ABSTRACT

Signal Acquisition and Processing of
Biomedical Vital Signs for Ubiquitous Healthcare

Fan Zhang, M.S.E.C.E

Mentor: Liang Dong, Ph.D.

Healthcare is transforming from reactive and hospital-centered to preventive, proactive and person-centered. In addition to treating diseases, it is important that more effort is on monitoring and maintaining the well-being of individuals. In this thesis work, we focus on the non-invasive signal acquisition and signal processing of biomedical vital signs for ubiquitous healthcare. These vital signs include electrocardiography, pulse oximetry, Stethoscope, and blood pressure. Information and communications technology is required to develop and deliver high-quality and efficient healthcare. We discuss the sensor technology, develop the schemes of digital signal processing, communications and networking, as well as implement an e-health system with special applications to elder care.

Signal Acquisition and Processing of
Biomedical Vital Signs for Ubiquitous Healthcare

by

Fan Zhang, B.S.,M.S.

A Thesis

Approved by the Department of Electrical and Computer Engineering

Kwang Y. Lee, Ph.D., Chairperson

Submitted to the Graduate Faculty of
Baylor University in Partial Fulfillment of the
Requirements for the Degree of

Master of Science in Electrical and Computer Engineering

Approved by the Thesis Committee

Liang Dong, Ph.D., Chairperson

Paul Grabow, Ph.D.

Michael W. Thompson, Ph.D.

Accepted by the Graduate School
May 2014

J. Larry Lyon, Ph.D., Dean

Page bearing signatures is kept on file in the Graduate School.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my advisor Dr. Liang Dong for all his guidance, support and patience in my graduate study and research. Besides my advisor, I would like to thank the rest of my committee: Dr. Michael W. Thompson and Dr. Paul Grabow for reviewing my thesis and giving valuable comments. My sincere thanks also go to Dr. Michael W. Thompson for the help he gave in completing the Masters program. I am thankful for the education of Department of Electrical and Computer Engineering and Baylor University. Last but not the least, I would like to thank my family in China, and thank my wife, for all their support and encouragement.

DEDICATION

To My Mom, Dad and α

CHAPTER ONE

Introduction

1.1 Motivation

Populations in this World are rapidly ageing. As shown in the Figure 1.1 and Figure 1.2, in 2010, the United States have 40 million people are age 65 and over, which accounting for 13 percent of the total population. This group grew from 3 million in 1900 to 40 million in 2010. The Baby Boomers (those born between 1946 and 1964) started turning 65 in 2011, and the number people 65 and over will increase dramatically during the 2010-2030 period. In 2030 the older population will represent nearly 20 percent of the total U.S. population. [1] [2]

In 2010, 43 percent of Sumter County, Florida, was age 65 and over, the highest proportion in the country. In several Florida counties, the proportion was over 30 percent. [1]

At the other side of the Pacific Ocean, China government also faced the problem of ageing (Figure 1.3 and Figure 1.4). The older people in China in 2000 years are 7%, and it reached to 7.8% in 2005. After 2005 the aging speed will accelerate. According to the Projection, from 2015 to 2035, the older people in china will be double, reach to 20%. Which is 0.4 billion. [3] [4]

Japan, the country have highest life expectancy, aging population is outweigh all other nations. As the country has more than 23% of the citizens are over the age of 65 today. [5] [6]

In Europe, there is a phase called greying of Europe, which means the older people in Europe become more and more. [7] In Germany [8] [9], Italy and Greece [10] [11]the percentage of population age 65 and over is more than 20%.

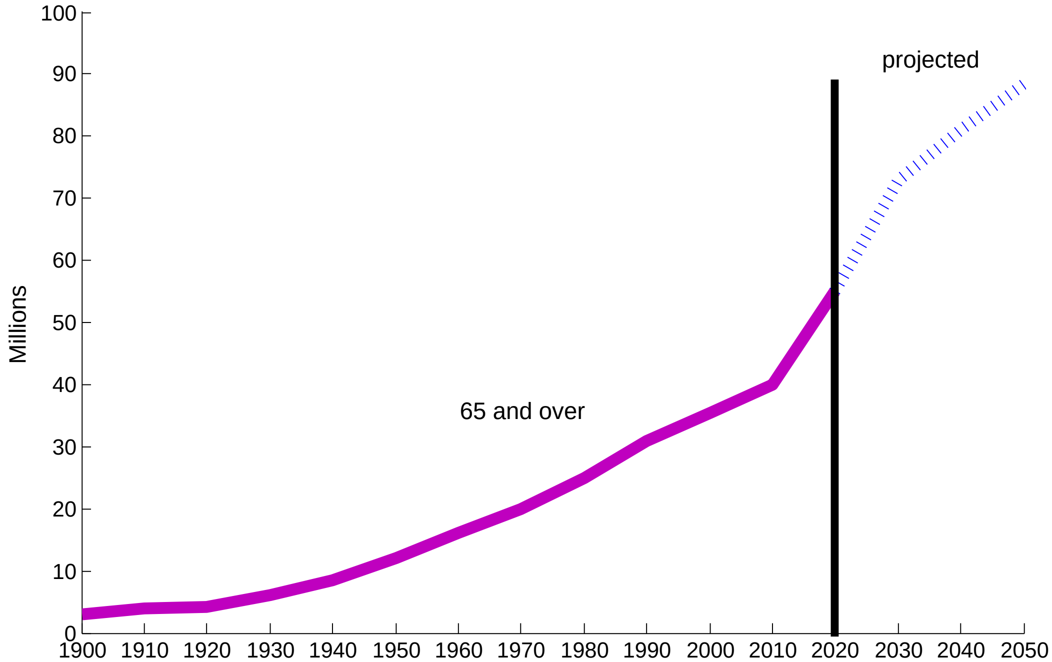

Figure 1.1. The Population of USA age 65 and over, selected years 1900-2010 and projected 2020-2050

Table 1.1. The percentage of the elderly in other countries

Country	Percentage of age over 65	Country	Percentage of age over 65
Italy	>20%	Spain	18-20%
Greece	18-20%	Denmark	18-20%
Austria	18-20%	France	16-18%
Sweden	18-20%	UK	16-18%
Germany	>20%	Finland	16-18%

Due to the older people increase fast in future worldwide, the need for healthcare is extremely big. That will become a big problem for the government. In American, the National Since Foundation (NSF) and National Institutes of Health (NIH) [12] opened a program together named Smart and Connected Health (SCH). The goal of SCH Program is to accelerate the development and use of innovative approaches that would support the much needed transformation of healthcare from reactive and hospital-centered to preventive, proactive, evidence-based, person-centered

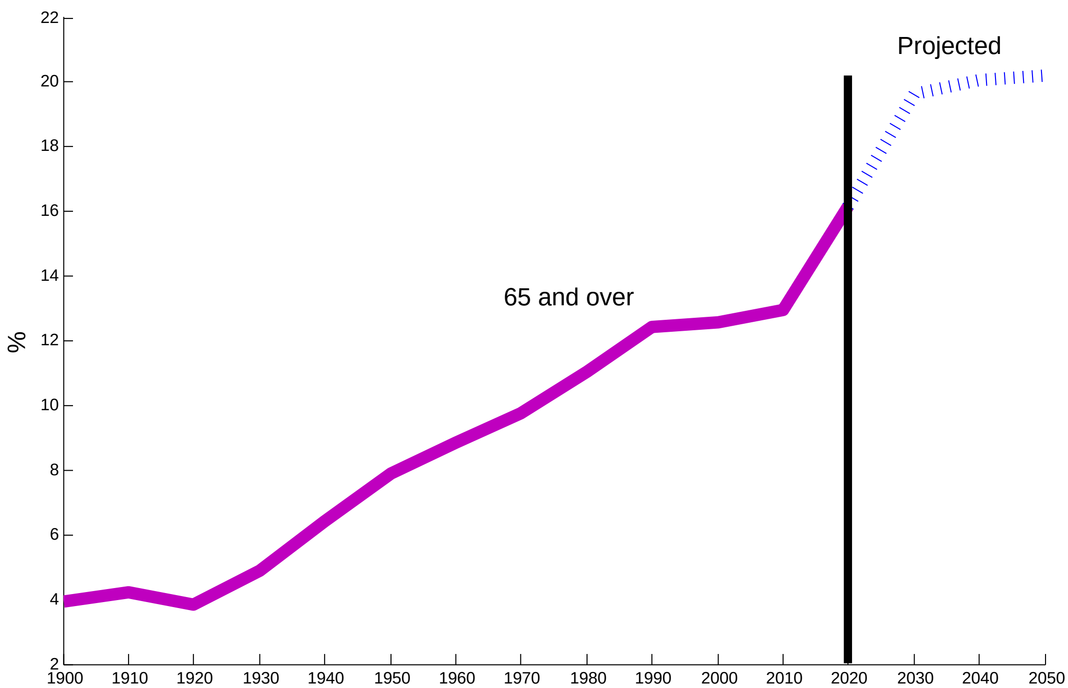

Figure 1.2. The Population of USA age 65 and over (% of total)

and focused on well-being rather than disease. The objectives of SCH is seek improvements in safe, effective, efficient, equitable, and patient-centered health and wellness services through innovations in computer and information science, engineering, social, behavioral and economic science and medical science. That lead to the concept of E-Health which we will discussed following.

1.2 E-Health

Joaquin (2010) [13], defined e-health as the use of information and communications technologies (ICT) in support of health and health-related fields, including health-care services, health surveillance, health literature, and health education, knowledge and research and noted that it has the potential to greatly improve health service efficiency, expand or scale up treatment delivery to thousands of patients in developing countries, and improve patient outcomes. According to Joaquin (2010), information systems, such as electronic health records (EHRs) and mobile phones and

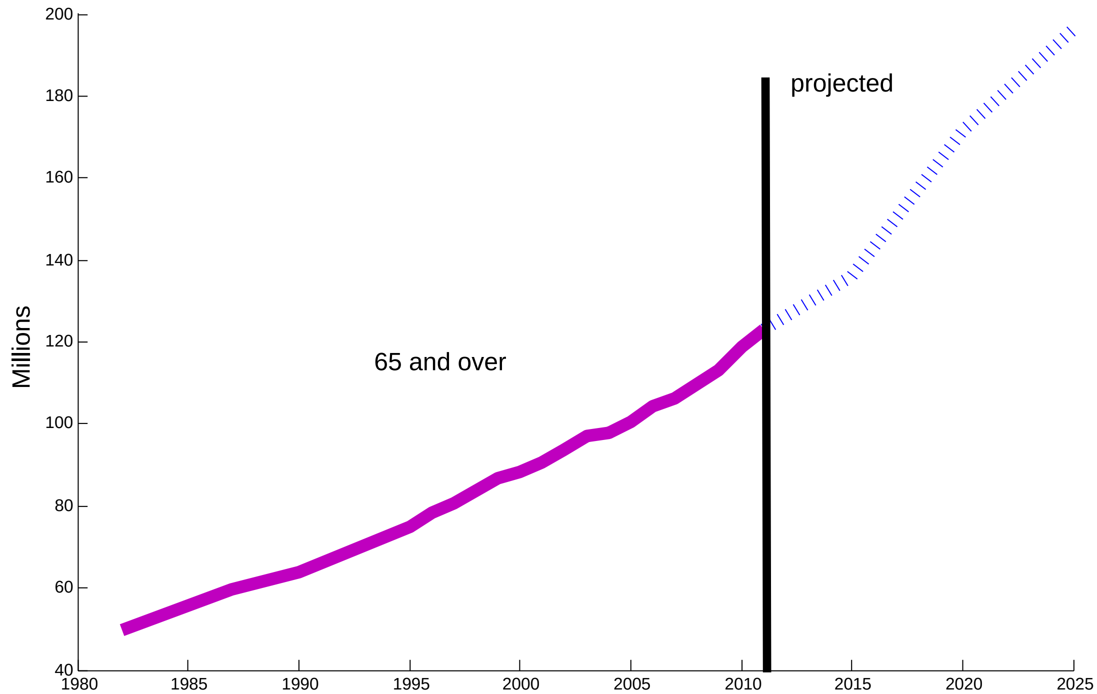

Figure 1.3. China Population age 65 and over, selected years 1980-2011 and projected 2012-2025

handheld computers, can be of enormous value in providing health care in multiple settings as they can support a health workers performing clinician duties where there are no doctors and can help keep track of patients in HIV programs where the loss rate (patients who drop out of treatment) can be as high as 76 percent. Joaquin (2010) further noted that when e-health is used to monitor inventories, these systems can save lives and prevent the increase of drug resistance by keeping medicines in stock and can provide accurate, timely information for strategic planning, especially in areas where hand-compiled data are often years out of date.

The World Health Assembly recognized e-health as the way to achieve cost-effective and secure use of ICTs for health and related fields, and urged its member states to consider drawing up long-term strategic plans for developing and implementing e-health services and infrastructure in their health sectors [14].

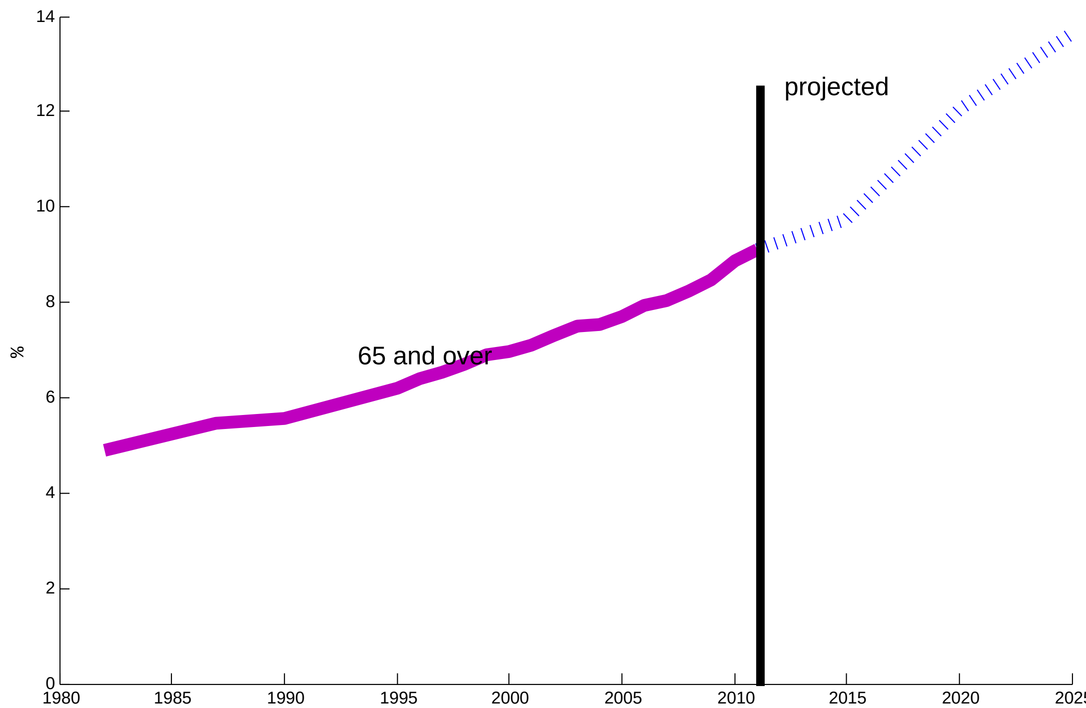

Figure 1.4. China Population age 65 and over (% of total)

The implementation of e-health systems and services in all countries, particularly in developing countries, is a challenge which is shared by the United Nations agencies and health authorities at the international, national and local levels and there is a clear need for guidance on an approach and methodology which hold the most promise for success that should make it possible to avoid costly errors and enhance the efficiency of health systems themselves and ultimately support the sustainable and effective use of such services [15].

Healy (2005) [15] noted that the first step in the implementation of e-health solutions depends on the degree to which e-health applications are dependent on technologies (networks, high-speed transmission, access facilities and the associated costs), local network infrastructures which in turn are highly dependent on local economies and as for the least developed countries, with an average annual income per person of less than USD 1,000 and account for two and a half billion people contributes to difficulties in its implementation.

Given the sensitive nature of healthcare information, and the high degree of dependence of health professionals on trustworthy records, the issues of reliability (data residing in the electronic health record are accurate and remains accurate), security (owner and users of the electronic health record can control data transmission and storage), and privacy (subject of data can control their use and dissemination) are of particular significance and must be clearly and effectively addressed by health and health-related organizations and professionals.

1.3 Thesis Organization

The vital signs signals acquisition is described in Chapter 2. In Chapter 3, digital signal processing is made though Matlab. Chapter 4 shows the architecture of the E-health patient monitoring system and discusses the solutions for wireless transmission of those signals in wireless body area network. At the end of chapter 4 we make a conclusion that Bluetooth-low-energy will be the technology to transmit the signals. Chapter 5 shows a demo with the Bluetooth-low-energy technology.

CHAPTER TWO

Vital Signs Acquisition

2.1 Introduction

The first step of Ehealth system is vital signs acquisition. In this chapter we will talk about 4 kinds of signals acquisition. They are pulse oximetry signal (SpO2), electrocardiography signal(ECG), stethoscope signal, and blood Pressure signal [16]. [17]

2.2 Pulse Oximetry Signal (SpO2)

2.2.1 PPG Measurements

The color of the blood will change based on the level of of the HBO_2 [18]. The oxygenated blood is redder than deoxygenated blood becauseHBO_2 and HB have different abilities to absorb light in a certain spectrum. When light is in a frequency between 400 and 700nm (red light),HB will absorb more light, but in the frequency between 700 and 1000nm (near-infrared),HBO_2will absorb more light. This situation is described in Figure 2.1.

The absorbance of light at a specific wavelength by a homogenous solution can be determined by the Beer-Lambert's law. The equation for Beer-Lambert's law is:

$$I_t = I_0 e^{-acd} \tag{2.1}$$

Where I_t is the transmitted light intensity, I_0 is the incident light intensity, a is the specific absorption coefficient of the sample, c is the concentration of the samples, and d is the path length of light transmission.

