:

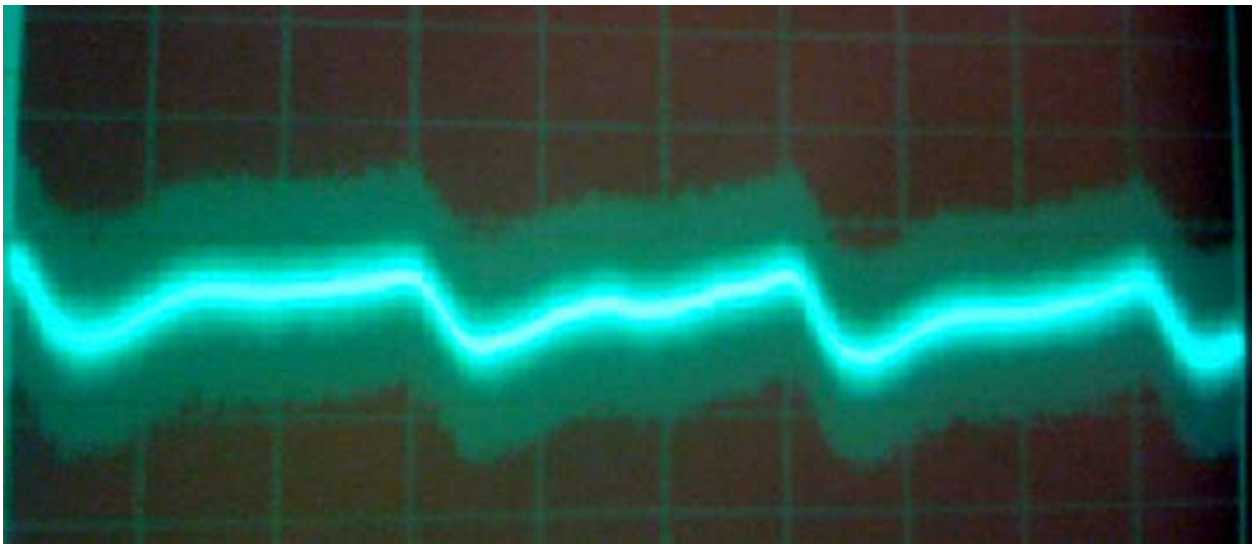

Figure 14: Pulsatile signal obtained using IR LED

Note that the red LED gave extremely similar results, however due to the nature of this signal (which will be discussed shortly) we are unable to adequately utilize it, therefore it was not presented.

The initial system has some advantage, as well as some major drawbacks. A summary are presented in table 1:

Advantages	Disadvantages
Simple design/easily implementable	AC signal is superimposed on a large DC offset
Saves on space	A lot of noise! (from various sources)
	Low signal amplitude
	Low signal amplitude + noise→ low SNR (signal to noise ratio)

Table 1: Summary of the advantages and disadvantages of the initial design

The one advantage to using the initial system (shown in figures 12 and 13) is that it is very simple in the fact that it only requires few components to implement. Due to this fact, it saves us space and allows us to easily implement it in the lab as well as incorporate it onto any wearable system. Although we are obtaining the pulsatile signal there are many drawbacks to this system, which can be due to the signal obtained (shown in figure 14). These issues pertain to our ability to transmit and receive this signal wirelessly with high fidelity. These number of problems are described in detail below.

Firstly, the pulsatile signal is superimposed on a much larger DC offset. This measured DC offset is approximately 100 times that of the amplitude of the AC signal (which is our desired output). This becomes a problem when we wish to post process the signal on the receiver side, as we wish to amplify the signal so that the data acquisition unit can actually detect the signal. However, if this signal is transmitted and received the large DC offset will also be amplified and will cause the amplifier to saturate much faster (since it is 100 times larger than the AC signal). We will therefore be unable to amplify

the signal to our desired value of approximately 1-5 V if we allow this DC offset to exist when we transmit the signal. Therefore we must remove this offset before transmission and amplification.

Also, there exists an overwhelming amount of noise (as can be seen in figure 14). This noise can be attributed to many sources, along with the 60 Hz power line noise, motion noise from movements by the user, and noise from any surrounding light sources (due to the fact we are detecting from the visible spectrum as well). This becomes a problem because there is a great amount of noise corrupting our signal and if we transmit this signal, it will only cause more noise to be added (in the wireless transmission and recovery). This may further swamp our signal to the point where we may be unable to detect a signal from noise. Therefore we must somehow remove this excess noise before transmission.

Furthermore, due to the nature of the signal (being a physiologic signal from the human body), the (AC) signal amplitude is extremely small. The amplitude is only approximately 1-10 mV. This is a problem in two ways. One is when we wish to transmit the signal wirelessly, due to the power required for the signal to radiate (even by small distances) we will have a signal loss at the receiver side of the transmission system. If our signal is only 10 mV before transmitting, our recovered signal will be in the range of μV! Also, since noise is also in the range of μV, our signal will be too corrupted at the receiving end of the transmission system to detect. Therefore we must amplify our signal as much as possible before transmitting this signal.

Finally, with a low signal amplitude in combination with noise, we will get a low SNR (signal to noise ratio), which is undesirable because then we cannot confidently say that the measurements extracted from the signal are actually signal measurements as opposed to measuring noise.

Although we are able to obtain a pulsatile signal that corresponds to the desired signal we wish to detect, due to the numerous issues mentioned earlier we are unable to

get a proper (or confident) measurement of voltages that correspond to the AC signal value. These values are needed for inputting into pulse oximetry equations (equations 2 and 3 given in chapter 3) so that we are able to obtain an oxygen saturation reading.

Due to these issues, we wish to remove such problems in order to improve our confidence and fidelity when transmitting and receiving the signal and thereby post process the signal in order to obtain an oxygen saturation reading that we can confidently say is correct. This can be done by including some post-processing of the signal before transmitting, receiving and processing it (again). The post processing that we included are: a band pass filter to remove the excess noise and DC offset and an amplifier to increase the signal amplitude to our desired value. By having the DC offset removed, we are able to amplify our signal without having to worry too much about saturating the amplifier. By removing the noise we get a "cleaner" signal that corresponds to the actual signal as opposed to random noise. Finally by amplification we increase the amplitude of the signal so that it can be detected by the data acquisition unit as well as increase the SNR which gives us that increased confidence in our measurements and therefore increased confidence in our oxygen saturation readings (as the oxygen saturation reading depends on the measurements obtained).

These changes can be reflected in our new design (that was presented in chapter 4) in the following figures:

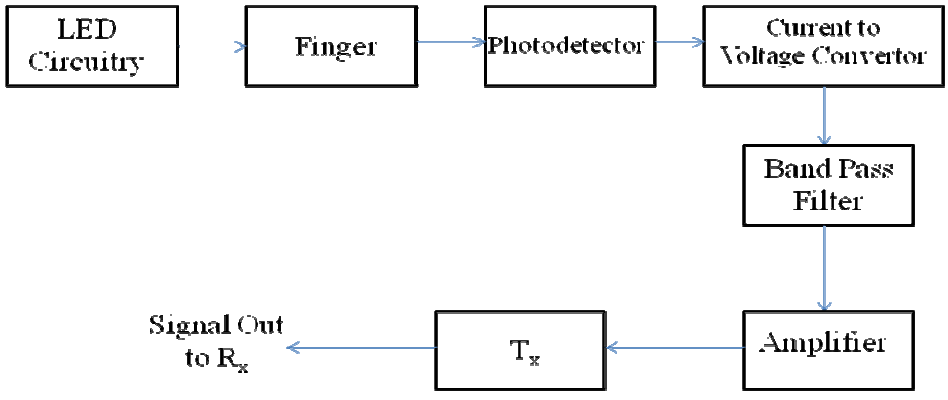

Figure 15: New design for pulse oximeter system, note that after the current to voltage convertor we have a filter and amplifier that does some post processing of the signal before transmission

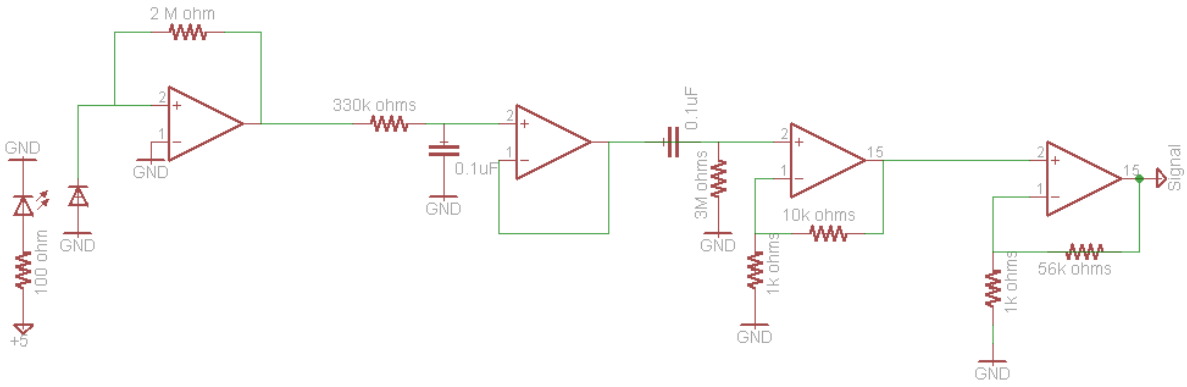

Figure 16: Schematic diagram for the new design of the pulse oximeter system

However, before continuing and simply implementing this system, we worked in a modular fashion. Since this new design is simply an extension of the initial design, we first implemented each new block in order to create a check point and ensure that our system is working at each of these points. Also working in this manner allows us to ensure that each new block is actually accomplishing its task. If ever a problem arose in the signal acquisition, or task of the block, we knew exactly where the problem is occurring.

The following is the implementation of an intermediate block diagram and schematic:

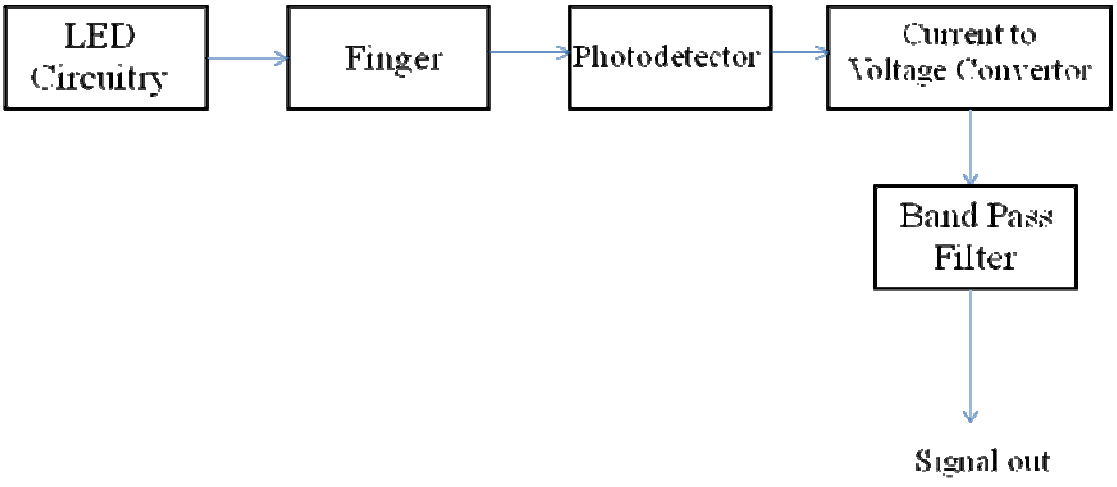

Figure 17: Intermediate block diagram of the new design, incorporation of a band pass filter only

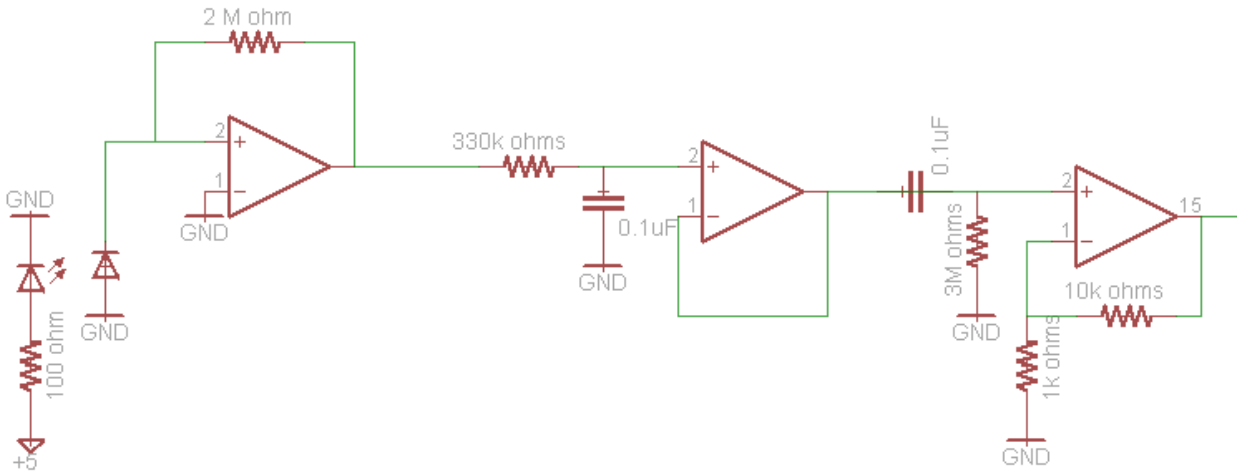

Figure 18: Intermediate schematic diagram of the new design, incorporation of the band pass filter only

The oscilloscope measurements obtained from this intermediate step are given on the following page for both the red LED and the IR LED:

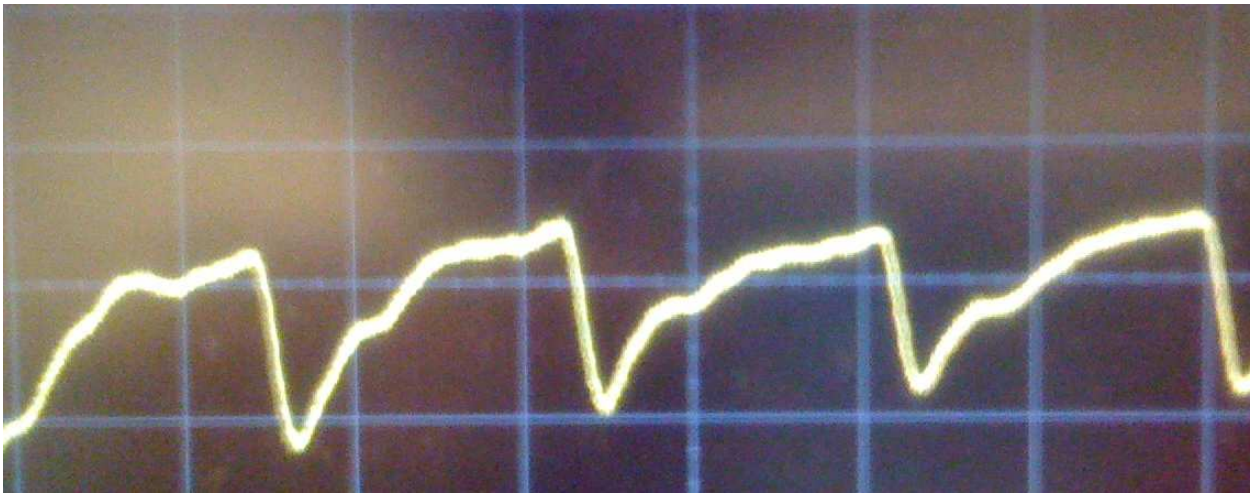

Figure 19: Oscilloscope reading from the red LED (each division is 10 mV)