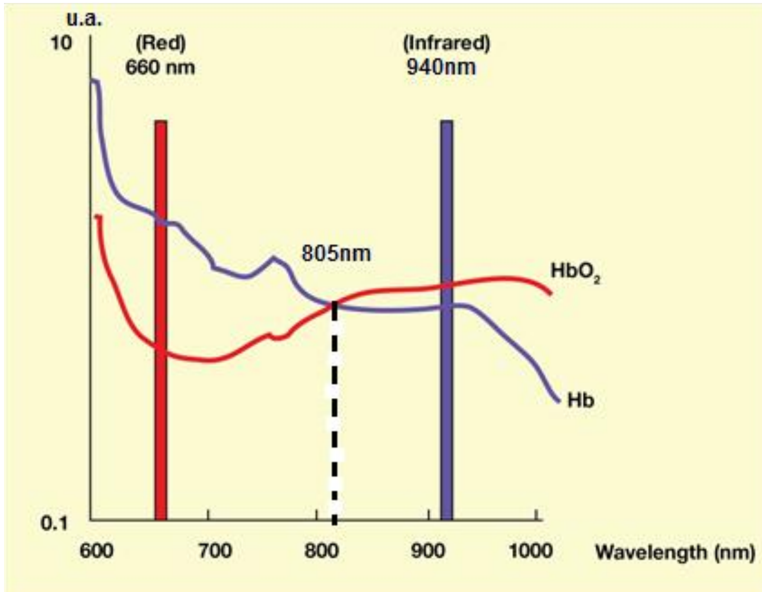

Figure 2.1. The absorption of HBO_2 and HB in different wavelengths (frequency)

In oximetry, it is assumed that two categories make up the blood sample, and the light absorbance of the two categories is additive. One category is the mixture of HBO_2 and HB which are what we want to measure. The second category is composed of other light absorbed mixtures which produced the noise in the measurement. The mixtures, such as bone, skin, tissue, muscle, also scatter light. The thickness and the color of the skin are also random variables to contribute the noise. Therefore, Beer-Lambert's law is unable to remove noise directly. That's why we employ the detection of the photoplethysmographic (PPG) signals. PPG signals produced by variations in the quantity of arterial blood are associated with the heartbeat rhythm. As you can see in Figure 2.2, the magnitude of the PPG signal depends on the amount of blood ejected from the heart with each systolic cycle, the optical absorption of blood, absorption by skin and various tissue components, and the specific wavelengths used to illuminate the vascular tissue bed. During systole, when the arterial pulsation is at its peak, the volume of blood in the tissue increases. This additional blood absorbs more light, thus reducing the light intensity which is either transmitted or backscattered. During diastole, less blood is present in the vascular bed, thus increasing the amount of light transmitted or backscattered. The pulsatile part of the PPG signal is considered as the AC component, and the non- pulsatile part, resulting mainly from the venous blood, skin and tissue, is referred to as the DC component. The variance in the LED brightness or detector sensitivity can change the intensity of the signal generated by the sensor. This dependence on transmitted or backscattered light intensity can be compensated for by using a normalization technique where the AC component is divided by the DC component, as given in the equation below:

$$\frac{R}{IR} = \frac{AC_R/DC_R}{AC_{IR}/DC_{IR}} \tag{2.2}$$

Thus, the time invariant absorbance due to venous blood or surrounding tissues does not have any effect on the measurement. This normalization removed noise and applied for both the red (R) and the infrared (IR) wavelengths, as shown in Figure 2.3. The normalized R/IR ratio of ratios can then be related empirically to SpO_2, as shown in Figure 2.2. When the ratio is 1, the SpO_2 value is about 85%.

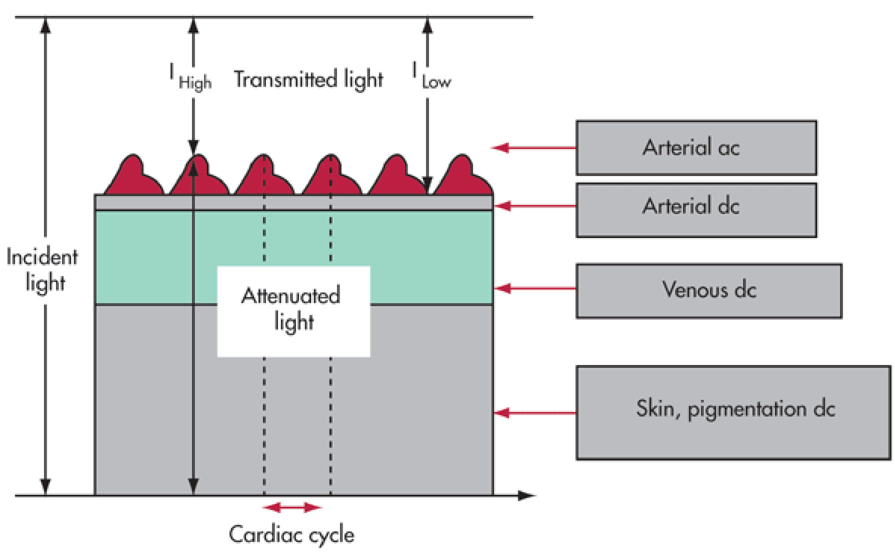

Figure 2.2. AC part and DC part of PPG signal

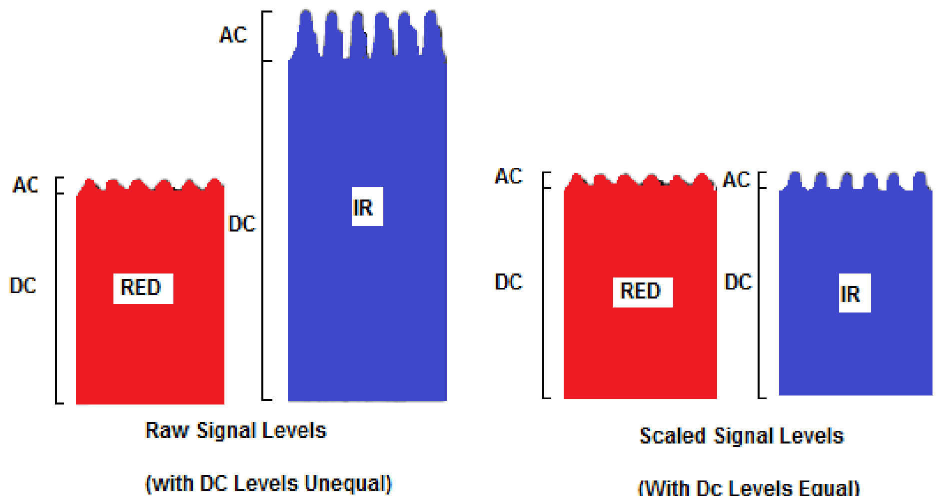

Figure 2.3. Normalization of R and IR PPG signal to remove the noises.

Most pulse oximeters measure absorbance at two different wavelengths and give an estimation of SaO_2 using the empirical relationship in the equation:

$$SaO_2\% = A - B(\frac{R}{IR}) \tag{2.3}$$

R/IR is based on a normalization where the pulsatile (AC) component is divided by the corresponding non-pulsatile (DC) component for each frequency, and A and B are linear regression coefficients that are related to the specific absorptions coefficients of HBO_2 and HB. Figure 2.4 shows the relationship between S arterial SaO_2 and the normalized (R/IR) ratio.

2.2.2 Hardware of PPG Measurements

The key components required for acquiring the PPG signals are the LED, photo detector and analog front end (AFE). There are some commercially AFEs available in the market, we choose one of them to explain here. TI's AFE4400 is a good AFE, which integrates both the LED driver circuitry and the photodiode signal conditioning circuitry in one chip, shown in Figure 2.5 [19].

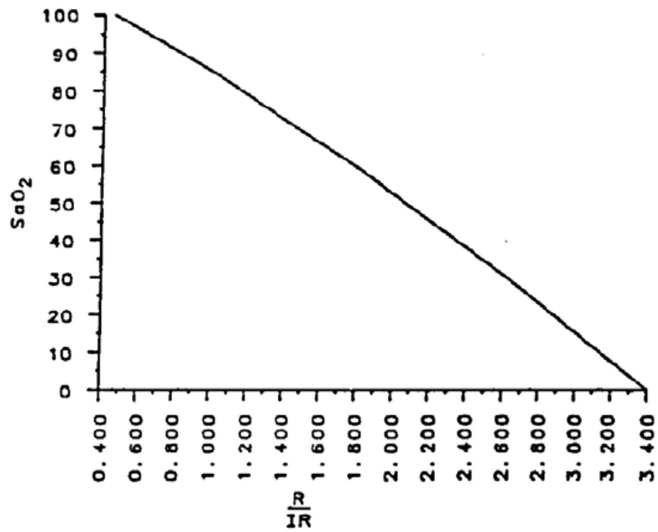

Figure 2.4. Empirical relationships between arterial SaO_2 and normalized R/IR ratio

2.3 Electrocardiography Signal (ECG)

2.3.1 Electrical Activity of the Heart

In the heart, there are electrical signals to control the muscles that pump blood. These signals are generated by the depolarization and repolarization of myocardial cells, which control the muscles in the heart that make the blood flow. The electrical impulse starts in the sinoatrial node and flows through the atria, reaching the atrioventricular node and causing the atrium contraction. After that, there is a brief pause and the current flows through the His bundle toward the ventricles, causing their contraction. Finally, current arrives to the Purkinje fibers and the heart tissue [20].

The following sequence represents this electrical activity, during a heartbeat. as depicted in Figure 2.6.

(1) Atrium begins to depolarize.

(2) Atrium depolarizes.

(3) Ventricles begin to depolarize at apex. Atrium repolarizes.

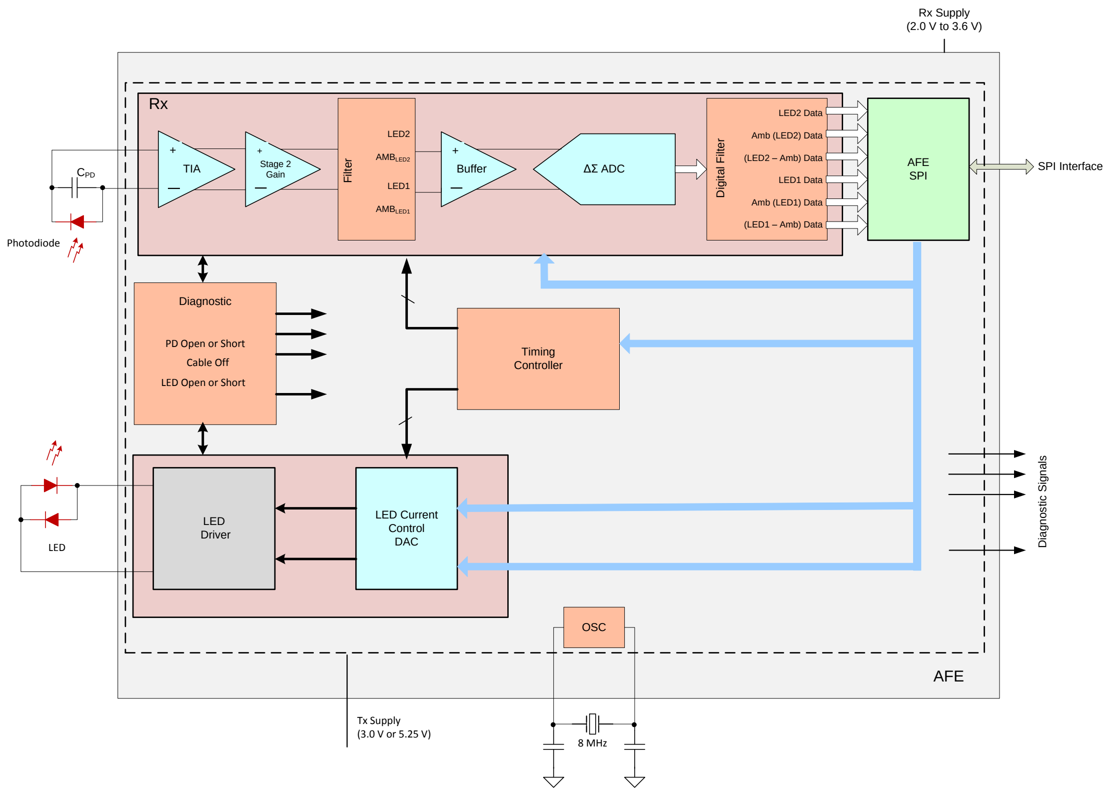

Figure 2.5. TI AFE440 integrate the LED driver and photo diode signal conditioning circuitry in one chip

(4) Ventricles depolarize.

(5) Ventricles begin to repolarize at apex.

(6) Ventricles repolarize.

2.3.2 Heart Signals and the P-QRS-T Complex

The resultant waveform (Figure 2.7) of an ECG is known as a P-QRS-T complex, in medical terminology. It is a multi-feature periodic signal that displays the rhythmic beat pattern corresponding to a heartbeat. Heart muscles generate different voltages on the order of hundreds of microvolts. This signal has very low amplitude with a significant amount of electrical noise. The QRS complex is usually the central and largest part of the electrocardiogram signal. The P wave represents the

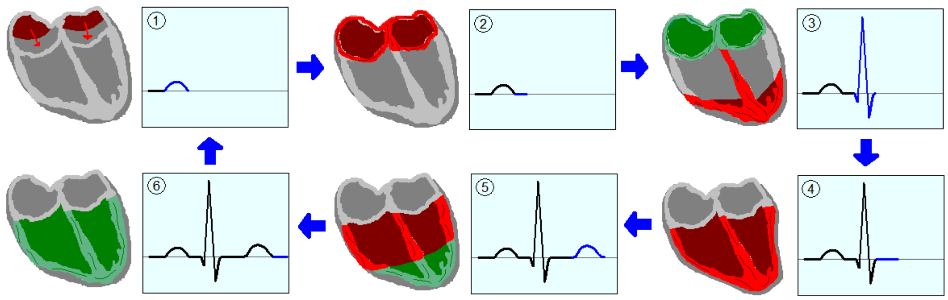

Figure 2.6. represent the voltage signals generated during heartbeat

atrium contraction, while the QRS complex and T wave represent the actions of the ventricles. The amplitude of the QRS complex is higher than the P wave because the ventricles contain more muscle mass than atria. Actually, there is one atrium repolarization wave that resembles an inverse P wave, but it is overlapped by the QRS wave. The electrocardiogram signal is useful in diagnosing cardiac arrhythmias, conduction abnormalities, ventricular hypertrophy, myocardial infarction, electrolyte derangements, and other heart diseases [21].

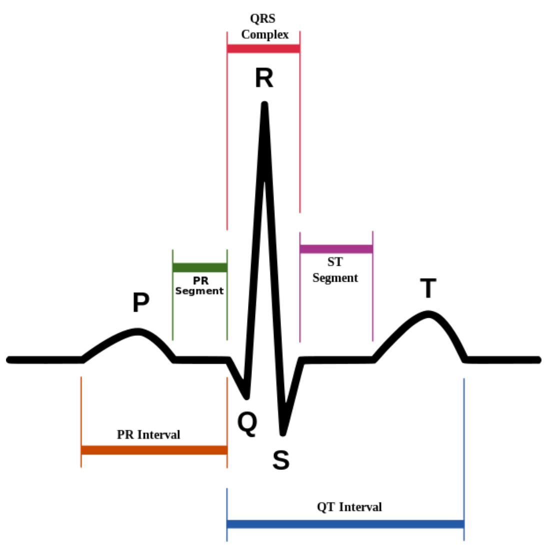

Figure 2.7. P-QRS-T Diagrams

2.3.3 *ECG Signal Acquisition (Figure 2.8)*

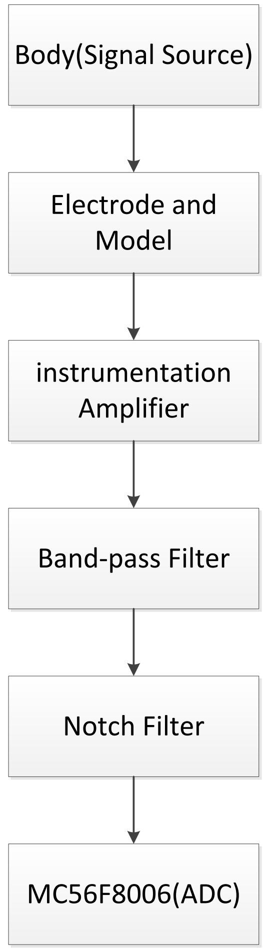

Figure 2.8. the flow chart of ECG signal acquisition

2.3.3.1 Electrode Impedance and Model An ECG data acquisition system is typically comprised of electrodes constructed from Ag-AgCl that contact with the skin to effectively detect the electrical depolarization of the heart. Assuming a LEAD I configuration (i.e. voltage potential between left and right arm with respect to a right leg reference shown in Figure 2.9) [22] the impedance of the electrode (along with the contact to the skin) can be combined with a battery in series with a parallel RC combination of 47nF and 52k. The battery model is ideally be 0V; however, over time and with varying external conditions, it is possible for the Ag-AgCl voltage to become

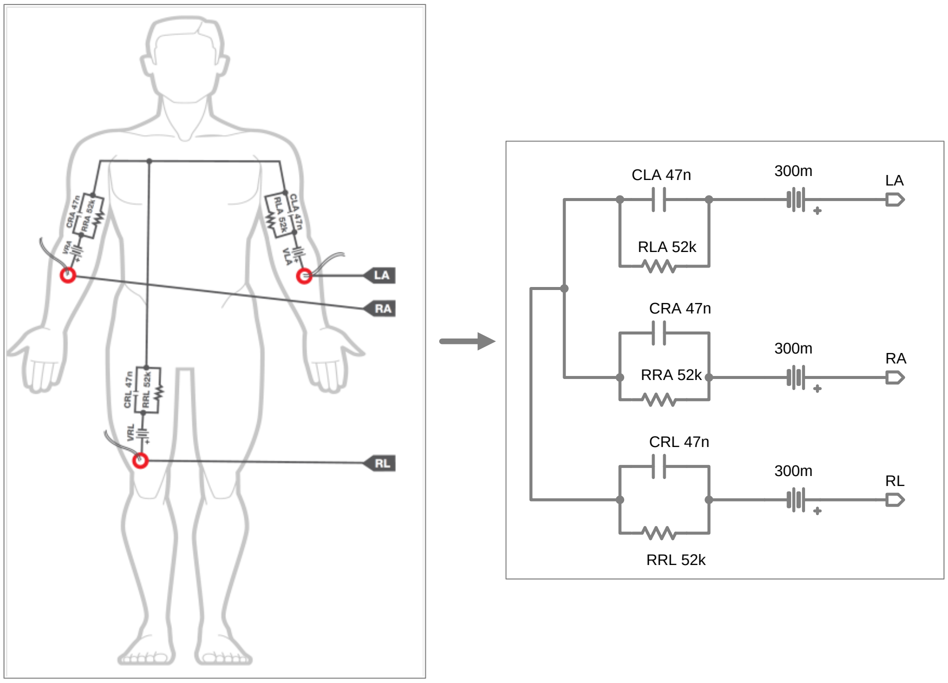

Figure 2.9. Model of human body and ECG electrode impedance

300mV, a factor that must be carefully considered when designing the front-end gain stage. An electrical model of the body impedance is very useful when designing the analog front end of the ECG signal chain. The primary reason for this that the body itself forms an electrical path from the output of the right leg-drive amplifier back to the input of the analog front-end gain. The loop formed around the right leg-drive amplifier (to be discussed in detail in a later section) can be inherently unstable and requires a secondary feedback path to compensate for this inherent instability [23].

2.3.3.2 Instrumentation Amplifier An instrumentation amplifier is a differential amplifier that has been outfitted with input buffer amplifiers, eliminating the need for input impedance matching and thus making the amplifier particularly suitable for use in measurement and test equipment. Additional characteristics include a very low DC offset, low drift, low noise, very high open-loop gain, very high common-mode rejection ratio, and very high input impedances(Figure 2.10).