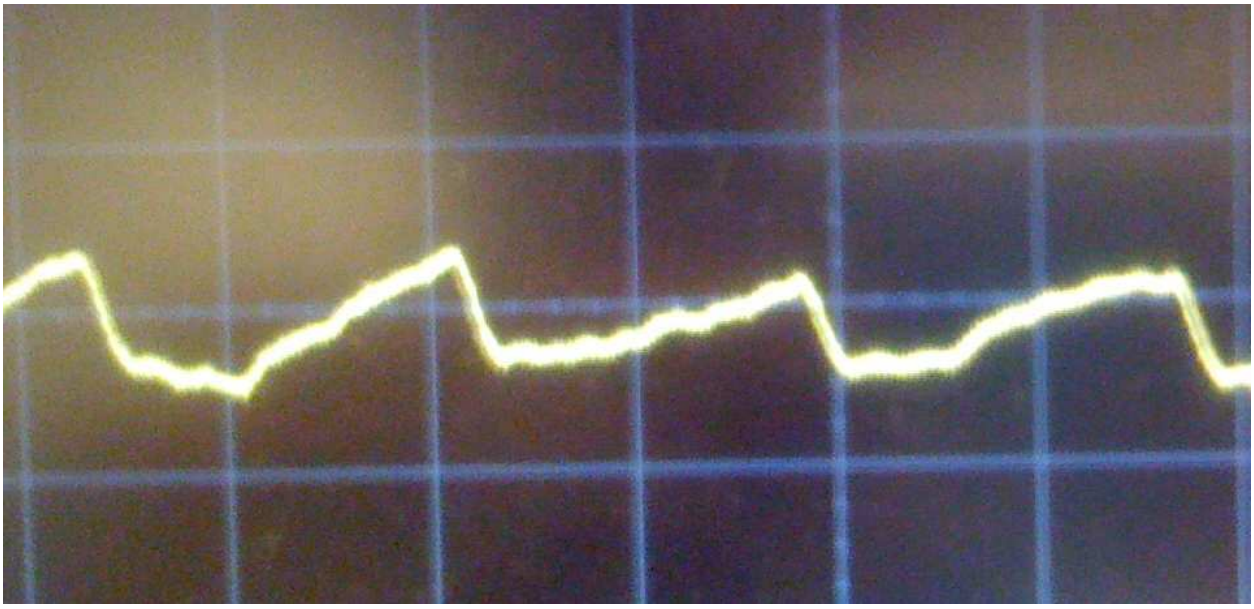

Figure 20: Oscilloscope reading from the IR LED (each division is 10 mV)

As you can see the band pass filter is accomplishing its tasks by removing the excess noise present in the signal, as well as removing the large DC offset. It does this due to the cascade of a low pass filter (whose cut-off frequency is 5 Hz) and a high pass filter (whose cut-off frequency is 0.5 Hz). The low pass stage (the combination of the 300 k Ω resistor and the 0.1μF capacitor, which give a ~ 5 Hz cut-off) eliminates any of the high frequency noise present in the signal. This also helps attenuate noise at the 60 Hz frequency range, which is our well known noise from the power lines. The high pass stage (the combination of the 3MΩ resistor and the 0.1 μF capacitor, which gives a ~ 0.5 Hz cut-off) attenuates the DC offset that we wish to eliminate, as well as any low frequency noise artifacts that are present due to motion of the individual user.

Although the signal amplitude is much too low to transmit it confidently, we still measure the voltage values for a trial run to ensure we are getting a proper oxygen saturation reading (using manual calculations for 3 different individuals). These results are tabulated in the table below:

Person #	IR voltage reading (mV)	Red voltage reading (mV)	Oxygen Saturation %
1	110	344	91.4
2	253	584	95.0
3	144	450	94.2

Table 2: Voltage readings for each of the LED's as well as the oxygen saturation in % for intermediate block diagram shown in figure 1.5.6

Note that none of these readings correspond to the figures above and were taken at a separate time, which will give different results. Also, the pre amplification for these measurements was increased from 10 times to approximately 57 times in order to get measurements in the 100 mV range. These results are from 3 different people, and measurements were done on the oscilloscope. The calculations were done manually by referring to equation 2 and 3 as well as the relevant constants (given in appendix C). As stated earlier (in chapter 3) for a healthy individual the oxygen saturation reading is >91% and in all three cases (in our INTERMEDIATE design) that these readings were all greater than 91%. This indicates that we are on the right path.

Now we must try and amplify this signal as much as possible so that it can be recovered confidently at the receiver. The block diagram and schematic for this portion is exactly the same as the ones in figure 15 and 16, and therefore are not shown again. However one difference to note is that the readings were taken from the scope and were not (yet) transmitted wirelessly for post processing.

The oscilloscope measurements obtained from our "final" design are given on the following page for both the red LED and the IR LED:

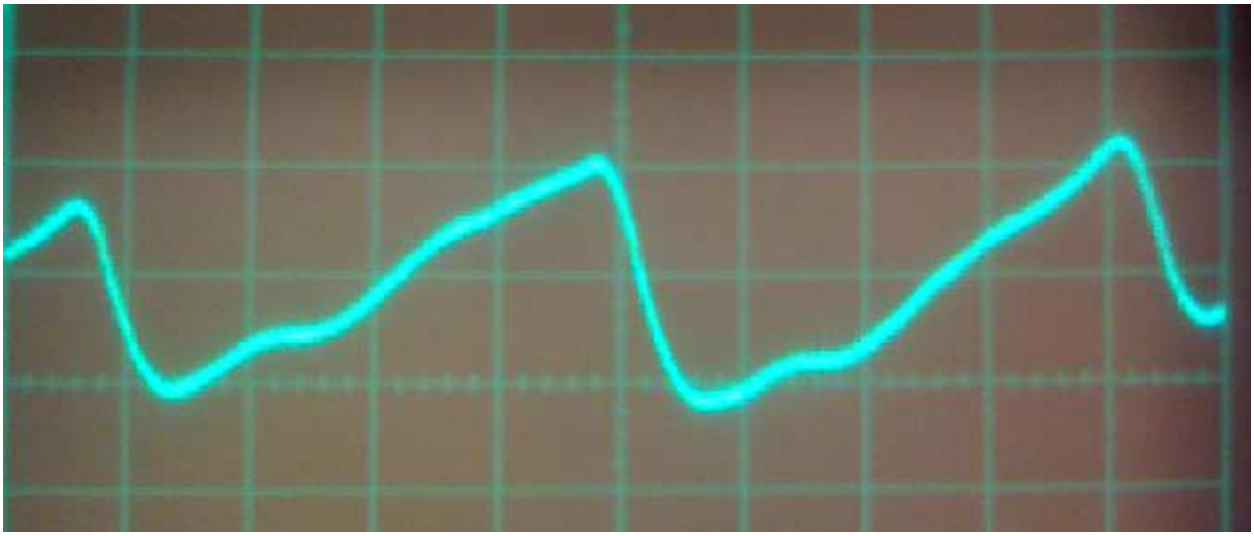

Figure 21: Oscilloscope reading from the IR LED (each division is 1 V)

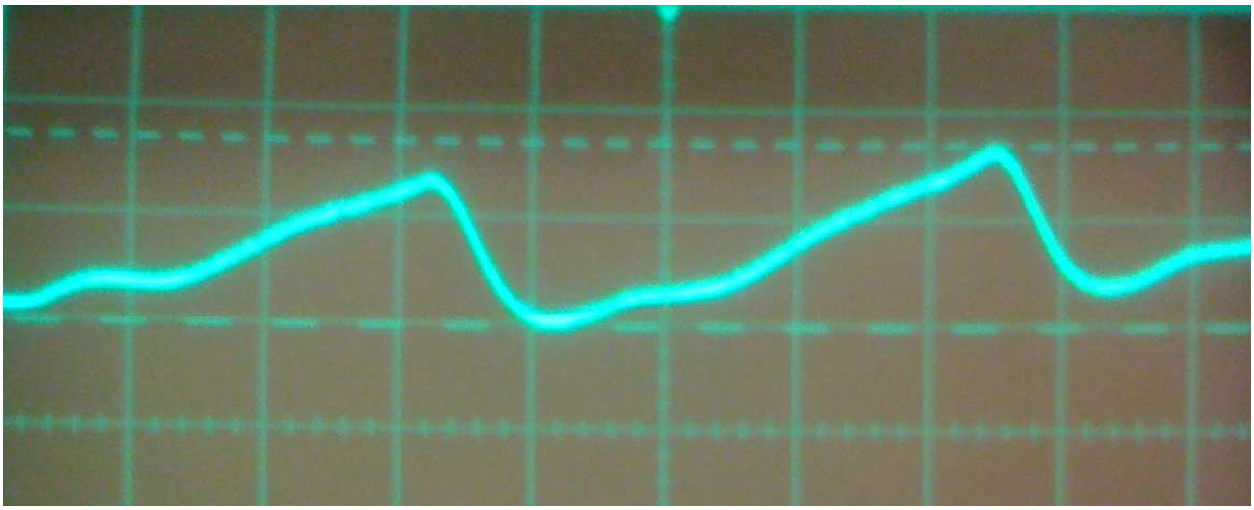

Figure 22: Oscilloscope reading from the IR LED (each division is 1 V)

As you can see the post amplification stage is accomplishing its task in amplifying the signal before transmitting it wirelessly to the receiving station where it will be further processed. The amplification was achieved by using a non-inverting operational amplifier configuration shown in figure 1.5.5 where the gain is given by $1+ R_2/R_1$, where R_2= 56 kΩ and R_1= 1 kΩ. This gives a gain of 57 times.

Since this is our desired signal we wish to transmit wirelessly and process at the base station, we measure the voltage values for a trial run to ensure we are getting a proper oxygen saturation reading (using manual calculations for 3 different individuals). This is done before wireless transmission to ensure accurate results. This also helps in troubleshooting, when if there is a problem with the oxygen saturation reading after implementing the wireless component we can conclude that something must be wrong with the wireless transmission or post processing, (as long as the oxygen saturation readings can be considered correct before hand). These results are tabulated in the table below:

Person #	IR voltage reading (V)	Red voltage reading (V)	Oxygen Saturation %
1	1.95	1.34	93.2
2	2.10	1.29	96.1
3	2.75	1.37	98.1

Table 3: Voltage readings for each of the LED's as well as the oxygen saturation in % for the final design

Note again, that none of these readings correspond to the figures above and were taken at a separate time, which will give different results. The pre-amplification of the band pass filter was readjusted to 10, while the amplification stage was 57 times. These results are from 3 different people, and measurements were done on again the oscilloscope. The calculations were done manually by referring to equation 2 and 3 as well as the relevant constants (given in the appendices). As stated earlier (in chapter 3) for a healthy individual the oxygen saturation reading is > 91% and in all three cases that these readings were all greater than 91% (mostly around 96%). This just reiterates that we are carrying on correctly.

Now that we have completed and shown that an implementation of a pulse oximeter system works, we move onto integrating it with the whole Quick Doc system. This means to now incorporate the wireless transmission aspect to the system and ensure

that it works correctly. As in chapter 1, the wireless transmission, recovery and post processing of the signal was handled by our colleague Kundan Thind. Therefore for a detailed description on this aspect of the project we ask the reader to refer to his report. However, we will present the pertinent details of his results that relate to the pulse oximeter project to show the reader that this goal of the project was accomplished.

The following figures are the results (MATLAB graphical) for both IR and red LED circuitries after wireless transmission but before post processing of the signal:

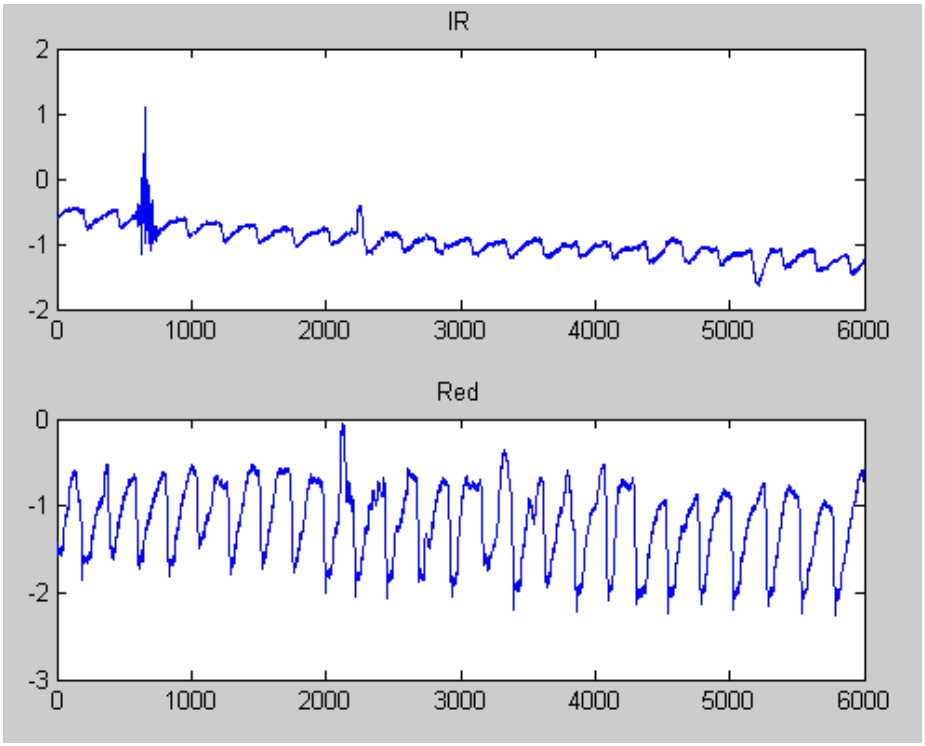

Figure 23: The signal after wireless transmission and acquisition for the IR LED, (note this is before any post processing/manipulating) taken courtesy from Kundan Thind