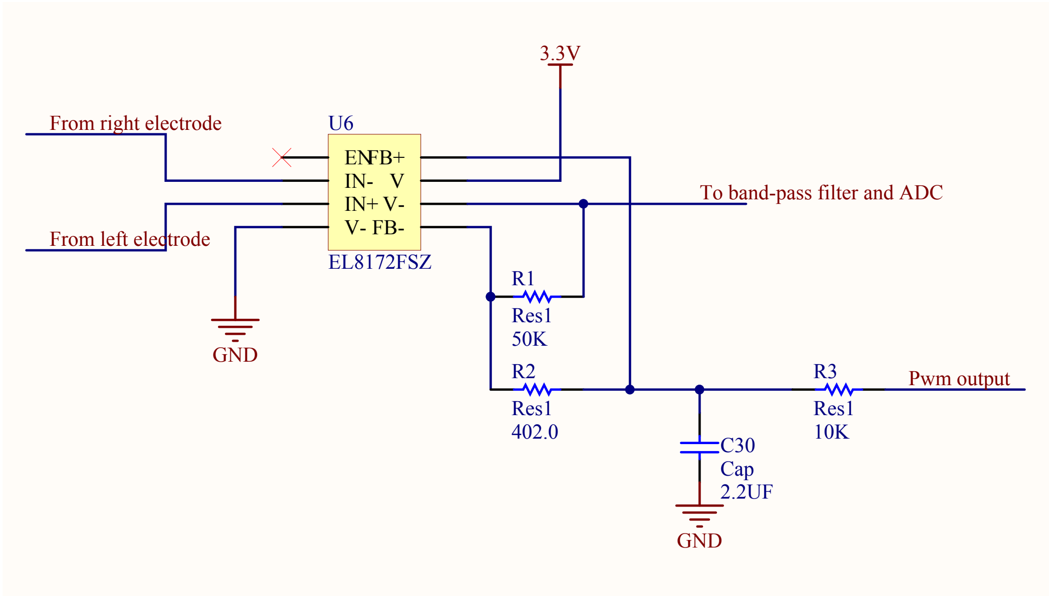

Figure 2.10. Instrumentation amplifier

The gain of the amplifier is determined with R1 and R2. The calculation is shown below:

$$G = \frac{R_1}{R_2} + 1 = \frac{50K}{402} + 1 = 125.3781 \tag{2.4}$$

The digital signal controller generates a PWM signal that functions as an offset generator, with the intention of maintaining the EKG signal variations with a base level, giving stability to the signal shown in the GUI and resulting in a more precise heart rate measurement.

The output of this amplifier is sent to the respective band-pass filter, and the output is also used by the DSC as a reference to generate the adequate PWM feedback signal.

2.3.3.3 Band-pass Filter(0.5Hz-153Hz) Although instrumentation amplifiers have a high CMRR, it is still necessary to filter the signal. Noise can be due to line noise, muscle contractions, respiration, electromagnetic interference, or electromagnetic emissions from electronic components. A band-pass filter helps to attenuate this noise. The low limit rejects signals caused by respiration and muscle contractions. The high limit filters electromagnetic high-frequency interferences(Figure 2.11).

The low and high limit frequencies for the first band-pass filter are 0.5 and 250 Hz, respectively. The values for capacitors and resistors and the equations for calculating the cutoff frequencies are described below:

High limit (153 Hz): C=22nF R=47kΩ

$$f = \frac{1}{2\pi RC} = \frac{1}{2\pi(47k\Omega)(22nF)} = 153.0Hz \tag{2.5}$$

Low limit (0.5 Hz): C=0.33uF R=1MΩ

$$f = \frac{1}{2\pi RC} = \frac{1}{2\pi(1M\Omega)(0.33uF)} = 0.5Hz \tag{2.6}$$

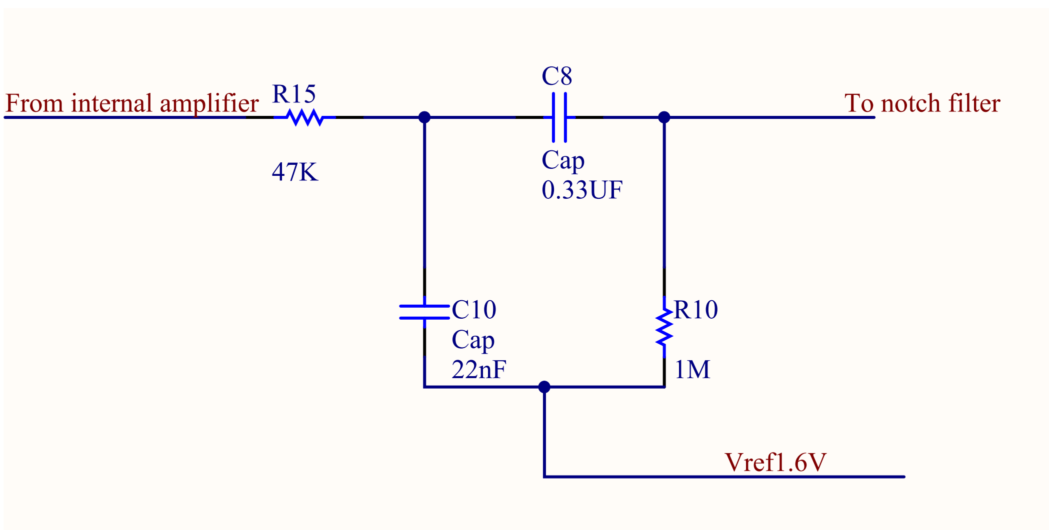

Figure 2.11. Band-pass filter

2.3.3.4 Notch Filter (60Hz) The notch filter is designed to remove the 60 Hz signal. this eliminates any noise related electrical power source, since electrical installations in the U.S. have a 60 Hz frequency. Figure 2.12 shows the distribution of the components that form the notch filter. The diagram also includes two more filters and an operational amplifier. The filters are high-pass and low-pass, but with the same cutoff frequencies as the band-pass filter.

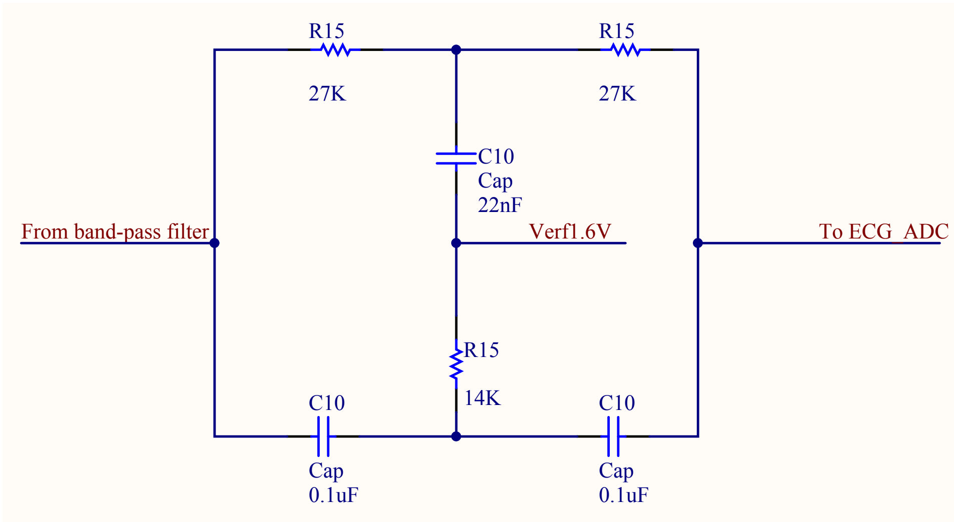

Figure 2.12. Notch filter

2.4 Digital Stethoscope

A stethoscope is an acoustic medical device for auscultation, or listening to the internal sounds of an animal or human body. It is often used to listen to lung and heart sounds. It is also used to listen to intestines and blood flow in arteries and veins. In combination with sphygmomanometer, it is commonly used for measurements of blood pressure.

As shown in figure 2.13, a digital stethoscope has six parts.

2.4.1 Diaphragm and Condenser Microphone

Sound waves from the acoustic amplifier (diaphragm) are fed to the condenser microphone. The sound waves hitting the condenser microphone change its capacitance by changing its impedance, which produces a voltage swing proportional to the amplitude of the input sound waves [24] [25].

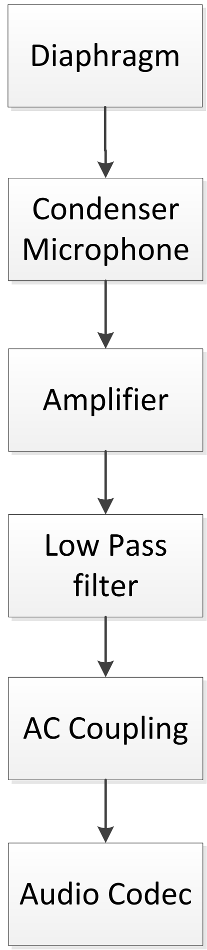

Figure 2.13. The flow chart of stethoscope signal acquisition

2.4.2 Amplifierle

The input signal from the sensor is very feeble, therefore, an amplifier stage is needed. Usually the gain of the amplifier is around 30.

2.4.3 Low-Pass Filter

The stethoscope has three modes:

- Bell mode (20 Hz to 220 Hz) emulates the light touch of a stethoscope to pick up low frequency sounds.

- Diaphragm mode (50 Hz to 600 Hz) emulates the firmer contact method for picking up higher frequency sounds.
- Extended range (20 Hz to 2000 Hz) of course covers the whole range, rather than emulating a traditional acoustic sensor.

The details of this will be discussed in chapter three.

2.4.4 AC Coupling

The AC coupling used to remove the DC signal.

2.4.5 Audio Codec

An audio Codec is capable of coding or decoding a digital data stream of audio. Here it is used as the A/D converter.

Because the sampling rate of a digital stethoscope is relatively low, usually we can use digital signal process (DSP) to process these data. The DSP will be described in Chapter 3.

2.5 Blood Pressure

Blood pressure monitors can use Korotkoff, Oscillometry, or Pulse Transit Time methods to measure blood pressure. They employ a pressure cuff, pump, and a transducer to measure blood pressure and heart rate in three phases: Inflation, Measurement, and Deflation. They include an LCD, selection buttons, memory recall, power management, and a USB interface. [24] [26]

A pressure transducer produces the output voltage proportional to the applied differential input pressure. The output voltages of the pressure transducer range from 0 to 40 mV, which must be amplified so that the output voltage of the DC amplifier has a range from 0 to 5V. Thus, we need a high-gain amplifier. Then the signal from the DC amplifier will be passed on to the band-pass filter. The DC amplifier amplifies both DC and AC component of the signal. The filter is designed to have large gain at around 1-4 Hz and to attenuate any signal that is out of the pass band. The AC component from the filter is important for determining when to capture the systolic/diastolic pressures and heart rate of the patient. The final stage of the front end is an AC coupling stage, after which the signal is sent to analog-to-digital converters, and then digitized.

The digital measurements of pressure and heart rate are performed by the microprocessor. Measurement results are stored in EEPROM or FLASH memory as a data log that can be uploaded to a PC via a USB connection. The analog circuit is used to amplify both the DC and AC components of the output signal of the pressure transducer so that we can use the MCU to process the signal and obtain useful information about the patient's health (Figure 2.14).

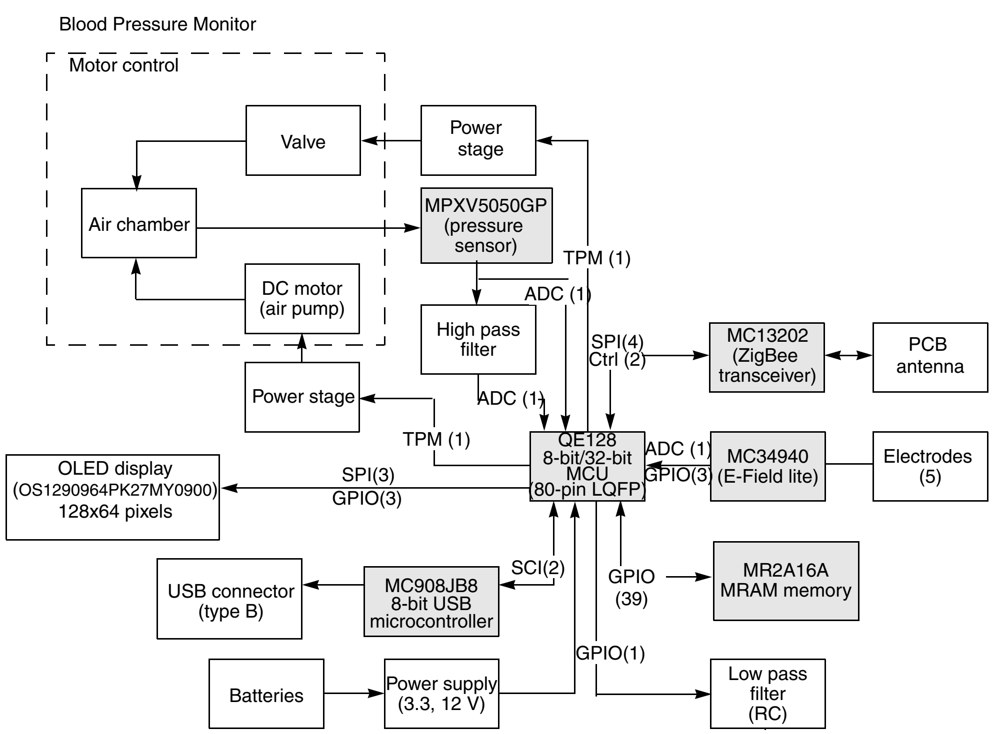

Figure 2.14. The BPM mode from freescale

2.5.1 Heartbeat Detection

The heartbeat rate is a vital patient measurement. The following procedure is used to obtain this measurement. While deflating a cuff that is attached to a person's arm, slight variations in the overall cuff pressure may be detected(Figure 2.15). This variation in the cuff pressure is due to the pressure change from blood circulation. This variation is amplified through a filter designed at 1 Hz, and set to an offset. This resulting signal is the heartbeat signal. The signal in Figure 2.16 shows variations in the pressure signal and is a graphical representation of a patient's heartbeat over time.

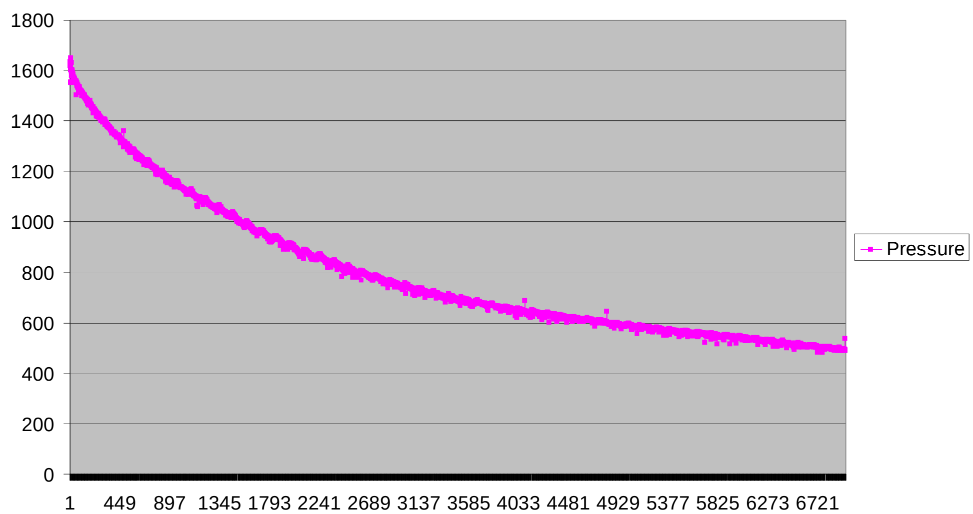

Figure 2.15. Heartbeat Signal

2.5.2 Invasive Blood Pressure Monitors

The most accurate way to measure blood pressure is to take the measurement directly from an arterial line. The advantage of this method is continuous measurement, versus a discrete measurement using the non-invasive method. Freescale has long been a provider of sensors for invasive blood pressure monitoring.

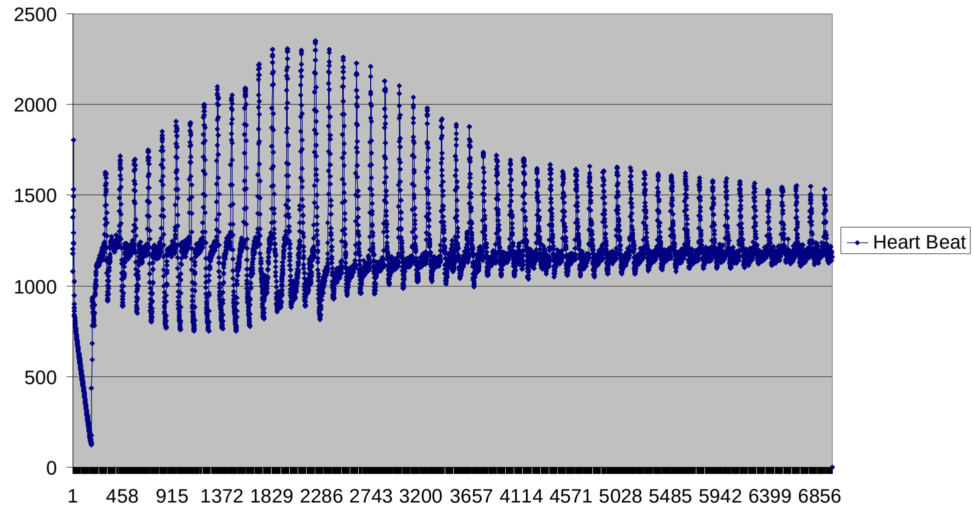

Figure 2.16. Heartbeat Over Time

2.5.3 Obtaining Pressure Measurements

Using the heartbeat detection as just described, a simple oscillometric method can be used to determine systolic blood pressure (SBP) and diastolic blood pressure (DBP). This simplified measurement is based on the idea that the amplitude of the heartbeat signal changes as the cuff is inflated over the SBP. While the cuff is deflated, the amplitude of the heartbeat signal grows as the cuff pressure passes the systolic pressure of the patient. As the cuff pressure is further reduced, the pulsations increase in amplitude, until they reach a maximum pulse known as the mean arterial pressure (MAP), and then reduce rapidly until the diastolic pressure is reached (Figure 2.17).