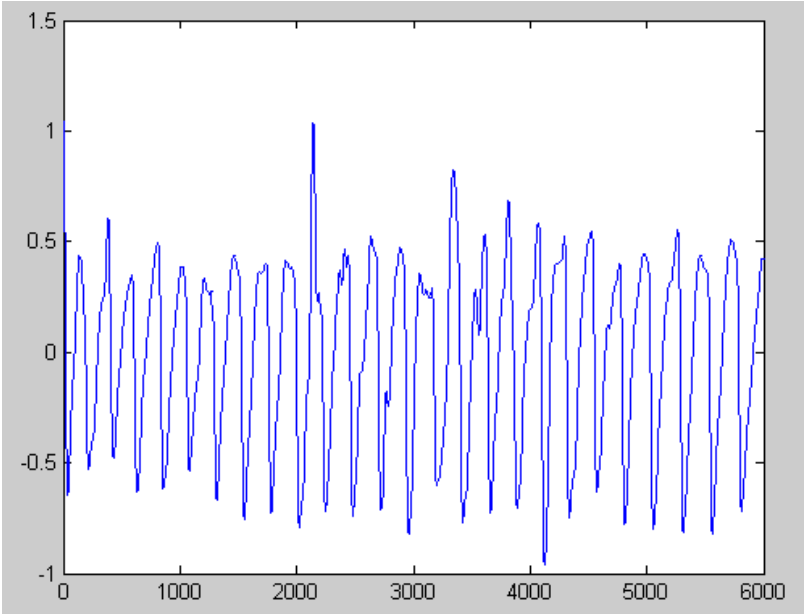

Figure 24: The signal after wireless transmission and acquisition for the red LED, (note this is before any post processing/manipulating) taken courtesy from Kundan Thind

After transmission and data acquisition the signal was post processed to give an oxygen saturation reading. The following are the signals after post processing of the signal:

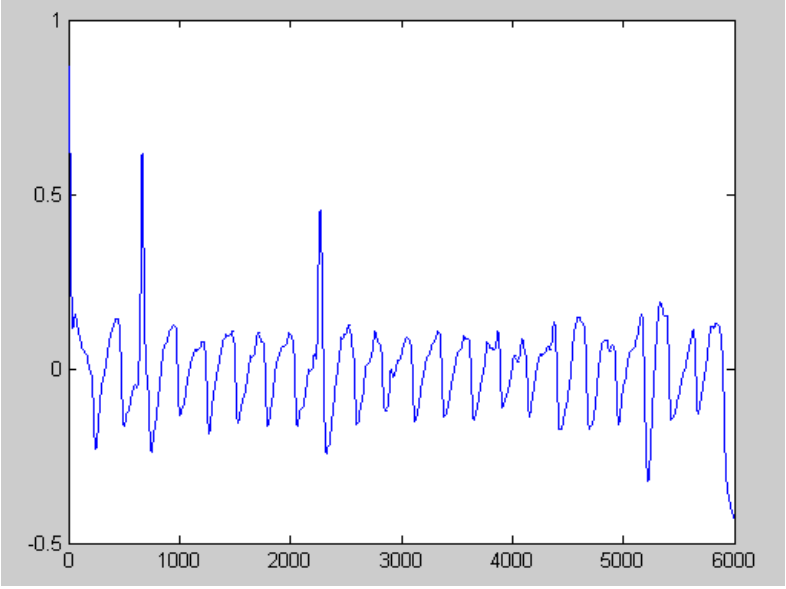

Figure 25: The signal after post processing of the IR LED signal taken courtesy from Kundan Thind

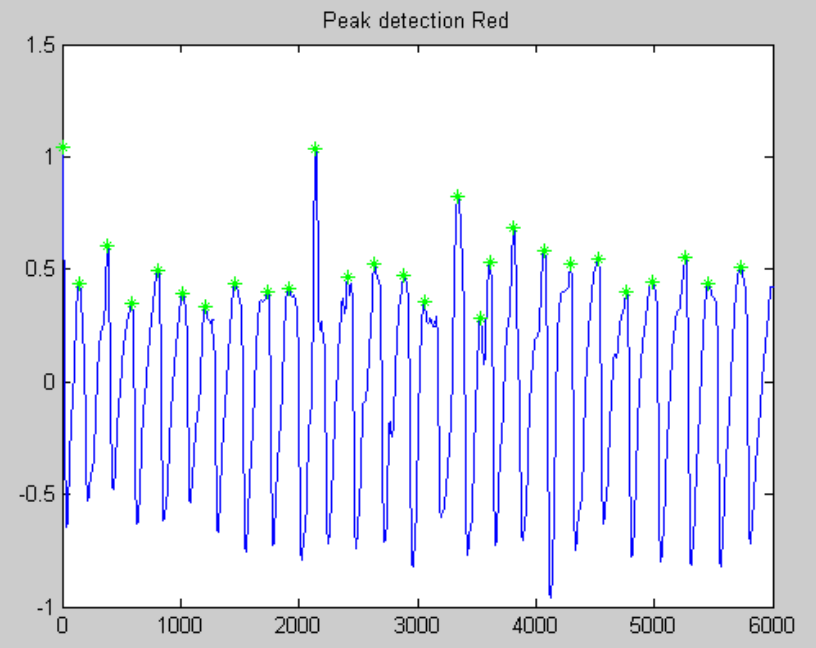

Figure 26: The signal after post processing of the red LED signal, taken courtesy from Kundan Thind

Due to time limitations we were only able to transmit, receive, acquire and manipulate the signal once, and therefore only have one set of results, which are given below. Note the scale of the vertical axis does not correspond to a scaled voltage value, while the horizontal axis corresponds to the number samples the data acquisition unit took (again for a more detailed and discussion on this please refer to the report by our colleague Kundan Thind).

The results obtained are given in the following table:

IR average	Red average	R ratio (given by equation 2)	Oxygen Saturation (%)
0.1170	0.4657	0.3561	96.35

Table 4: Results of signal manipulation in order to get an oxygen saturation reading

As stated many times before in this report we wish to obtain results (for healthy individuals) > 91%. The results from wirelessly transmitting acquiring and processing the signal have shown this and therefore we can conclude that they are correct/accurate.

5.3 Further Developments/Improvements and Conclusion

Although these results are accurate, they are also somewhat misleading. For our system we were sequentially acquiring each signal in time, as opposed to acquiring it parallel, i.e. at the same time. This was because of the fact that the wireless transmitter and receiver unit only had 1 channel and therefore we could not send more than one signal at a given time. Our Quick Doc project group looked into acquiring a more robust system, but due to limiting funds and the expense of such a transmitter receiver module (excess of $400) we decided to forgo such an acquisition scheme. Therefore our results do not correspond to an absolute oxygen saturation reading but rather an average of the blood oxygen saturation over the given acquisition time. This does not skew our results, because with our system we can tell if an individual is already at respiratory failure. Also, this system can easily be extended into one that gives an absolute oxygen saturation reading, which will be briefly described below.

The system for this can be accomplished by (rapidly) pulsing each of the LED's in time. Due to the fact we would be pulsing the LED's very rapidly in time we would then use a sample and hold circuit which can be use to reconstruct the pulsed signal. We would then send both the IR signal and red signal simultaneously via our wireless acquisition scheme (this wireless transmission system would have to send at least 2 signals at the same time). The rest of project in terms of post processing would remain the same. We would also need a timing circuit in order to ensure that all this runs synchronously in time. This would accomplish the goal in terms obtaining an absolute oxygen saturation reading in time. This can be represented by the following block diagram on the next page:

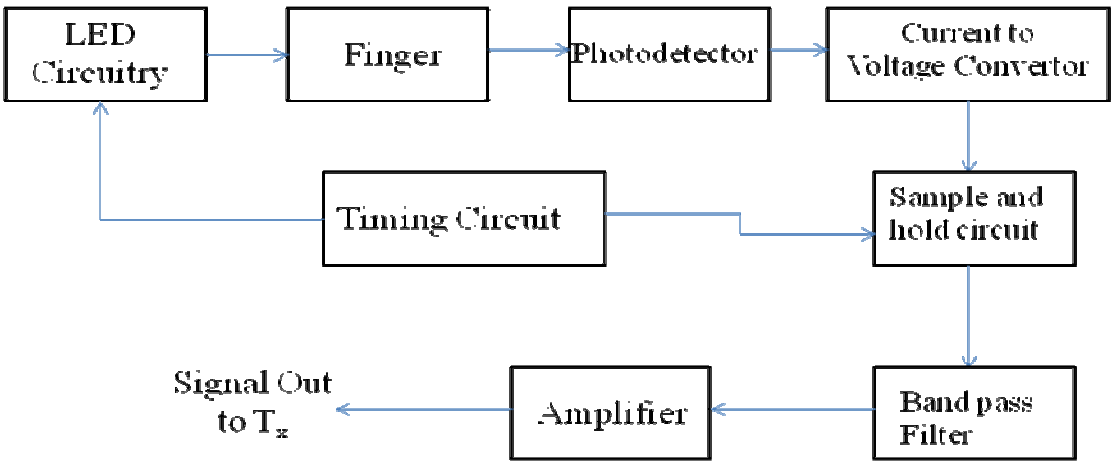

Figure 26: Block diagram for more robust model, however this was not implemented

In conclusion, this section has proven that we are able to obtain a pulsatile signal by using the theory and principles of pulse oximetry. We started by describing and implementing the initial design, which gave us a pulsatile signal, however was not adequate in order to wireless transmit and post process in order to obtain an oxygen saturation reading. We then went on to describe the next design which solved these issues, working in a modular fashion by implementing each block at a time. We then proved that this signal could be obtained and transmitted with high fidelity to obtain meaningful and correct results that we can be confident in. Therefore the proof of concept has been accomplished given our results.

Chapter 6

Conclusions and Recommendations

6.1 Introduction to Problem and Design Consideration

This chapter will be a concise and brief overview of the entire report and project, as well as emphasize the significant conclusions that we have reached throughout the year. We will also be presenting recommendations that can be sought out by the reader (if intended to work on a similar project).

Our group started by identifying a critical flaw in the health care system. We then went about identifying useful technology that exist, and how we can improve upon it. From this we came to the conclusion that we will be implementing a clinical diagnostic system that takes 3 physiologic measurements (an ECG, blood oxygen monitor, and blood pressure monitor) and transmit these signals wirelessly to a base station for processing so that they can be displayed in a useful manner. This was the problem/solution identification stage of our project. The block diagram for this whole project was previously presented in both chapter 1 and chapter 4 (figures 1 and 3 respectively)

6.2 Implementation and Conclusions Reached

This report deals with the implementation (specifically hardware implementation) of the blood oxygen monitor, which is better clinically known as the pulse oximeter. We first went about research into this field and why pulse oximetry is useful (see chapter 2 for literature review). After coming to a proper understanding behind the science of such a technology, we then went about a way to design a system that uses these principles to give us an electrical signal that we can use to find the oxygen saturation reading (this was presented both in chapter 3 and chapter 4 of this report). Once this was accomplished we went about actually implementing and trying to receive meaningful results from our designs.

An initial and simple design was first implemented using an LED to transmit light through the finger, a photodetector to "sense" the transmitted light and a current-to-voltage convertor in order to convert this into a more useable electrical signal. Implementation of this system was successful (see results and discussion chapter as well as figure 14). However, with this system we came to the following conclusion: it cannot be used in the Quick Doc system due to the simplicity of the design and the number of issues that do not allow us to confidently transmit our signal for processing (please see chapter 5 for a more detailed discussion). The problems that existed with this system were: large DC offset (approximately 100 times that of the AC pulsatile signal), a lot of noise from various sources that was corrupting our signal, low signal amplitude, and low SNR (signal to noise ratio).

From this initial conclusion, we came to the realization that there must exist some sort of (no matter how simple) post processing in order to transmit our signal wirelessly to the base station. We did this by adding a band pass filter to reject the large DC offset (at 0 Hz) and the reject any frequency higher than 5 Hz (thereby eliminating anything high frequency noise along with the 60 Hz noise). We also added an amplification stage so that in the transmission of the signal that it can still be recoverable and still have a high enough SNR at the receiver side to be detected with high fidelity by the data acquisition unit. This was presented in detail in chapter 4 and chapter 5 (block diagram given by figure 8 and schematic diagram given by figure 11).

We then went about implementing this new design modularly by first implementing one block at a time and ensuring that it was accomplishing its task as well as make some preliminary oxygen saturation readings (manual calculation). It was concluded that this new design was successful in eliminating all the previous issues (DC offset, noise, increasing signal amplitude), as well as (theoretically) allow for proper wireless transmission. The oxygen saturation readings that were obtained were between 91% - 97% (see results and discussion), and this can be considered accurate and correct as a healthy individual has an oxygen saturation > 91 %.

The next step was to implement the system wirelessly and ensure that we were getting a correct oxygen saturation reading. As stated earlier, the transmission, recovery and post processing of the signal was a separate component handled by our colleague Kundan Thind (therefore for a more detailed description on the transmission scheme, algorithm for processing the signals etc... please see Kundan Thinds report). It was found that we could implement the pulse oximeter system wirelessly (see results and discussion chapter) and obtain an oxygen saturation reading of 96.35%. We can conclude from this result that the main goals and objectives of the project have been reached, as we can obtain a pulse oximeter signal, transmit it wirelessly to a base station and process it to obtain meaningful and correct results.

6.3 Recommendations/Further Developments

We now present some recommendations that can be considered by the reader in order to further extend this project, but due to our constraints we were unable to implement them. Firstly, the current "final" design of our system gives us an oxygen saturation reading that can be considered an average of the oxygen saturation over the given acquisition time. This is due to the fact that our transmission unit could only transmit one signal at a time, and therefore we were constrained to sequentially sending signals, as opposed to sending them simultaneously. A further extension could then be to set up a wireless transmission system so that we are sending all of our signals at the same time. This allows for continuously and real-time monitoring of the individual. If this transmission scheme is used we can then extend the pulse oximeter project by using a timing circuit to pulse each signal and a sample and hold circuit to reconstruct the signal (see chapter 5 for block diagram, figure 27). The timing circuit would be necessary in order to ensure that all the events are happening synchronously in time. This however does have the draw back in making our system more complex and causing it to take up more room.

6.4 Final Conclusion and Remarks

In conclusion, in this project we have shown and proven with our implementation design, results, and discussion that a pulse oximeter signal can be obtained using transmission of light through the finger, which then can be processed by the necessary circuitry and then transmitted to the base station where it can be further processed. We have seen that the results of our implementation our successful due to the fact they give us a 96.35 % oxygen saturation reading (knowing that a healthy individual has an oxygen saturation reading of > 91 %). We can conclude that our main goals and objectives for this project have been reached.

Appendices

Appendix A: Physiology Theory/Background

In this portion of the appendix, we will be discussing a general overview of the physiological processes that happen in the body that are relevant to our project. Since the pulse oximeter is measuring the saturation of oxygen in the blood, we will be discussing the role/function of the blood in the circulatory system, gas exchange and gas transport in the blood for a respiratory point of view, as well a general overview of hemoglobin. The reader is not expected to have a very extensive background in these areas, but should have a very rudimentary understanding for these topics. We hope to have this section as a "refresher" for the reader.