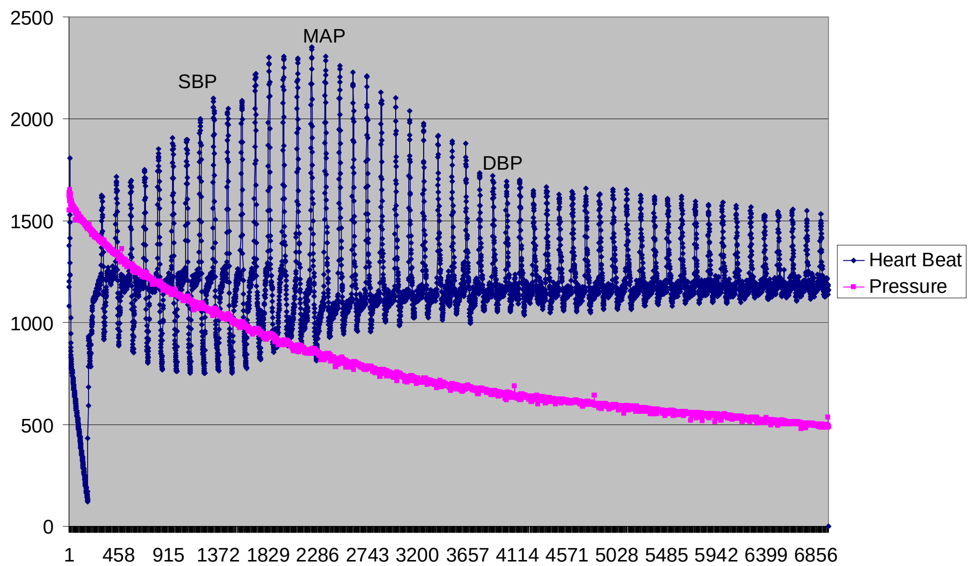

Figure 2.17. Heartbeat Over Time

CHAPTER THREE

Digital Signal Processing

After the analog part of the device gets the signals from the sampling, we use the DSP to extract the information from those signals. This will be explained using the example of a stethoscope signal and an ECG signal.

3.1 Stethoscope Signal Processing

A digital stethoscope has three different finite impulse response (FIR) filters implemented for the three operating modes. One filter uses a the FIR hamming window band pass with order of 20, which provides a sharp cutoff with an attenuation of about 50dB, with a sampling frequency is 22050 samples/second. The shifting convolution algorithm is used to implement the filter.

There are 3 modes in the stethoscope:

- Bell mode (20 Hz to 220 Hz) emulates the light touch of a stethoscope to pick up low frequency sounds (typically the heartbeat sound).
- Diaphragm mode (50 Hz to 600 Hz) emulates the firmer contact method for picking up higher frequency sounds.
- Extended mode (20 Hz to 2000 Hz) of course covers the whole range, rather than emulating a traditional acoustic sensor.

3.1.1 Bell Mode

Here we design a band-pass FIR equiripple filter with Fs= 22050Hz using Matlab. [27]:

```
Fs = 22050;                  % Sampling Frequency
Fstop1 = 18;                 % First Stopband Frequency
Fpass1 = 22;                 % First Passband Frequency
Fpass2 = 220;                % Second Passband Frequency
Fstop2 = 225;                % Second Stopband Frequency
Dstop1 = 0.001;              % First Stopband Attenuation
Dpass  = 0.057501127785;     % Passband Ripple
Dstop2 = 0.0001;             % Second Stopband Attenuation
dens   = 20;                 % Density Factor

% Calculate the order from the parameters using FIRPMORD.
[N, Fo, Ao, W] = firpmord([Fstop1 Fpass1 Fpass2 Fstop2]/(Fs/2), [0
   1 ...0], [Dstop1 Dpass Dstop2]);

% Calculate the coefficients using the FIRPM function.
b  = firpm(N, Fo, Ao, W, {dens});
```

This FIR filter is shown in Figure 3.1. There are two curves in Figure 3.1, the upper one is the magnitude response, it is a bandpass filter with the passband from 20 Hz to 220 Hz. The lower one is the phase response of this filter, it has the liner phase shift on passband.

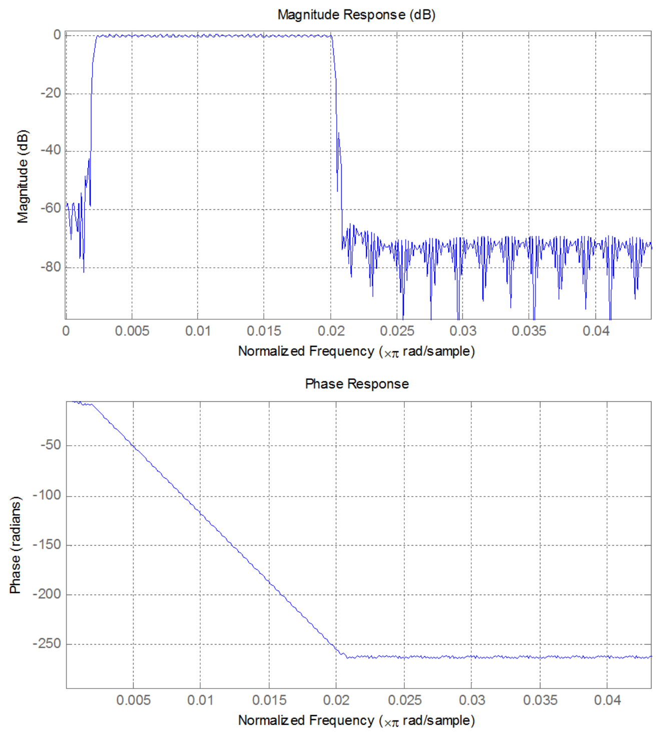

Figure 3.1. The Bell FIR filter.

Figure 3.2 shows the sound waveform before and after applying the filter for the Bell Mode.

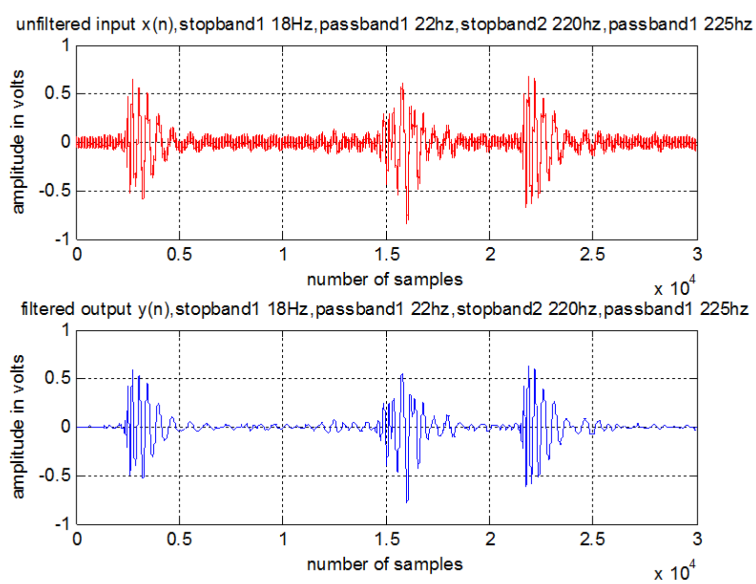

Figure 3.2. Signal before (Upper) and after (lower) applying the filter for the Bell Mode.

3.1.2 Diaphragm Mode

Here we describe a band-pass FIR equiripple filter with Fs= 22050 using Matlab code.

```
Fs = 22050;                  % Sampling Frequency
Fstop1 = 48;                 % First Stopband Frequency
Fpass1 = 52;                 % First Passband Frequency
Fpass2 = 590;                % Second Passband Frequency
Fstop2 = 610;                % Second Stopband Frequency
Dstop1 = 0.001;              % First Stopband Attenuation
Dpass  = 0.057501127785;     % Passband Ripple
Dstop2 = 0.0001;             % Second Stopband Attenuation
dens   = 20;                 % Density Factor

% Calculate the order from the parameters using FIRPMORD.
[N, Fo, Ao, W] = firpmord([Fstop1 Fpass1 Fpass2 Fstop2]/(Fs/2), [0
  1 ...0], [Dstop1 Dpass Dstop2]);

% Calculate the coefficients using the FIRPM function.
b  = firpm(N, Fo, Ao, W, {dens});
```

This FIR filter is shown in Figure 3.3. There are two curves in this picture, the upper one is the magnitude response, it is a bandpass filter with the passband from 50 Hz to 600 Hz. The lower one is the phase response of this filter, it has the liner phase shift on passband.

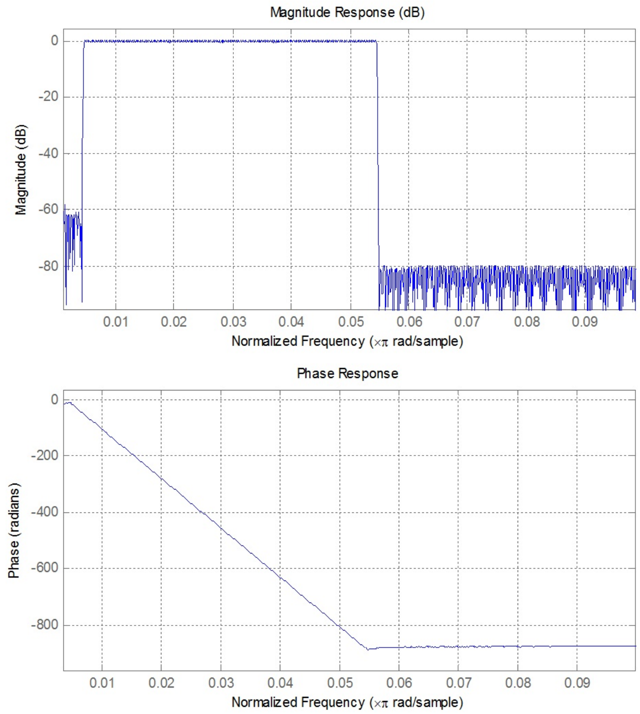

Figure 3.3. The Diaphragm FIR filter.

Figure 3.4 shows the sound waveform before and after applying the filter for the Diaphragm mode.

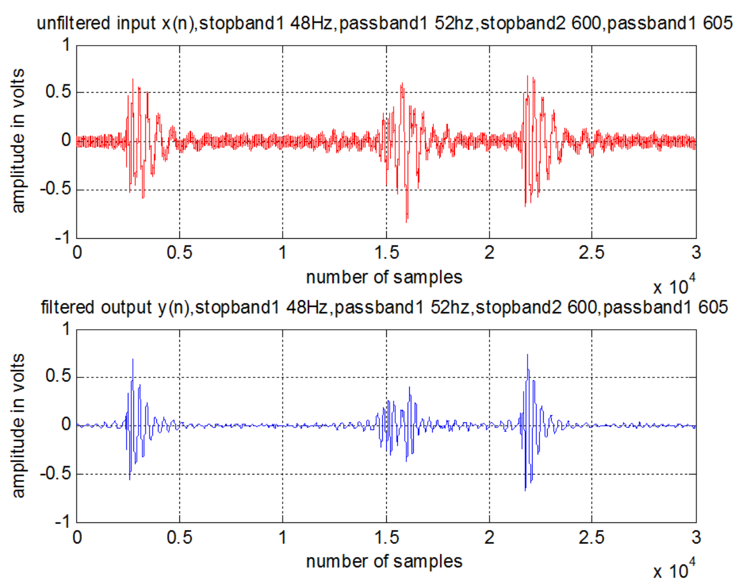

Figure 3.4. Signal before (Upper) and after (Lower) applying the filter for the Diaphragm Mode.

3.1.3 Extended Mode

Here we describe design a band-pass FIR equiripple filter with Fs= 22050 using Matlab.

```
Fs = 22050;                 % Sampling Frequency
Fstop1 = 18;                % First Stopband Frequency
Fpass1 = 22;                % First Passband Frequency
Fpass2 = 1990;               % Second Passband Frequency
Fstop2 = 2010;               % Second Stopband Frequency
Dstop1 = 0.001;             % First Stopband Attenuation
Dpass  = 0.057501127785;    % Passband Ripple
Dstop2 = 0.0001;            % Second Stopband Attenuation
dens   = 20;                % Density Factor

% Calculate the order from the parameters using FIRPMORD.
[N, Fo, Ao, W] = firpmord([Fstop1 Fpass1 Fpass2 Fstop2]/(Fs/2), [0
   1 ... 0], [Dstop1 Dpass Dstop2]);

% Calculate the coefficients using the FIRPM function.
b  = firpm(N, Fo, Ao, W, {dens});
```

This FIR filter is shown in Figure 3.5. There are two curves in Figure 3.5, the upper one is the magnitude response, it is a bandpass filter with the passband from 20 Hz to 2000 Hz. The lower one is the phase response of this filter, it has the liner phase shift on passband.

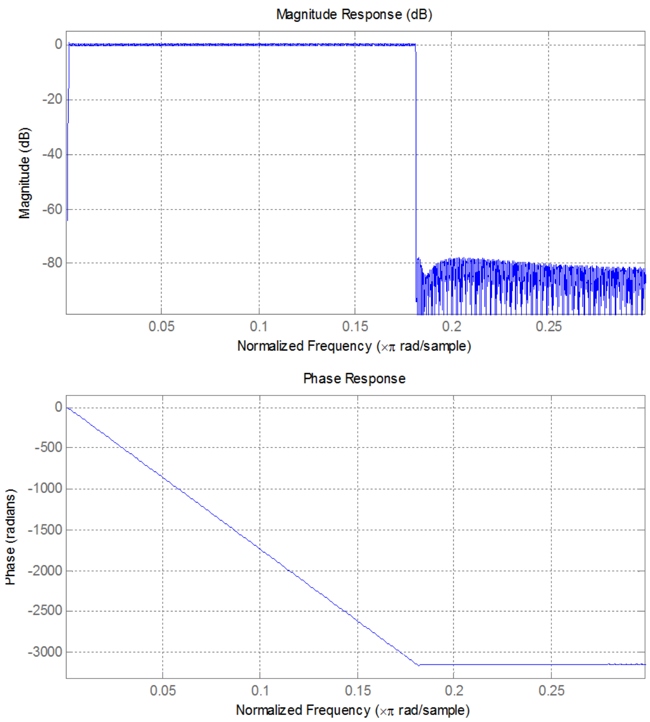

Figure 3.5. The Extended FIR filter.

Figure 3.6 shows the sound waveform before (Upper) and after (Lower) applying the filter for the Extended Mode.

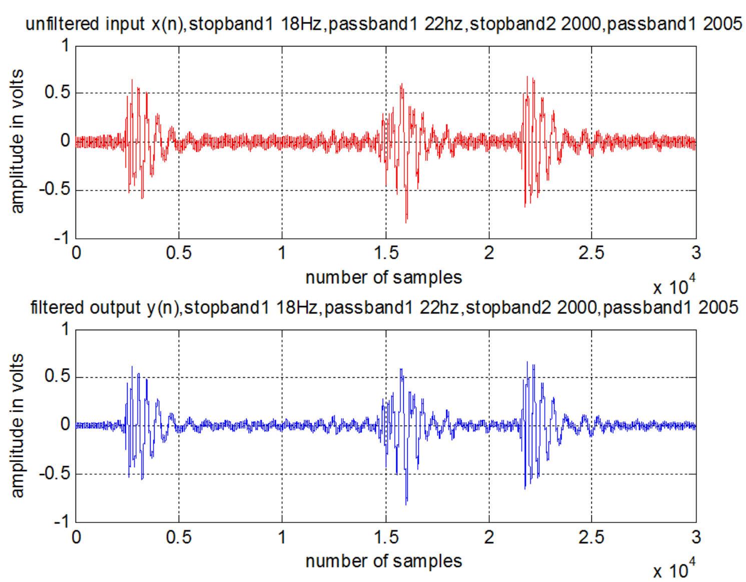

Figure 3.6. Signal before (Upper) and after (Lower) applying the filter for the Extended Mode.

3.1.4 *Heart Beat Detection*

3.1.4.1 Time Domain Detection: A heart beat consists of two kinds of sound. S1 is the first heart sound and S2 is the second heart sound. To detect the heart beat we only need to detect one of them. In this case we used S2. It is shown in Figure 3.7 [28]. The Figure 3.8 shows the original signal.

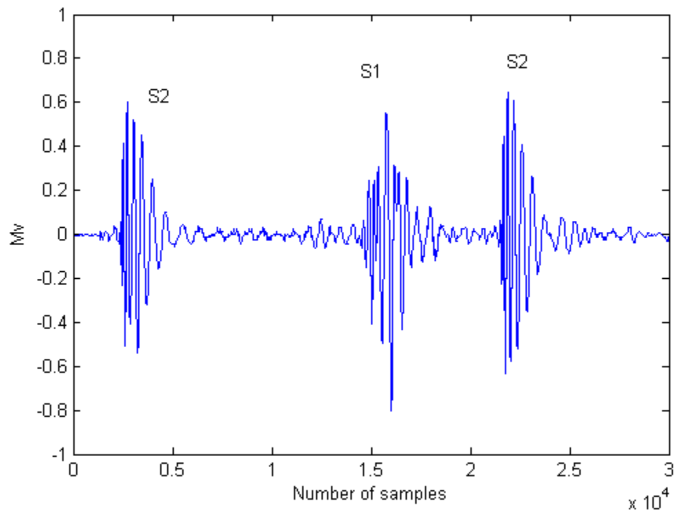

Figure 3.7. Heart Waveform Showing S1 and S2.

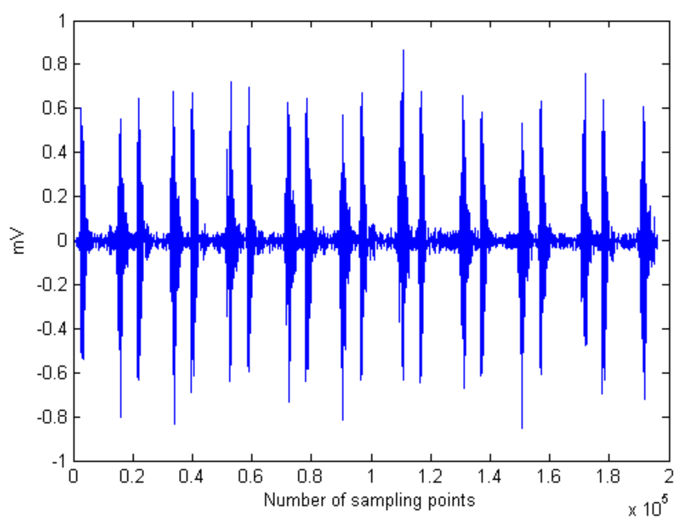

Figure 3.8. The original signal.

The heart rate detection algorithm has the following steps:

(1) Smooth the FIR filter output by using the 5 tap moving average filter.

(2) Find the pattern of S2.(Figure 3.9)

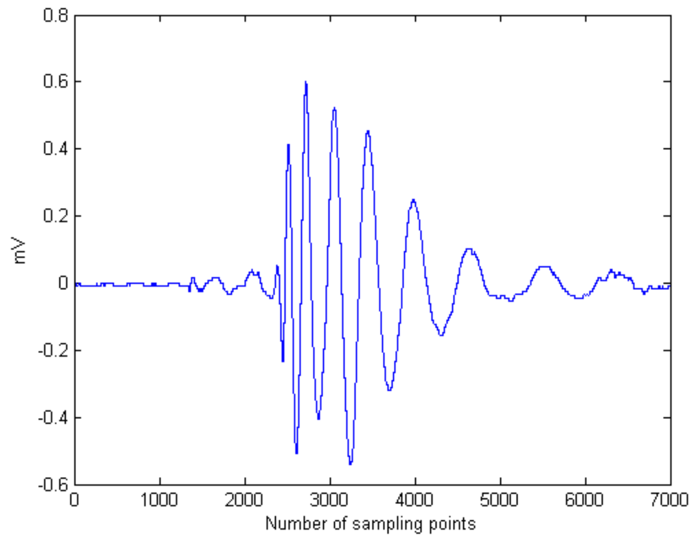

Figure 3.9. S2 Pattern.

(3) Convolve the signal with the invert pattern to find the autocorrelation function Rxy [29].(Figure 3.10)

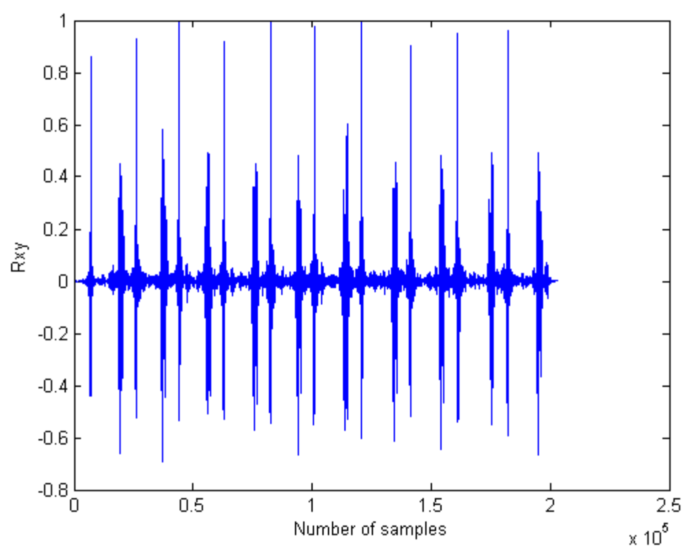

Figure 3.10. Signal after convolution.

(4) Calculate the energy of the result and detect the S2 (second heart sound) by comparing the maximum values of the waveform. (Figure 3.11) $Energy = Rxy^2$.

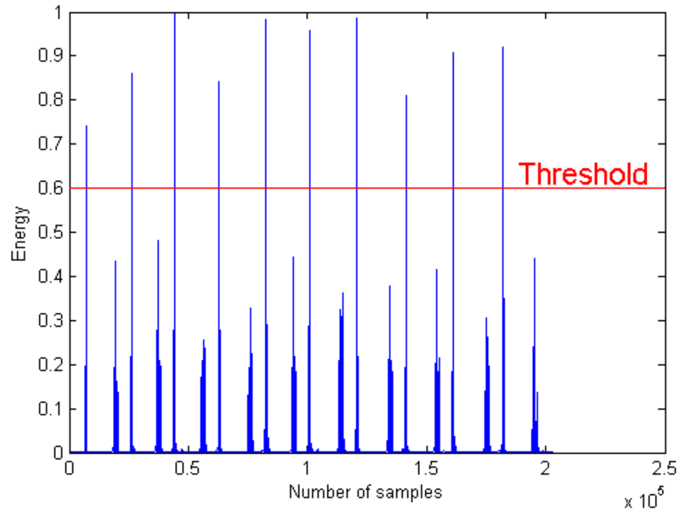

Figure 3.11. Energy and Threshold.

(5) Measure the number of samples between two consecutive S2's.

(6) Calculate the heart rate using the following formula:

$$HeartRate = \frac{SamplingRate * 60}{Number\ of\ samples\ between\ two\ consecutive\ S2\text{'s}}$$

$$SamplingRate = 22050\ Hz \tag{3.1}$$

(7) Apply eight data point moving average logic to compute the average heart rate.

$$HeartRate = 68.0011(beats/minute) \tag{3.2}$$

3.1.4.2 Frequency domain detection: The heartbeat signal is a periodic signal, and this period is the reciprocal of heartbeat frequency. So we also can process the data in the frequency domain to get the heartbeat rate frequency.

(1) We removed the DC signal with the Matlab code: (Figure 3.12)

```
N=length(y);
y=y-sum(y)/N;
```

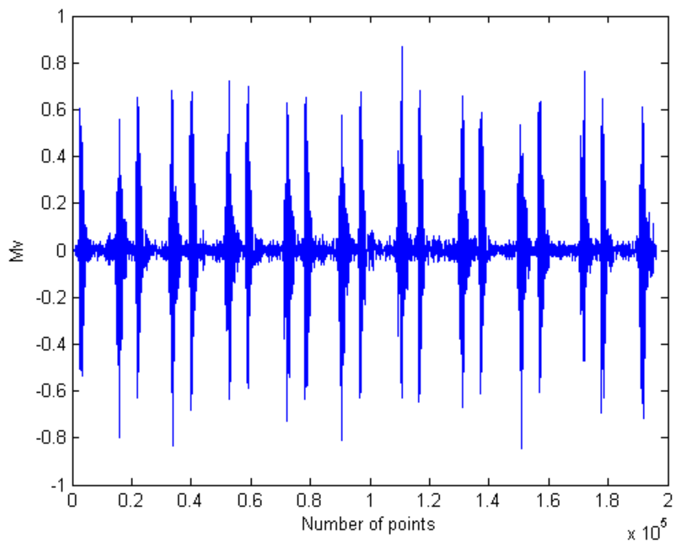

Figure 3.12. Signal after removing DC.

(2) Note that, the signal has more information than we want. A typical heart beat frequency is between 0.5Hz to 3Hz. So we must remove the higher frequency components. In order to remove those frequency components, we apply a Fast Fourier Transforms (FFT), then remove the frequency above 5 Hz and restore the signal by an inverse FFT. The result is shown in Figure 3.13.

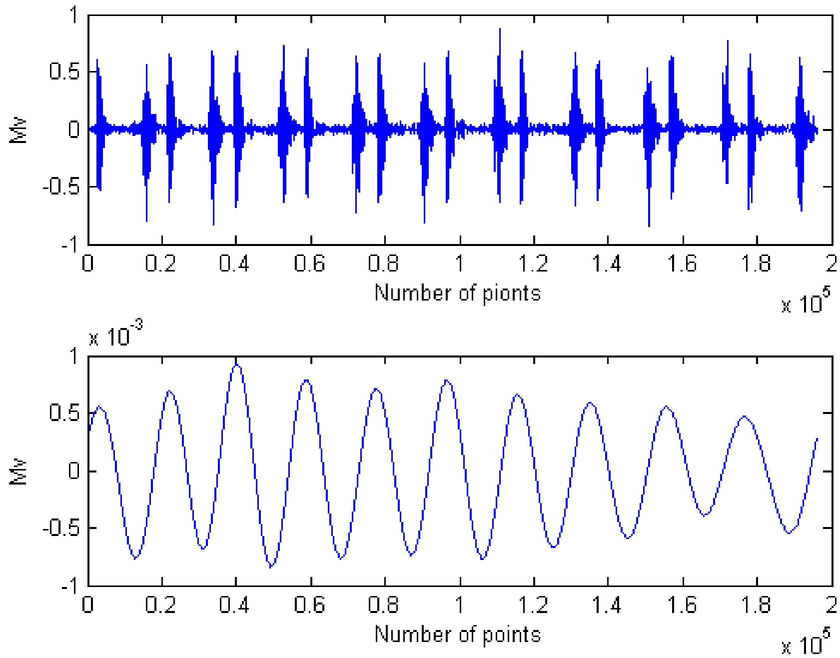

Figure 3.13. FFT filtered signal.

(3) We use windowing and zero padding to enhance the main lobe and to increase the resolution. The upper part of Figure 3.14 is a Hamming windowing function, while the lower part of Figure 3.14 is the FFT filtered signal function multiply with the Hamming windowing function. We can enhance the main beam and reduce the sidelobe by doing that. (Figure 3.14)

The upper part of Figure 3.15 is the signal after applying hamming windowing and zero padding, the lower part of Figure 3.15 is the Fourier transform of upper part of Figure 3.15. The spectral resolution is higher after using zero padding, so we can see the frequency more clear. (Figure 3.15) [30]

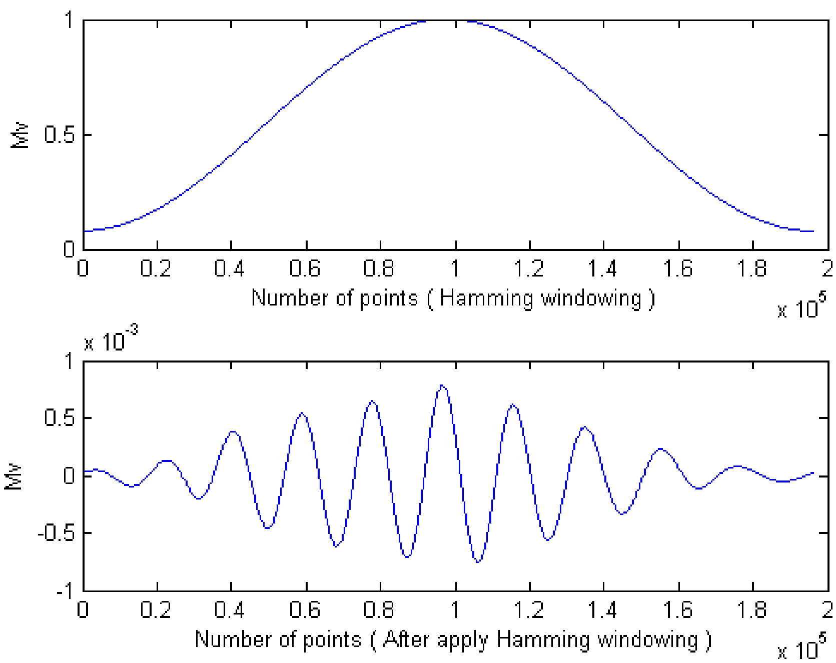

Figure 3.14. Hamming windowing.

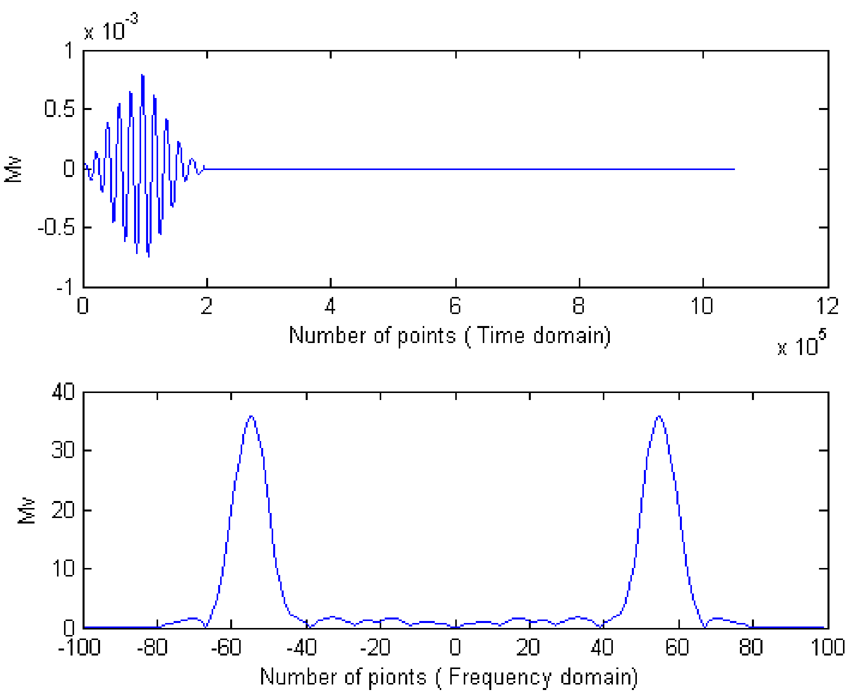

Figure 3.15. Zero padding.

(4) We calculate the heart rate using equation 3.3.

$$HeartRate = \frac{60 * 55 * Fs}{2^{20} - 1} = 69.39411(beats/minute) \tag{3.3}$$

3.2 ECG Signals Processing

The ECG signal have three components: p–wave, QRS complex and t–wave(Chapter 2, figure 2.7). The R pint is the Maximum value of the QRS complex. We can calculate R–R interval and heartbeat rate based on this point. This ECG signals processing is focus on the detection of the R pint of the wave. The ECG signal comes from MIT-BIH Database. [31] [32]

(1) The original signal (Figure 3.16).

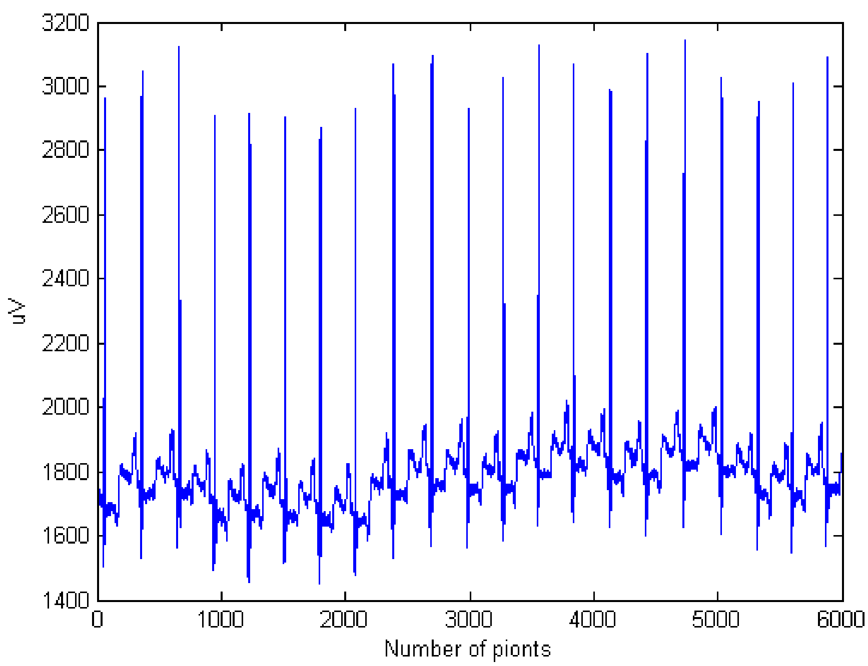

Figure 3.16. Raw ECG signal.

(2) We straighten this uneven signal by removing the low frequency (Figure 3.17). components. [33]

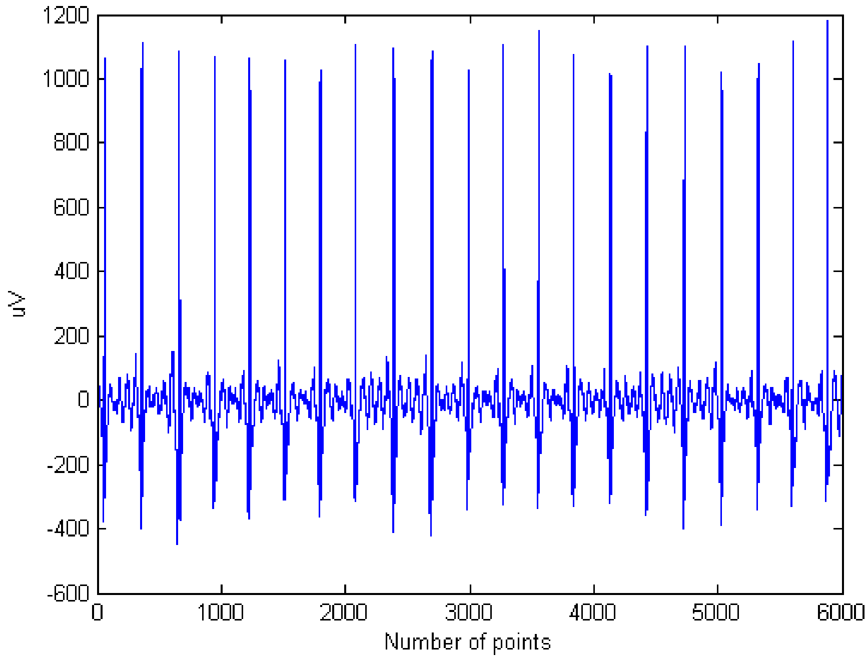

Figure 3.17. FFT filtered ECG.

(3) Then we find local maxima, using a windowed filter that only sees the maximum and ignores all other values with a default window size. (Figure 3.18)

(4) We remove small values and preserve the large ones with a threshold. The values larger than the threshold become 1 while the values smaller than the threshold are assigned to 0 (Figure 3.19).

(5) In this case the results are good but in general we cannot guarantee that we have all the peaks. So this step is to adjust filter window size by finding the minimal distance of two peaks and letting that distance become the length of windows. Then repeat filtering – Figure 3.20. Now the filtering result quality is much better.

(6) Now we are ready to get the final results as seen in figure 3.21.

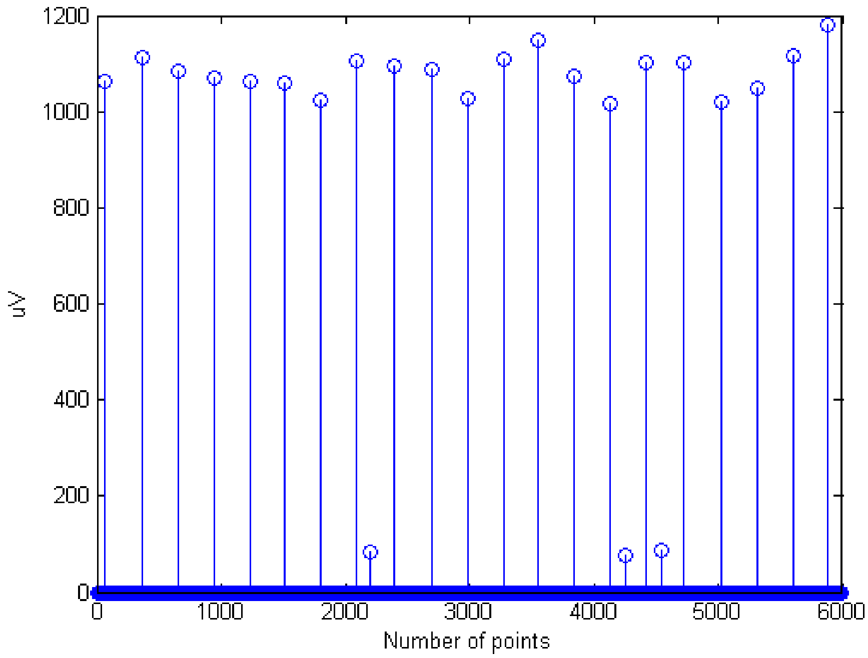

Figure 3.18. Filtered ECG - first pass.