It is obviously known that our body consists of blood. Blood serves many functions including: transportation of O_2, CO_2, nutrients, heat and hormones to the different tissues of the body, regulation of various aspects of the body including temperature, pH, and water content of the cells and protection from diseases and loss of blood. Blood consists of 3 different components: 1) plasma which is the liquid or "watery" component of the blood, this constitutes 55% 2) Erythrocytes, better known as red blood cells which constitute 45% and 3) Leukocytes, better known as white blood cells, which constitute less than 1%. Each of these components is required to perform its function. We are mainly interested in the red blood cell component, as it is the oxygen carrier of the blood and our goal is to measure the oxygen saturation of blood. Red blood cells are shaped like a biconcave disc as shown in the figure below. Red blood cells mainly consist of the protein hemoglobin which is the actual oxygen carrying molecule of the blood. Hemoglobin consists of 4 different protein structures (2 alpha chains and 2 beta chains) and each protein consists of a heme molecule that contains a centrally located Iron. The heme molecule is the actually responsible for binding with oxygen, and therefore each hemoglobin molecule can bind up to 4 oxygen molecules. A typical red blood cell consists of millions of hemoglobin molecules! Hemoglobin is depicted in the figure below, showing the details of the protein structure as well as the heme group which

binds to oxygen. These figures were taken from lecture notes from the Health Science 2LL3/2FF3 class taught at McMaster University:

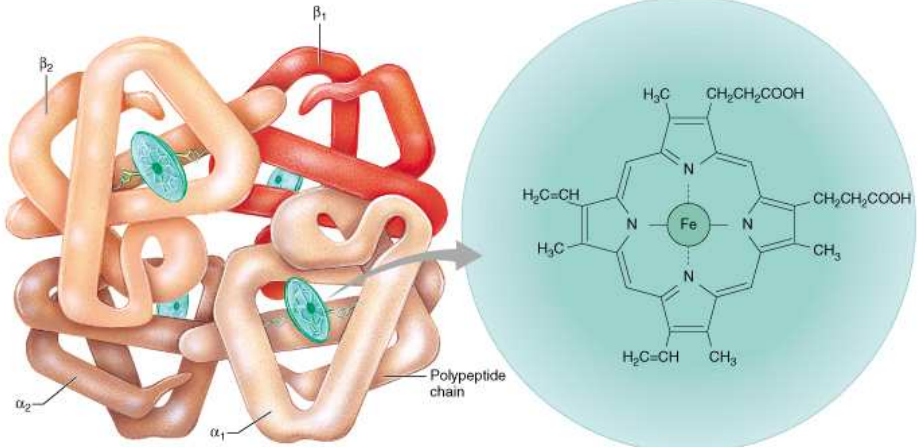

Figure 27: Hemoglobin protein showing the different structures

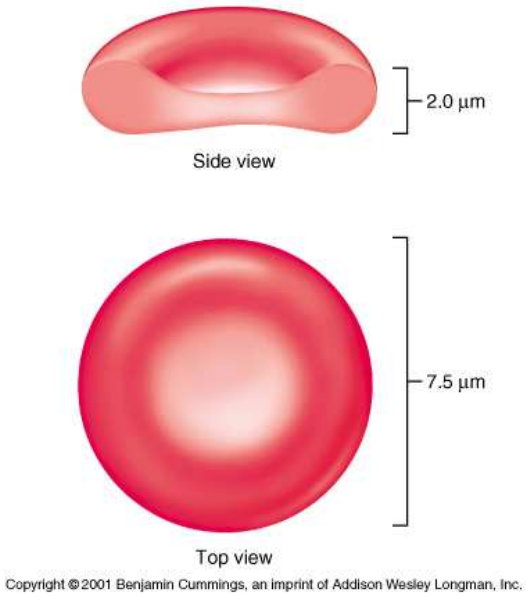

Figure 28: Red blood cell structure

Once air is breathed into the lungs blood that is pumped into the pulmonary system exchanges CO_2 and takes up (binds to) O_2. This is known as gas exchange in the blood. This occurs due to a partial pressure gradient that exists between the blood and inhaled air. Blood coming into the lungs has a lower partial pressure of O_2 and a higher partial pressure of CO_2. Due to the laws of gases, a gas particle will diffuse (move) from an area of higher pressure to lower pressure. Therefore this partial pressure gradient that exists facilitates the movement of oxygen to the red blood cells and carbon dioxide back out into the environment.

Hemoglobin (as mentioned earlier) has a property that when bound to oxygen it causes the hemoglobin to bind more easily to more oxygen. This gives a characteristic oxygen-hemoglobin dissociation curve that is well known to physiologists and is presented below (again this figure was taken from the lecture notes from Health Science 2LL3/2FF3 class taught at McMaster University):

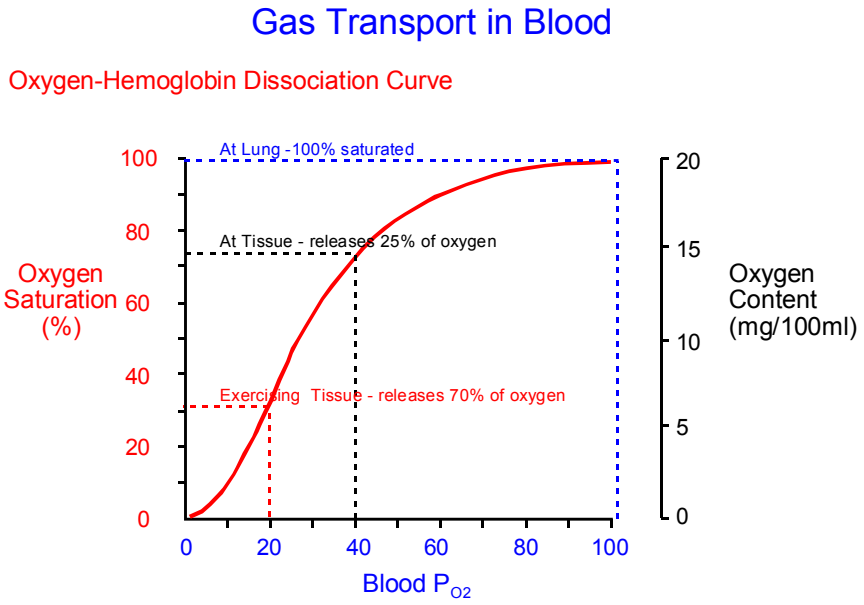

Figure 29: Oxygen-Hemoglobin dissociation curve

From this figure we can conclude that arterial blood must be close to 100% saturated when delivering blood to the various body tissues. We can also see from this figure that once oxygen is also released (or taken up) that this facilitates more oxygen to be released and therefore gives a characteristic "S" shaped curve.

Appendix B: Details of Pulse Oximetry

This portion of the appendix will be a more detailed overview of pulse oximetry. Some of the information presented here will be repeated from chapter 3 which gives an overview of the subject.

As described earlier in the appendix hemoglobin is the molecule that binds to oxygen, and we wish to measure the oxygen content of the blood. This is most commonly done by the following formula that is known as the oxygen saturation formula:

$$SaO_2 = [HbO_2] / [\text{total concentration of hemoglobin}]$$

Equation 1

This SaO_2 is normally given as a percentage, and for a healthy individual is > 91% (on average however is around > 97%).