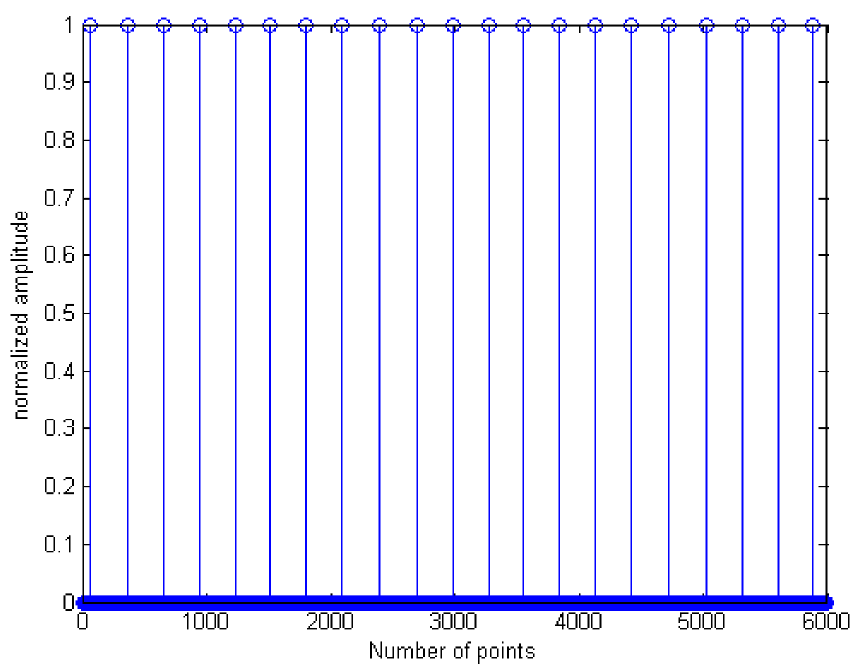

Figure 3.19. Peaks larger than the threshold (600 uF).

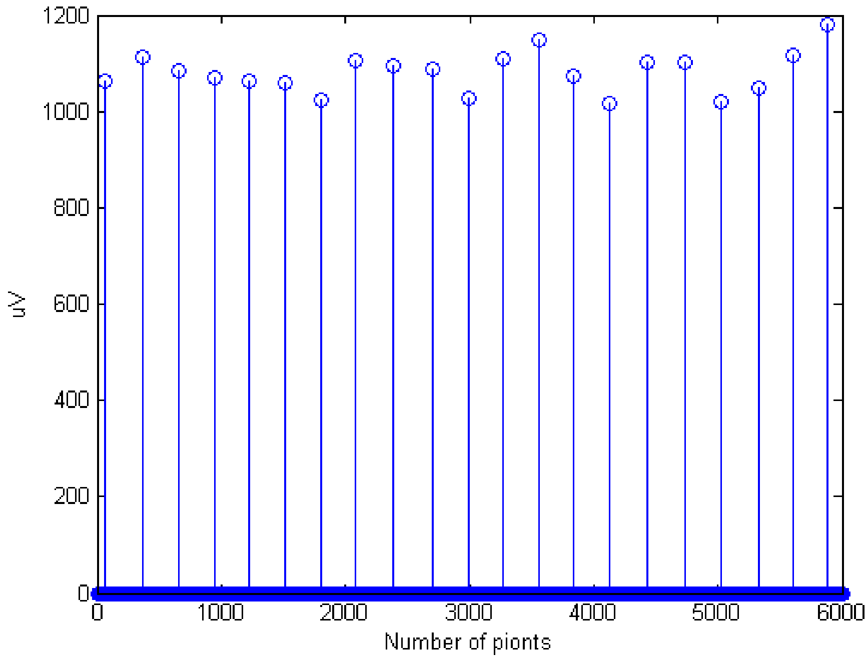

Figure 3.20. Filtered ECG - second pass.

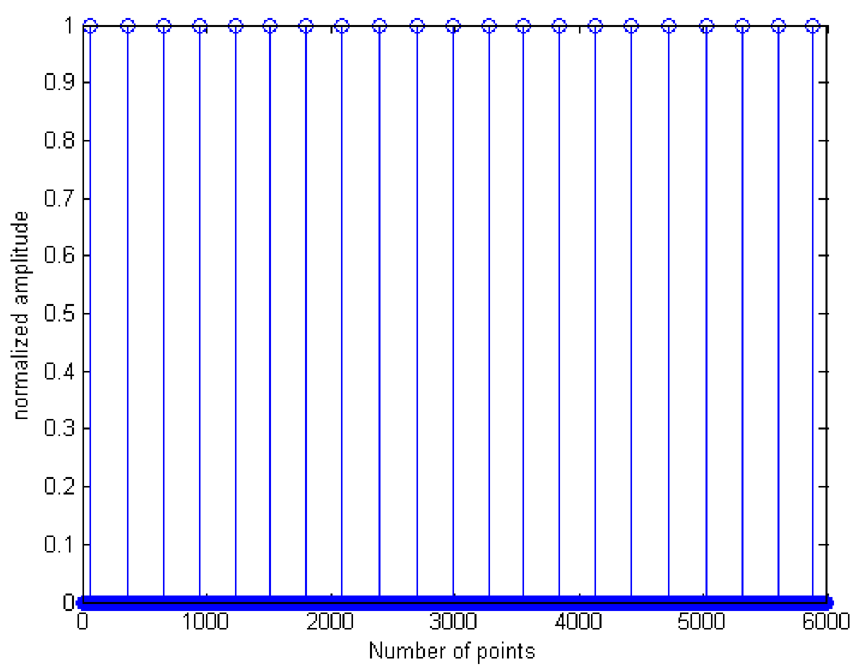

Figure 3.21. Final result. (Threshold is 600 uF)

CHAPTER FOUR

Communication Technology in the E-Health Patient Monitoring System

4.1 Architecture of the EHealth Patient Monitoring System

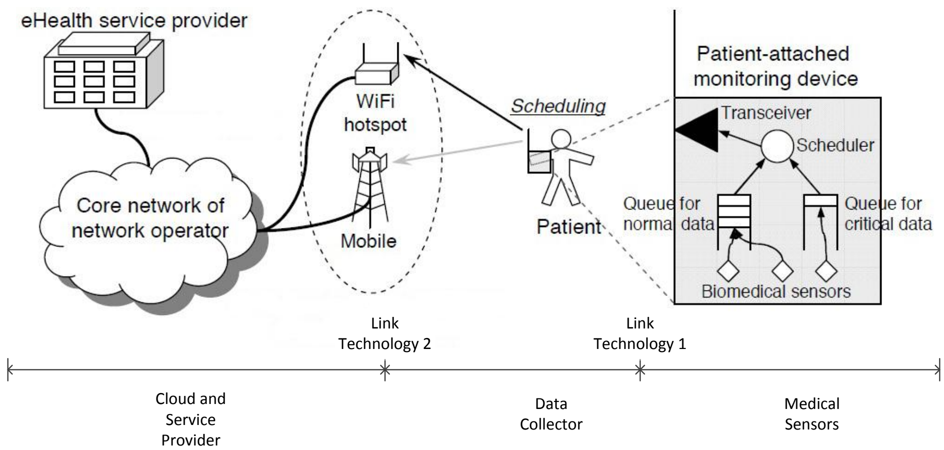

Figure 4.1. Architecture of the eHealth system

The typical architecture of eHealth patient monitoring system is shown in Figure 4.1 [34] [35] [36]. It has three main components: a medical sensor; a data collector and a cloud and service provider. The medical sensor extracts vital signs from human body. The data collector is usually a smartphone that collects the signals from the sensors. The cloud and service provider represents carriers and hospitals. To let these components to work together, we must choose proper communication technologies. We call the communication technology between medical sensors and data collector Link Technology 1 and that between data collector and cloud and service provider as Link Technology 2. In this paper we focus on find a solution for Link Technology 1, but we have also done some research on Link Technology 2. [37]

4.2.1 Wireless E-Health Communication Technologies

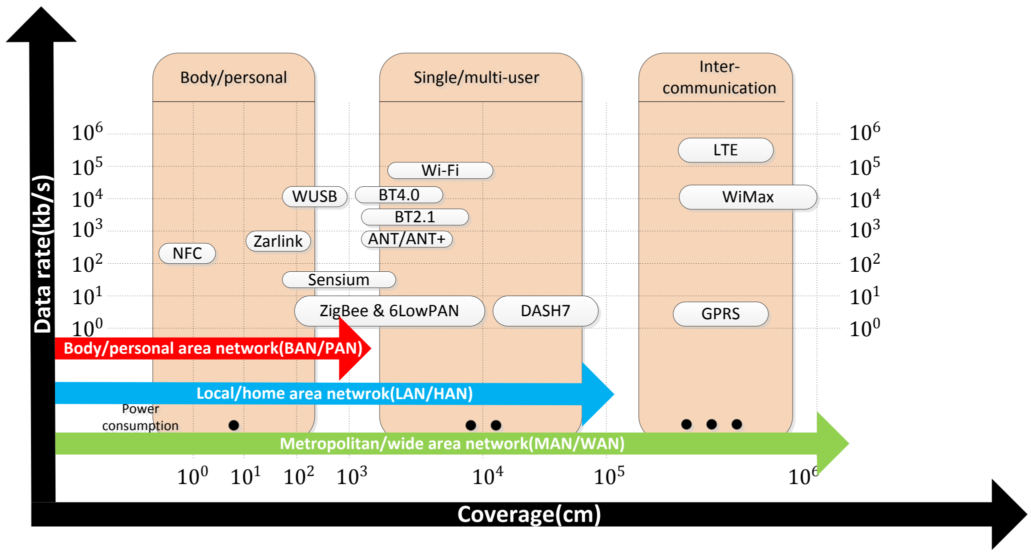

Figure 4.2. Wireless communication technologies

There are three groups of communication technologies: Body/personal area network domain (BAN/PAN), Local/home area network domain (LAN/HAN) and Metropolitan/wide area network domain (MAN/WAN) (Figure 4.2).

4.2.1.1 BAN/PAN Domain The first group includes Bluetooth Low Energy (BTLE), ZigBee, Near Field Communications (NFC), Wireless Universal Serial Bus (WUSB), IPv6 over low-Power Wireless Personal Area Networks (6LoWPAN) and DASH7 [38] [35].

BTLE is integrated into the latest version of BT (4.0) and features ultra-low-consumption idle operation mode, low latency, simple device discovery service, and point-to-point reliable transfer. BTLE also features two implementation modes: single-mode (which has low power consumption for integrated and compact devices) and dual-mode (which reuses BT classic hardware, sharing a single antenna and radio, and adds low-power features from the new protocol stack). It also features a native application layer for vital signs monitoring.

ZigBee implements on the IEEE 802.15.4 standard, which only defines the physical layer and media access control (MAC). It is focused on applications that require low-data-rate transmission, long battery life, and data encryption. The hardware is considerably simpler than BT, achieving several years of battery life through minimal power consumption.

NFC is a group of technologies featuring low coverage, fast data exchange, and a small frame payload. WUSB is the wireless USB standard extension, which is based on the emerging ultra wideband (UWB) radio technology, and features extensive bandwidth, a proximity-based association mechanism, and security similar to wired communications.

6LoWPAN is defined by the Internet Engineering Task Force (IETF) and is oriented toward embedded devices (personal health, ambient monitoring). Its main features are IP connectivity with a simple, header frame design and a hierarchical addressing model.

DASH7, originally developed for military purposes and based on the ISO/International Electrotechnical Commission (IEC) 18000 standard, implements low-power technology and has one of the widest coverage ranges among technologies (redefined for BAN/PAN applications), while the data rate is considerably lower. It also features low latency in object location, reduced protocol stack, encryption, and IPv6.

The second group comprises proprietary technologies such as ANT, Sensium Life Platform (Sensium), Zarlink, and Z-Wave. ANT is a general–purpose technology designed for wireless sensor networks (WSNs), which features a simple design, low latency, low power, and a variable transfer rate through adjusting power consumption. At the top of this technology model is ANT+, an interoperability layer ensuring compatibility between ANT devices from different manufacturers and distributors.

The ANT+ device profiles define the network parameters and data structure so that products from different manufacturers can communicate seamlessly.

Sensium is a wireless system for monitoring vital signs featuring low power consumption and based on a master-slave topology, where a slave device node periodically sends readings to the central node. The network is managed centrally, while all communications are single-hop via a bridge that can connect up to 16 nodes. These in turn are connected to a dedicated gateway for external access. To reduce energy consumption, all nodes are in the idle state until the central node assigns a time slot. It integrates modules to represent devices oriented to medical applications such as heart rate (HR), ECG, temperature, and physical activity, and new ones can easily be added.

Zarlink is an implantable radio frequency transmitter for ultra-low power consumption in accordance with the Medical Device Radio Communications Service (MedRadio).When the transmitter is configured as an implantable medical device (IMD), it remains in a very low-power sleep state until it is awakened.

Z-Wave is a proprietary protocol based on low consumption technology designed for communicating home electronic devices while providing remote control by simple commands (e.g., turn on-turn off or upload-download) with highly optimized headers with the ability to incorporate metadata. Its operating frequency range is not affected by interference from other short-range wireless protocols.

4.2.1.2 LAN/HAN Domain Some of the technologies described in the previous group (e.g., BTLE, ZigBee, and 6LoWPAN) may also be included within this group, depending on the distance to the signal receiver to which they are usually linked, and whether the scenario is individual or multi-user [39]. In any case, it is clear that the most representative of wireless LAN (WLAN) technologies is the family of IEEE 802.11 standards (wireless Ethernet extension), because there is no other

WLAN technology to rival them. However, Wi-Fi Direct, a certification program developed by the Wi-Fi Alliance, it consists of a series of software protocols (Wi-Fi peer-to-peer specification) that allow Wi-Fi devices to communicate with each other directly without a wireless access point (AP). In terms of security, it uses the Wi-Fi protected setup to create connections (using WPA2) between devices. In addition, there are new emerging technologies such as Gigabit WLAN, also known as WiGit, that operates in the 60 GHz band providing data rates on the order of gigabits per second. WiGit will not replace the existing Wi-Fi technology, but complement it, featuring higher data transfer speed over a shorter range.

4.2.1.3 MAN/WAN Domain. The emergence of new technologies in this environment is strongly marked by the evolution of the telecommunications consumer market dominated by large companies, from device manufacturers (e.g., Ericsson and Huawei) to service providers (e.g., Vodafone or Verizon). Currently, the most extended wireless WAN technologies, classified by their generation, are: second generation (2G; Global System for Mobile Communications, GSM), 2G transitional (general packet radio service, GPRS; enhanced data rates for GSM evolution, EDGE), third generation (3G; Universal Mobile Telecommunications System, UMTS; code-division multiple access, CDMA2000) and 3G transitional (highspeed packet access, HSPA; evolved HSPA, HSPA+; Long Term Evolution, LTE; WiMAX).

Some of the latest technologies, such as LTE and WiMAX, have become known as fourth generation (4G) technologies, but this definition only applies to the emerging technologies LTE Advanced (still in the process of standardization) and Mobile WiMAX Release 2 (also known as Wireless MAN-Advanced). To achieve the official 4G designation, both technologies must meet the International Mobile Telecommunications (IMT) Advanced requirements, including peak rates of 100 Mb/s and 1 Gb/s in scenarios of high and low motion, respectively, and based entirely on IP packet switching and able to switch between 4G, 3G, and Wi-Fi networks. The main difference between WiMAX and LTE is that WiMAX takes advantage of earlier developments and deployments, while LTE is being developed by companies and telecom operators, who will choose which technology is finally deployed. However, because the frequency spectrum is allocated in many countries is specified for time-division duplex (TDD) or frequency-division duplex (FDD) transmission, the coexistence of both technologies seems to be appropriate for the market, since LTE focuses more on the FDD spectrum and WiMAX on the TDD spectrum [40].

4.2.2 E-Health Communication Specifications

The IEEE 802.15.6 [41] [42] is a communication standard that is optimized for low-power wireless wearable devices worn on the human body (or implanted) that may interact with data collectors (e.g., Smartphone). A list of medical monitoring applications under WBAN includes: Blood pressure, heart pulse, temperature, respiration, pulse oximeter (SpO2), electroencephalogram, electrocardiography (ECG), electromyography, motion detection, cochlear implant, artificial retina, audio, and voice. IEEE 802.15.6 specifies a single MAC layer and three physical layers; narrowband, ultrawideband, and human body communications. The operational frequency bands include: below 1 GHz (402958 MHz) and 2.4 GHz (2.362.4835 GHz). The average and peak current vary from 10 to 20 mA. Table I (adapted from [43] [44]) presents the typical performance benchmarking (e.g., data rate, bandwidth, resolution) values for health-related applications. The exact bandwidth and resolution for a specific application are normally device-dependent. Latency requirements are not listed in this table, since they are dependent on priority requirements. The author of this thesis believes that the latency of the biomedical applications in Table I should to be limited to a range of a few seconds up to 1 min. Life dependent biomedical applications (e.g., heart-pulse rate) should be transmitted and received in less than 5-s delay with the highest priority possible. The transmission of biomedical applications requiring less priority (e.g., weight scaling) could be delayed up to 60 s. [40]

Health-based proprietary and WPAN link technologies are discussed in Sections VI and VII, with their technical details, such as [44]: Operation frequency spectrum, data rate, wireless range, security capabilities, the number of nodes in the network, battery life, and other specifications.

4.2.2.1 ISM Band The industrial, scientific, and medical (ISM) radio bands are used to specify frequency allocation for wireless and wired medical systems and applications, including WBAN sensors and link technologies. Devices operating in ISM bands (unlicensed) may be required to tolerate interference from other ISM devices and equipment.

The ISM band starts from 6.765 MHz (used by Radio Frequency Identification RFID) systems and goes up to 246 GHz (used by radio astronomy and radiolocation), some of which are subject to local acceptance. Table II (adapted from [44]) specifies the ISM and medical bands (ISM and non-ISM bands).

The federal communications commission FCC made an announcement in August 2000 to set aside 14 MHz of spectrum for the wireless medical telemetry exclusive usage, referred to as the wireless medical telemetry service (WMTS). This licensed spectrum is divided into three bands: 608614; 13951400; and 14291432 MHz, where interference is minimal and suitable for the operation of medical devices. Prior to this division, other operational frequency bands (e.g., 174 MHz) were used, which were prone to interference from systems operating in these bands, such as digital television signals, making them unsuitable for medical applications.

4.2.2.2 Physical Layer Specifications From a communications perspective, a biomedical application is characterized by the nature and volume of the generated data and its operational frequency range. The link technology, transmitting biomedical data, must accommodate the application's requirements plus being bounded to its own rules, including wireless range and other physical layer requirements. These requirements are used in the selection of a specific wireless access technology that matches all the applications' criteria, including [44]:

- Data Rates: Data rates can be as low as 20 kb/s (Passive RFID) and as high as 300 Mb/s (IEEE 802.11n).

- Modulation: There are a wide variety of modulation schemes used in different wireless protocols, such as: phase-shift keying (PSK), which has a number of variants, such as: binary PSK (BPSK), quadrature PSK (QPSK), and offset QPSK (OQPSK), that are used in a number of protocols, such as Wi–Fi and ZigBee. Other modulation schemes include: frequency shift keying (FSK) and its variant Gaussian FSK (GFSK), which are used in a number of protocols (e.g., Bluetooth). Direct sequence spread spectrum (DSSS), quadrature amplitude modulation (QAM) and its variants (16-QAM and 64-QAM) are mainly used in Wi-Fi protocols.

- Wireless Range: This can be as short as 0.1 m [near-field communication (NFC)] and as high as 100 m (Wi-Fi/ZigBee/Active RFID).

- Network Topology: It can be in the form of a star, mesh, multipoint-to-point, or distributed topologies.

- Number of Nodes: The number of nodes in one network can vary from 7 + 1 (e.g., Bluetooth) to unlimited [e.g., Bluetooth low energy (BT-LE)].

- Peak Current: The maximum operational current in a wireless node depends on many factors, including the design of the chip, the operational data rate, and the antenna structure.

Table 4.1. Biomedical application data rates and resolutions

Biomedical Application	Maximum Data Rate(kbps)
Blood Pressure	10kbps(40-200 samples/sec)
Heart Pulse Rate	10kbps(40-200 samples/sec)
Respiration	10kbps(10-80samples/sec)
Glucose Monitoring	10kbps(40-200 samples/sec)
Thermometer	10kbps(2-10 samples/sec)
Blood Oxygen - Pulse Ox meter (SpO2)	10kbps(50-500 samples/sec)
Weight - Scaling	10kbps(10-50 samples/sec)
Electrocardiography(ECG) 6 Leads	100kbps(500 samples/sec/channel)
Electrocardiography(ECG) 12 Leads	300kbps(1000 samples/sec/channel)
Electromyography(EMG)	400kbps(1000 samples/sec/channel)
Electroencephalogram(EEG)	50kbps(100 200 samples/sec)
Still Image(e.g. X-Ray)	2000(50k-250k samples/sec)

- Battery Life: Battery life can be as low as 12 h (Wi-Fi) and as high as 3+ years (ZigBee).
- Duty Cycle: The secret to ultra-low-power wireless protocols is because the sensors are not active most of the time and only wake up to transmit information before going back to sleep. The frequency of their wake up is called duty cycle, which is usually around 1% of the time, meaning that the sensor is asleep 99% of the time.

4.2.3 Promising Low-Power Wireless Sensor/Link Technologies

4.2.3.1 Sensium Sensium [45] [46] is a proprietary sensor technology, featuring ultra-low-power sensing capability mostly used for BAN applications in healthcare and medical areas (e.g., temperature, ECG/heart rate, oxygen, blood sugar level onitoring), as well as a wide range of other applications. It operates in the 862- 870/902-940-MHz ISM bands, capable of a 50-kb/s data rate over a maximum range of 10 m. Toumaz systems are based on the Sensium technology (e.g., TZ1030). Sensium lacks fundamental security features, however, Sensium offers the following reliability features [32]: Unique chip ID, forward error correction (FEC), and cyclic redundancy

Table 4.2. Sensium performance parameters

Performance Parameter	Range
ISM Frequency Band	862-870 MHZ and 902 940 MHz
Data Rate	50 kbps
Wireless Range	Up to 10 meters (3 meters nominal)
Number of Nodes	8 + 1
Battery Life	1 year
Peak Current	4 mA
Modulation	FSK/GFSK
Security Capabilities	None
Applications	ECG, heart rate, blood oxygen and glucose

check (CRC). Therefore, the platform requires strong security mechanisms (e.g., encryption and decryption) before it can be used in the end-to-end BlackBerry mHealth solution. Table III shows the details of Sensium technology.

4.2.3.2 ANT+ ANT+ is built based on the ANT technology [40], another proprietary multichannel adaptive wireless sensor technology (based on Nordic Semiconductor chipsets), that can be used in a PT–CT scenario and provides a seamless collection of automated personal and health-related data tracking and transmission. From the security point of view, ANT and ANT+ plans to add new features, including a roadmap for AES security. With proper encryption/authentication methods integrated with the ANT+ chips, ANT products could become suitable within the end-to-end BlackBerry solution. Table IV shows the details for ANT+.

4.2.3.3 BodyLAN BodyLAN (FitLinxx, Fitsense, and ActiHealth, based on Nordic Semiconductor) is another low-cost, ultra-lowpower, and reliable proprietary wireless sensor technology, that operates at the 2.4-GHz band in a star network topology. BodyLAN is based on a MAC-level protocol and has been around since the mid-1990 s and offers power-consumption rates much lower than Bluetooth. Table V shows BodyLAN's performance parameters [47]. In terms of security, following the

Table 4.3. ANT+ performance parameters

Performance Parameter	Range
ISM Frequency Band	2.4 GHz
Data Rate	Up to 1Mbps (250 kbps nominal)
Wireless Range	Up to 10 meters
Number of Nodes	65,000 + 1
Battery Life	3 year
Peak Current	17 mA
Modulation	GFSK
Security Capabilities	AES 128 data encryption
Applications	Sport, wellness, bed - side health - based

collection of health-related data, the ActiHealth network offers end-to-end security options between the ActiHealth data server and application servers provider via a secured VPN. However, the wireless sensors are not equipped with any security-enabled mechanisms [48].

Table 4.4. BodyLAN performance parameters

Performance Parameter	Range
ISM Frequency Band	2.4 GHz
Data Rate	32 to 1000 kbps
Wireless Range	2 -10 meters
Number of Nodes	127 + 1
Battery Life	1 year
Peak Current	15 mA
Modulation	OOC (Optical Orthogonal Code)
Security Capabilities	None
Applications	Weight scale, blood - pressure, heart rate, fitness

4.2.3.4 Z-Wave Z-Wave is another proprietary and low power, sensor-based technology used in the healthcare industry. It operates on the 908.42 MHz (US), 868.42 MHz (Europe), 919.82 MHz (Hong Kong), and 921.42 MHz (Australia/New Zealand) ISM frequency bands. Z-Wave 100-series devices may optionally deploy the 3 data encryption standard (DES) encryption scheme. Security, however,was removed in the current 200-series. Therefore, currently there are no security options available on the Z-Wave technology [49]. The cost associated with Z-Wave is typically lower compared to that of ZigBee; however, it is not suitable for health-related applications where both audio/video data transmissions are involved because of lacking of security. Table VI shows Z-Wave's performance parameters. [50]

Table 4.5. Z-Wave performance parameters

Performance Parameter	Range
ISM Frequency Band	868.42, 908.42, 919.82, 921.42 MHz
Data Rate	9.6 to 40 kbps
Wireless Range	Up to 30 meters
Number of Nodes	232
Battery Life	2 year
Peak Current	23 mA
Modulation	GFSK
Security Capabilities	None
Applications	Telemedicine, home and factory automation

4.2.3.5 Bluetooth Traditional Bluetooth is not considered a long-term healthrelated link technology because of its relatively high transmission power and high duty cycles. However, since BT-LE is an important candidate among low-power link technologies, it is important to consider Bluetooth within the bigger picture. Classical Bluetooth operates in the 2.4-GHz band using GFSK modulation with 1-Mb/s data rate and wireless ranges of 1100 m. Bluetooth v1.1 (ratified as IEEE 802.15.1-2002) was the first clean version of Bluetooth. Bluetooth v1.2 (ratified as IEEE 802.15.1-2005) features adaptive frequency-hopping spread spectrum. Bluetooth v2.0 + enhanced data rate (EDR), released in 2004, supporting 3 Mb/s of data rate and has a lower duty cycle compared to previous versions. Other versions of Bluetooth are: Bluetooth v2.1 + EDR (adopted by the Bluetooth Special Interest Group (SIG) on July 26, 2007) and Bluetooth v3.0 + high speed (adopted by the Bluetooth SIG on April 21, 2009), with a theoretical data rate of up to 24 Mb/s [51]. Newer versions of Bluetooth use differential phase-shift keying (DPSK) and QPSK in addition to

GFSK. Table VII shows Bluetooth's performance parameters. Bluetooth v4.0 introduced on June 12, 2007, was called Wibree by Nokia and Bluetooth SIG, and features an ultra-low-power Bluetooth technology, marking the birth of BT-LE.

Table 4.6. Bluetooth performance parameters

Performance Parameter	Range
ISM Frequency Band	2.4 GHz
Data Rate	0.1 to 24 kbps
Wireless Range	1 - 100 meters
Number of Nodes	7+1
Battery Life	5 10 days
Peak Current	40 mA
Modulation	GFSK, DPSK, and DQPSK
Security Capabilities	AES encryption algorithm
Applications	Consumer electronics and mobile phones

4.2.3.6 Bluetooth-Low Energy (BT-LE) BT-LE is Bluetooth's new protocol stack and is backward compatible with the existing BT protocol stacks. A profile based on BT-LE, specifically designed to be used in health-related scenarios, is the Bluetooth medical device profile (MDP). This profile was the result of the collaborative efforts of theMedical DevicesWorking Group and the ISO/IEEE 11073 Personal Health Devices Working Group [52]. The set of health and medical standards for devices, services, and protocols, makes it possible for different medical devices and remote systems to exchange and evaluate vital signs data efficiently. The Bluetooth MDP is based on USB and other transport methods, which require connections to be authenticated and transport traffic to be encrypted, similar to ZigBee [53]. Several medical devices can operate simultaneously through a timed synchronization scheme. The current BT-LE release (v4.0) operates at 2.4 GHz, with a data rate of 1 Mb/s over a wireless range of up to 10 m. The power consumption level is between 0.01 to 0.5mW. In terms of security, BT-LE features the Advanced Encryption Standard (AES) with counter-mode cipher block chaining-message authentication code (CBC-MAC) or (AES-CCM). Table VIII shows BT-LE's technical parameters. Both

Bluetooth and BT-LE use GFSK, however the modulation index of Bluetooth is 0.35 and 0.5 for BT-LE, which is close to Gaussian minimum shift keying (GMSK). [34]

Table 4.7. Bluetooth-Low Energy performance parameters

Performance Parameter	Range
ISM Frequency Band	2.4 GHz
Data Rate	1 Mbps
Wireless Range	1 - 10 meters
Number of Nodes	Limited by the application
Battery Life	1 year
Peak Current	15 mA
Modulation	GMSK
Security Capabilities	128 bit AES with Counter Mode CBC MAC
Applications	Fitness and long life health related applications

4.2.3.7 ZigBee The ZigBee specification is based on the IEEE 802.15.4 standard for WPAN, and is specifically for low-rate WPANs, which are for low–power, small devices, similar to the BT-LE deployment. ZigBee has been used for consumer electronics and is widely used in health-related applications for secure, reliable management and monitoring of low-acuity and noncritical healthcare services, including chronic disease management thermometers, glucometers, oximeters, and blood pressure monitors. ZigBee operates at the ISM band 869/915 MHz (similar to Sensium) and also in the 2.4-GHz band and is based on BPSK and OQPSK. ZigBee is the basis for many technologies (e.g., MeshNetics) and uses ISO/IEEE 11073 personal health data, similar to BT-LE. In terms of security, unlike Sensium, ZigBee has a strong and well-defined security capability, featuring the following four security services (see Table IX, adapted from [35]).

4.2.4 Summary of Wireless Sensor Technologies

It is believed that the future of the sensor-mHealth combination technologies will be based on nonproprietary and open standard technologies, therefore proprietary-based technologies, such as Sensium, ANT+, BodyLAN, and Z-Wave will either have

Table 4.8. ZigBee performance parameters

Performance Parameter	Range
ISM Frequency Band	868, 915 MHz and 2.4 GHz
Data Rate	20 - 250 Mbps
Wireless Range	1 - 100 meters (up to 1.5 km for ZigBee Pro)
Number of Nodes	65000
Battery Life	3 + year
Peak Current	20 mA
Modulation	BPSK/OQPSK
Security Capabilities	AES CBC MAC 128 and ECC Roadmap long life utility readers
Applications	Long life utility readers

to support interoperability with open standards (e.g., IEEE 802.15-based) or face limited growth.

The battery life ranges provided in the Tables 4.1 to 4.8 are based on average usage under normal working load (same usage across all platforms).

Consequently, the link technology finalists are BT-LE and ZigBee. Though they have comparable features that make them attractive for the sensor-mHealth deployment, it is believed that BT-LE has a better chance of winning this race in mHealth applications. This is mainly due to the fact that BT-LE is designed for an ultralow- power-WBAN utilized in a simple star network around a central unit (e.g., Smartphone). ZigBee, on the other hand, is meant for a low-power mesh networks with flexible routing, suitable for stationary nodes. Architectures based on ZigBee are more complex and since ZigBee operates in an asynchronous mode, the routers are required to constantly listen, making them less attractive from the green-energy perspective and more attractive for large sensor-based systems. That is why ZigBee has found suitable applications in the industrial domain, including smart metering. Therefor, Blue tooth Low Energy seems the best link technologies.

4.3 *Bluetooth Low Energy*

This section describes a demo using Bluetooth-Low-Energy (BT-LE). The demo demonstrates how to justify the connection parameters to save energy [54].

4.3.1 *Master-Slave Topology*

The topology of BT-LE is MasterSlave which is shown in Figure 4.3. A BT-LE system normally has one master and several slaves. The maximum number of slaves is seven. The master is a data process device such as a smartphone, while the slaves are data providers such as sensors.

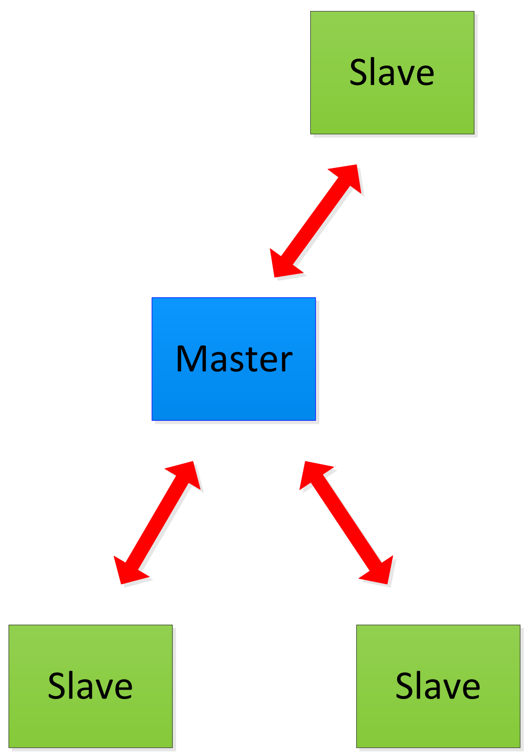

Figure 4.3. topology of BL-LE

4.3.1.1 Low Power Consumption Compared to Bluetooth and WiFi, BT-LE is much more energy friendly. The battery life of a BT-LE sensor is about one year with a coin cell battery (Figure 4.4). [55]

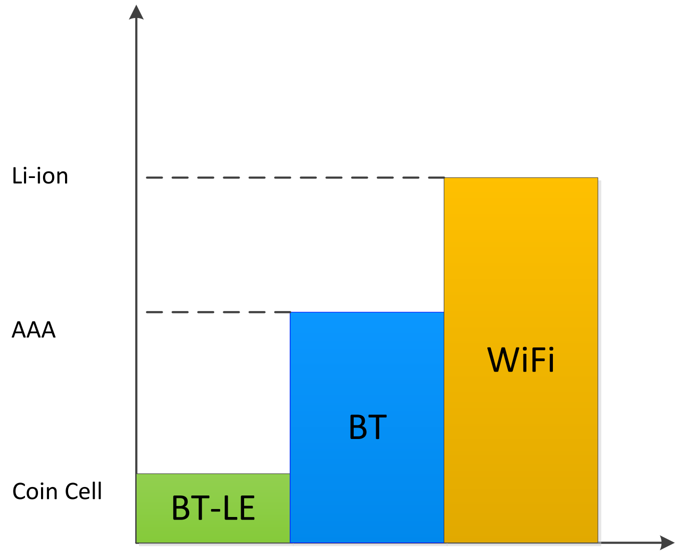

Figure 4.4. Power consumption of BL-LE compare with WIFI and Bluetooth

BT-LE saves energy because it has two kinds of events during operation. One is a connection event, and the other one is a sleeping event, as shown in Figure 4.6. Because the period during a sleep event consumes almost no energy, the efficiency of BT-LE is very high. Even in high throughput systems, a BT-LE device is transmitting for only a small percentage of the time that the device is connected. This will be illustrated in Demo 1.

4.3.2 Low Throughput and Shorter Range

For BT-LE, throughput is less than 100 kbps while for BT throughput is 3Mbps and for WiFi (abg) it is 54 Mbps. The range of BT-LE is about 50 meters, while Bluetooth' range is about 100 meters (Figure 4.5).

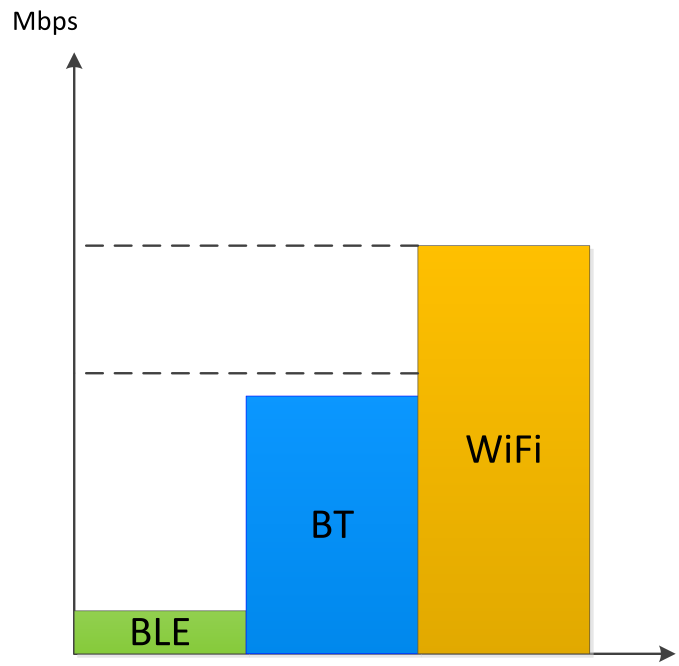

Figure 4.5. Throughput of BL-LE

4.4 BTLE Demo—Connection Parameters Adjusting

4.4.1 Connection Event

In BT-LE, all communication between two connected devices occurs during connection events. The current consumption during sleep is as low as 1 uA, while it becomes several mA when connection events are happening.