Hemoglobin has very special optical properties of both HbO_2 and Hb at 500nm-1000nm. Due to these properties it is possible to measure oxygen saturation. This can be shown by the following figure:

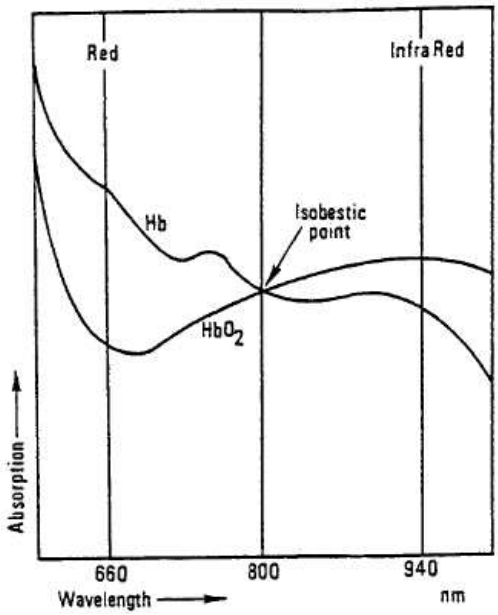

Figure 30: Optical properties of hemoglobin shown from 660 nm to 940 nm. This figure was taken from *Medical Electronics*, Dr. Neil Townsend 2001

From the above figure we can see that the absorption of light by hemoglobin varies with wavelength. Therefore we can use this fact and thereby measure the transmitted light (through the tissue, normally finger or earlobe) at two different wavelengths. Making the assumption that the transmission of light through the arterial bed is influenced only by the relative concentrations of oxygenated and reduced hemoglobin and their absorption coefficients at the two wavelengths, light intensity will decrease logarithmically according to Beer−Lambert's law.

Beer-Lambert's famous law relates the absorption of light to the properties of the material the light is passing through. This law states that the intensity of light will decrease via logarithmic dependence between the incident light (Io) through a substance and the product of the absorption coefficient of the substance, α, and the distance the light travels through the material (known as the path length), ℓ. This can be related by the following formula:

$$T = I/Io = 10^{-\alpha \ell}$$

Equation 2

This law is important as we try to use it in order to figure out the oxygen saturation. Assuming that the transmission of light through the arterial bed is influenced only by the relative concentrations of oxygenated and reduced hemoglobin and their absorption coefficients at the two wavelengths we obtain the following relation using the above Beer-Lambert's equation:

$I_1 = 10^{-(\alpha r1 * Cr + \alpha o1 * Co)}$ for light at wavelength 1 and $I_2 = 10^{-(\alpha r2 * Cr + \alpha o2 * Co)}$ for light at wavelength 2

Equation 3

Using these principles we can obtain an expression for the ratio of the intensity of light transmitted at two different wavelengths given by:

$$R = \log_{10}(I_1) / \log_{10}(I_2)$$

Equation 4

Where I_1 is the intensity of light at λ_1 (wavelength 1) and I_2 is the intensity of light at λ_2 (wavelength 2). Once we know the absorbance coefficients of HbO_2 and Hb at the two wavelengths, we can find the oxygen saturation via the following formula:

$$SaO_2 = (\alpha_{r2}R - \alpha_{r1}) / [(\alpha_{r2} - \alpha_{o2})R - (\alpha_{r1} - \alpha_{o1})]$$

Equation 5

Where:

- α_{r1} is the absorption coefficient of Hb at wavelength 1
- α_{r2} is the absorption coefficient of Hb at wavelength 2
- α_{o1} is the absorption coefficient of HbO_2 at wavelength 1
- α_{o2} is the absorption coefficient of HbO_2 at wavelength 2
- R is the ratio from equation 4

The wavelengths of transmitted light through the tissue, is chosen to be at 660nm (red light) and 940nm (Infrared light). These are the most practically used values, due to the fact that light at this wavelength is least attenuated by body tissues (tissue and pigmentation absorb blue, green and yellow light).

Appendix C: Optical coefficients

The following is a list of molar extinction coefficient *e* in order to calculate the absorption coefficient values which are in turn used to calculate the oxygen saturation. These values for the molar extinction coefficient *e* in [cm^{-1}/(moles/liter)] were compiled by Scott Prahl (prahl@ece.ogi.edu) using data from W. B. Gratzer, Med. Res. Council Labs, Holly Hill, London and N. Kollias, Wellman Laboratories, Harvard Medical School, Boston.

Since we wish to convert these values into a absorption coefficient (A), we need to convert this data by the following formula:

$$A = \frac{(e)\ [(1/cm)/(moles/liter)]\ (x)\ [g/liter]\ (1)\ [cm]}{64{,}500\ [g/mole]}$$

Lambda nm	HbO_2 cm^{-1}/M	HbO cm^{-1}/M
600	3200	14677.2
602	2664	13622.4
604	2128	12567.6
606	1789.2	11513.2
608	1647.6	10477.6
610	1506	9443.6
612	1364.4	8591.2
614	1222.8	7762
616	1110	7344.8
618	1026	6927.2
620	942	6509.6
622	858	6193.2
624	774	5906.8
626	707.6	5620
628	658.8	5366.8
630	610	5148.8
632	561.2	4930.8
634	512.4	4730.8
636	478.8	4602.4
638	460.4	4473.6
640	442	4345.2
642	423.6	4216.8

644	405.2	4088.4
646	390.4	3965.08
648	379.2	3857.6
650	368	3750.12
652	356.8	3642.64
654	345.6	3535.16
656	335.2	3427.68
658	325.6	3320.2
660	319.6	3226.56
662	314	3140.28
664	308.4	3053.96
666	302.8	2967.68
668	298	2881.4
670	294	2795.12
672	290	2708.84
674	285.6	2627.64
676	282	2554.4
678	279.2	2481.16
680	277.6	2407.92
682	276	2334.68
684	274.4	2261.48
686	272.8	2188.24
688	274.4	2115
690	276	2051.96

900	1198	761.84
902	1202	765.04
904	1206	767.44
906	1209.2	769.8
908	1211.6	772.16
910	1214	774.56
912	1216.4	776.92
914	1218.8	778.4
916	1220.8	778.04
918	1222.4	777.72
920	1224	777.36
922	1225.6	777.04
924	1227.2	776.64
926	1226.8	772.36
928	1224.4	768.08
930	1222	763.84
932	1219.6	752.28
934	1217.2	737.56
936	1215.6	722.88
938	1214.8	708.16
940	1214	693.44

942	1213.2	678.72
944	1212.4	660.52
946	1210.4	641.08
948	1207.2	621.64
950	1204	602.24
952	1200.8	583.4
954	1197.6	568.92
956	1194	554.48
958	1190	540.04
960	1186	525.56
962	1182	511.12
964	1178	495.36
966	1173.2	473.32
968	1167.6	451.32
970	1162	429.32
972	1156.4	415.28
974	1150.8	402.28
976	1144	389.288
978	1136	374.944
980	1128	359.656

The values here are given for the range of red light and IR light, (for this project however the red light that was used was from the 660nm wavelength, and the IR light was from the 940 nm wavelength).

Appendix D Part List

The parts that were used are given below:

Operational Amplifiers..... National Semiconductor LM1458/LM1558

IR LED.... FAIRCHILD Semiconductor 1N6264 GaAs INFRARED EMITTING DIODE

Red LED.....CML Innovative Technologies Inc CMD50B

Photodetector...LITE ON Technology Corporation IR Phototransistor NPN 160-1065-ND

Photodetector.....IR Photodiode SILONEX INC SLD-70IR2A

Photodetector.....Red Photodiode SILONEX INC SLD-70BG2A

Resistors.....Kit 1.0- 1.0M RS125-ND

Capacitors..... 0.1µF 399 4331-ND

All parts were ordered online from Digi-Key Corporation.

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