4.4.2 Connection Parameters

4.4.2.1 Connection Interval: The connection Interval is the time between each connection event, and is in the range of 7.5 ms to 4.0 s with the resolution of 1.25 ms (Figure 4.6). [17] [56]

4.4.2.2 Slave Latency: Slave Latency determines how many connection events the slave device can skip if it does not need to update the new data. That will save

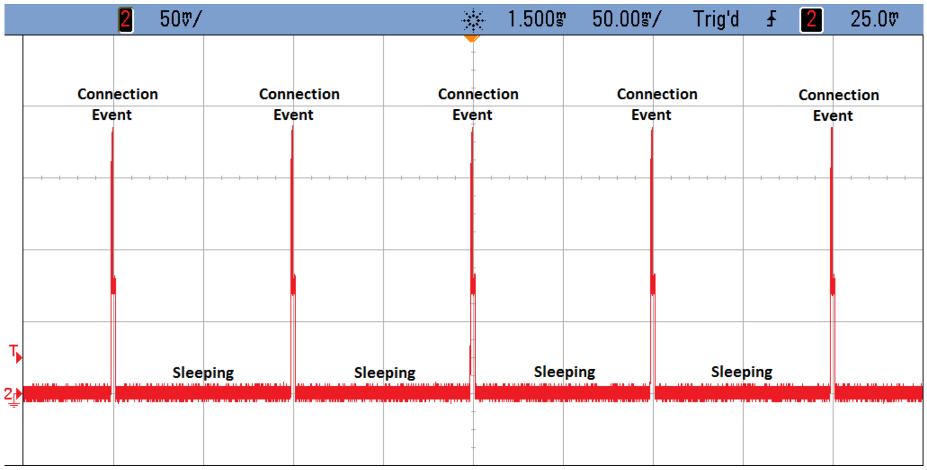

Figure 4.6. Connection Event

power on the slave side. Slave latency can be any value between 0 and 499 (Figure 4.7).

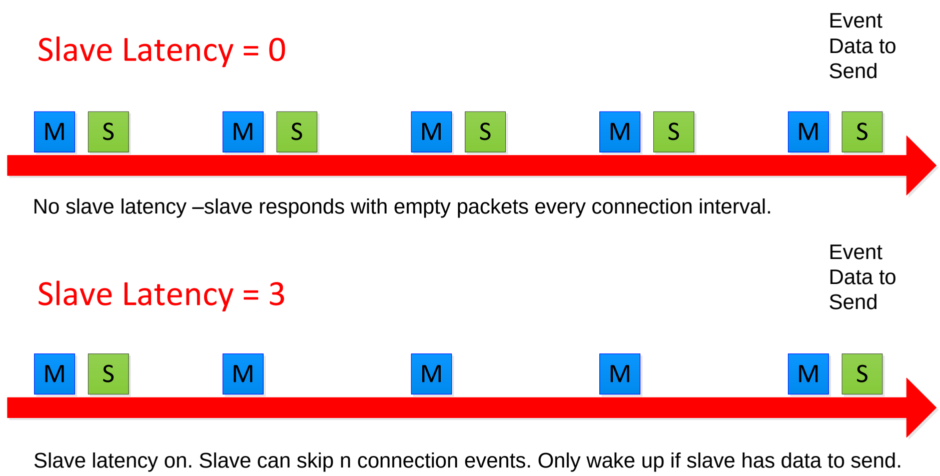

Figure 4.7. Slave Latency

4.4.2.3 Supervision Timeout: Supervision Timeout is the length of time before the BT-LE link will be dropped if no communication occurs. That may be because the master is out of range or there is simply no response. Supervision Timeout is in the range of 100 ms and 32.0 s with the increasement of 10 ms. It must fulfill the formula (4.1).

$$SupervisionTimeout > (1 + SlaveLatency) * ConnectionInterval \tag{4.1}$$

4.4.3 Demo

This demo uses two Bluetooth devices. One is set as Master; the other is set as Slave. The goal of this demonstration is to show BTLE can save energy by adjusting Connection Parameters. Here we use the TI CC2540 Development Kit to create the Bluetooth devices (Figure 4.8). [57]

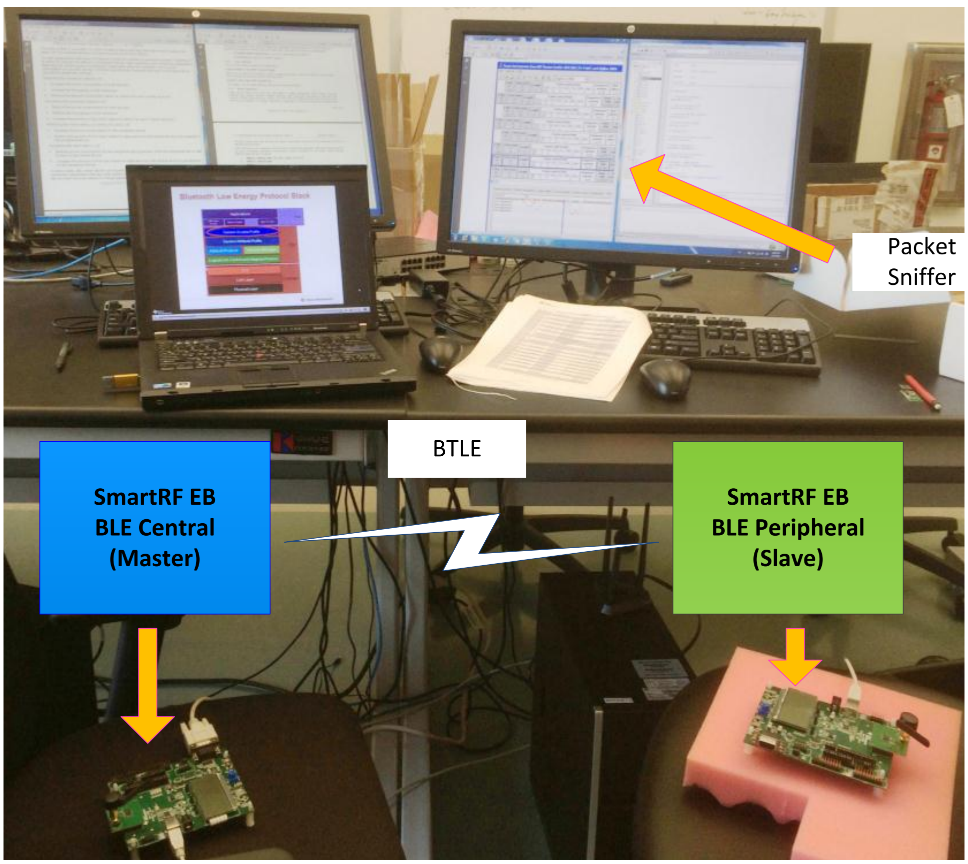

Figure 4.8. Block diagram of the demo

The CC2540DK is based on the Bluetooth chip cc2540, made by Texas Instruments. It contains the following hardware components (Figure 4.9) [58] [59]:

(1) 2 SmartRF05 Evaluation Boards (SmartRF05EB)

(2) 2 CC2540 Evaluation Modules (CC2540EM)

(3) 2 Pulse Antennas

(4) 1 CC2540 USB Dongle

Figure 4.9. CC2540 Develop Kit

The demo is operated as following:

(1) Connect the antennas to SMA connectors on the CC2540EM board. Then mount the CC2540EM board on to the connectors P5 and P6 on the SmartRF05EB.

(2) Set up the switches, jumpers and joystick, as shown in Figure 4.11. In this application, the joystick U1 (Figure 4.11) is used as the only input. The joystick (Figure 4.12) has five different movements: it can be moved up, down, left, and it can be pressed in, just like a button.

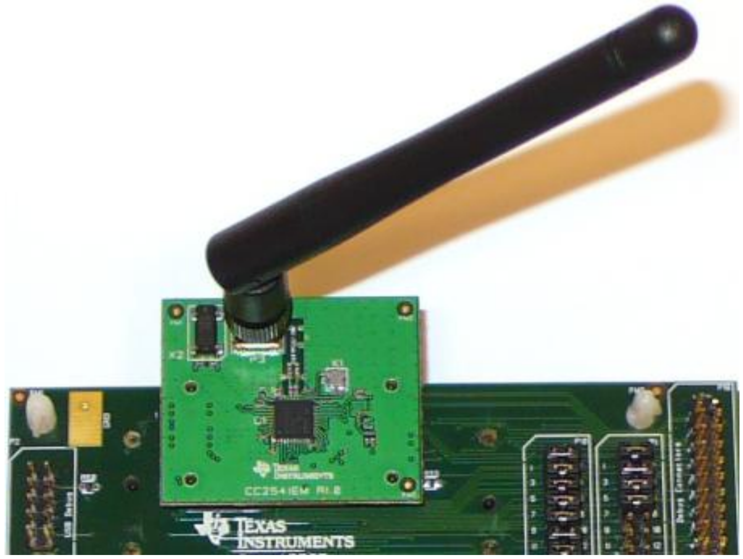

Figure 4.10. Assemble all parts

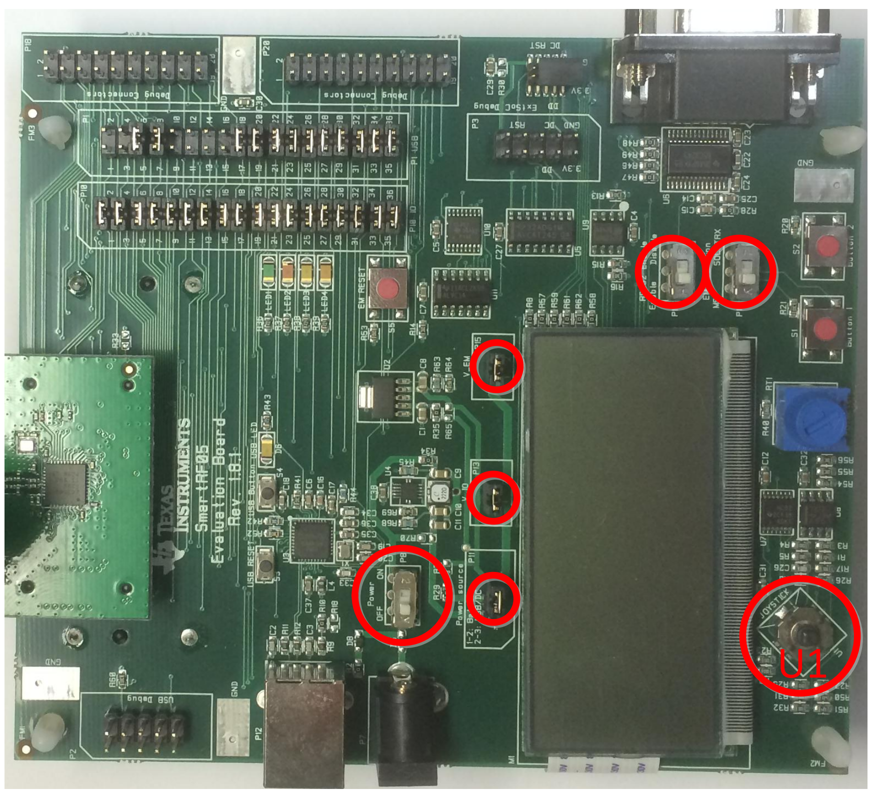

Figure 4.11. Switches and Jumpers setup

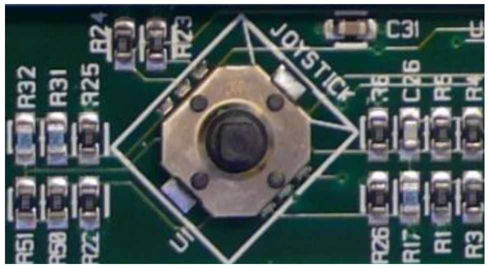

Figure 4.12. The joystick U1

(3) Download the firmware use the USB port to the two CC2540EM boards. One of the boards is BLE Central (Master) and the other one is the BLE Peripheral (Slave).

(4) Start-up Screen: After switching the power on the two devices, the start-up screens are as seen in Figure 4.13.

Figure 4.13. Start-up

(5) Establish Connection

Before the two devices can connect, the central device must first discover the peripheral device. To perform device discovery, press up on joystick U1 once. The LCD on the central device should display "Discovering. . . . . . ".

After a few seconds, it should display "Devices Found 1 <- To Select ". This means that the central device successfully discovered the peripheral. Press left on joystick U1 to view the address of the peripheral device. This address should match the address seen on the peripheral's LCD. Then press the joystick to establish the connection (Figure 4.14 and Figure 4.15).

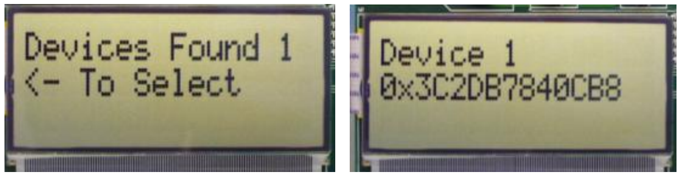

Figure 4.14. Choose the right Device

Figure 4.15. Establish Connection

The Connection Interval is 80 = 100 ms, Slave Latency is 0, Supervision Timeout is 1000 = 10 s, The code is as following [60]:

```
// Minimum connection interval (units of 1.25ms, 80=100ms) if automatic parameter update request is enabled
#define DEFAULT_DESIRED_MIN_CONN_INTERVAL     80

// Maximum connection interval (units of 1.25ms, 80=100ms) if automatic parameter update request is enabled
#define DEFAULT_DESIRED_MAX_CONN_INTERVAL     80

// Slave latency to use if automatic parameter update request is enabled
#define DEFAULT_DESIRED_SLAVE_LATENCY         0

// Supervision timeout value (units of 10ms, 1000=10s) if automatic parameter update request is enabled
#define DEFAULT_DESIRED_CONN_TIMEOUT          1000

// Whether to enable automatic parameter update request when a connection is formed
#define DEFAULT_ENABLE_UPDATE_REQUEST         TRUE
```

(6) Read / Write Data

The read /write operations are realized by pressing up on joystick U1. This time the Connection Interval is 100ms and the Slave Latency is 0, so we can see the numbers change almost immediately between Master and Slave (Figure 4.16 and Figure 4.17).

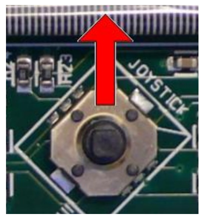

Figure 4.16. Read/Write operation realized by Pressing up on U1

Figure 4.17. Read/Write

(7) The Parameter updates operations is realized by pressing left on joystick U1 (Figure 4.18).

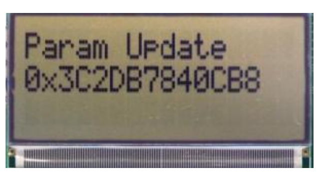

Figure 4.18. Update the Connection Parameter

The Connection Interval is 400 = 500 ms, Slave Latency is 4, Supervision Timeout is 1000 = 10 s, and the code is as following:

```
// Minimum connection interval (units of 1.25ms) if
  automatic parameter update request is enabled
#define DEFAULT_UPDATE_MIN_CONN_INTERVAL      400

// Maximum connection interval (units of 1.25ms) if
  automatic parameter update request is enabled
#define DEFAULT_UPDATE_MAX_CONN_INTERVAL      400

// Slave latency to use if automatic parameter update
  request is enabled
#define DEFAULT_UPDATE_SLAVE_LATENCY          4

// Supervision timeout value (units of 10ms) if automatic
  parameter update request is enabled
#define DEFAULT_UPDATE_CONN_TIMEOUT           1000
```

(8) Read / Write Data

Because the Slave Latency is 4 and the Connection Interval is 400 = 500 ms, we can see that there is some delay between Master and Slave.

4.5 Application Cases of E-health System for the Elderly

4.5.1 iCare

The iCare system is a mobile health monitoring system for the elderly. This system use wireless body sensors and smart phones to monitor the wellbeing of the elderly. It can offer remote monitoring and provide tailored services for each person based on their personal health needs. When detecting an emergency, the smart phone will automatically alert pre-assigned people, such as their family or friends, or call the ambulance. It can also act as a personal health information system and the medical guidance which offers one communication platform and a medical knowledge database so that the family and friends can cooperate with doctors to take care of him/her. The system also features some unique functions that cater to the living demands of the elderly, including regular reminder, quick alarm, medical guidance, etc. iCare is not only a real-time health monitoring system for the elderly, but also a reminder assistant which can make their lives more convenient (Figure 4.19). [61]

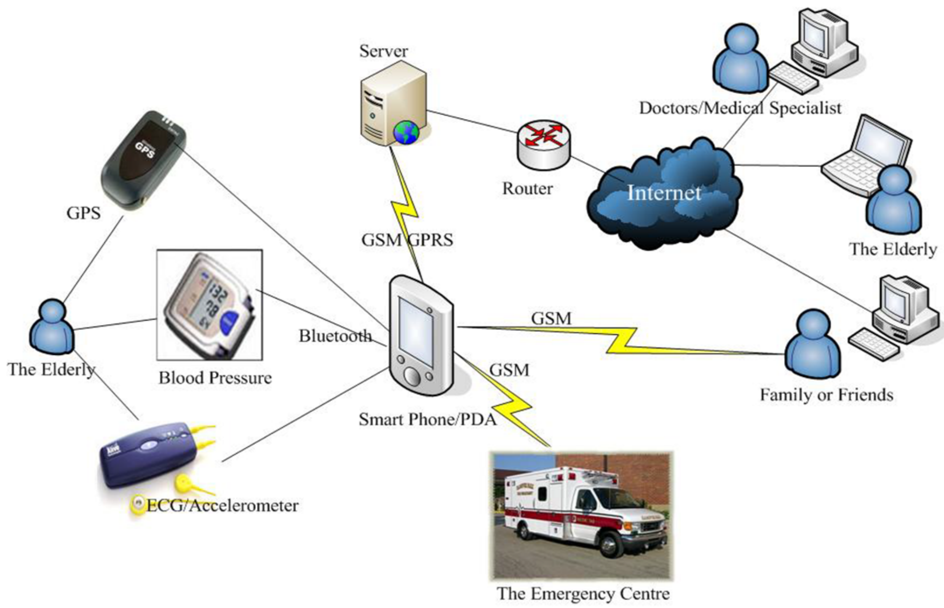

Figure 4.19. iCare system

4.5.2 Health OS System

In the department of Health Systems and Outcomes at the Johns Hopkins University, professor Sarah Szanton's group built a Health OS system to improving the wellness of low-income elders at home using game consoles. As shown in Figure 4.19 The Health OS system is an approach for improving the wellness of low-income elders at home using game consoles and a smartphone. There are three parts in the system: the elder's residence, the Health OS and Daily Alert. In the elder's residence, well designed wii games are used for balance exercises to prevent fall risks. The sensors and the wii balance board are used to monitor the risk of heart attacks. The Health OS collects data from the gaming systems and sensors, publishes the data to various applications for visualization and analysis using the Representational State Transfer (REST) application programming interfaces (APIs), and provides tools to add and manage new sensor devices. Daily Alert is a system in the cloud for clinicians and caregivers to build, schedule, and deliver timely alerts and information to the smartphones of elders family members. In addition, Daily Alert analyzes the data pushed from HealthOS, and if certain conditions are met, it automatically generates alerts. In that way a fully closed-loop system is created that can improve and automate the intervention process of exercise monitoring for at-home elders (Figure 4.20). [62]

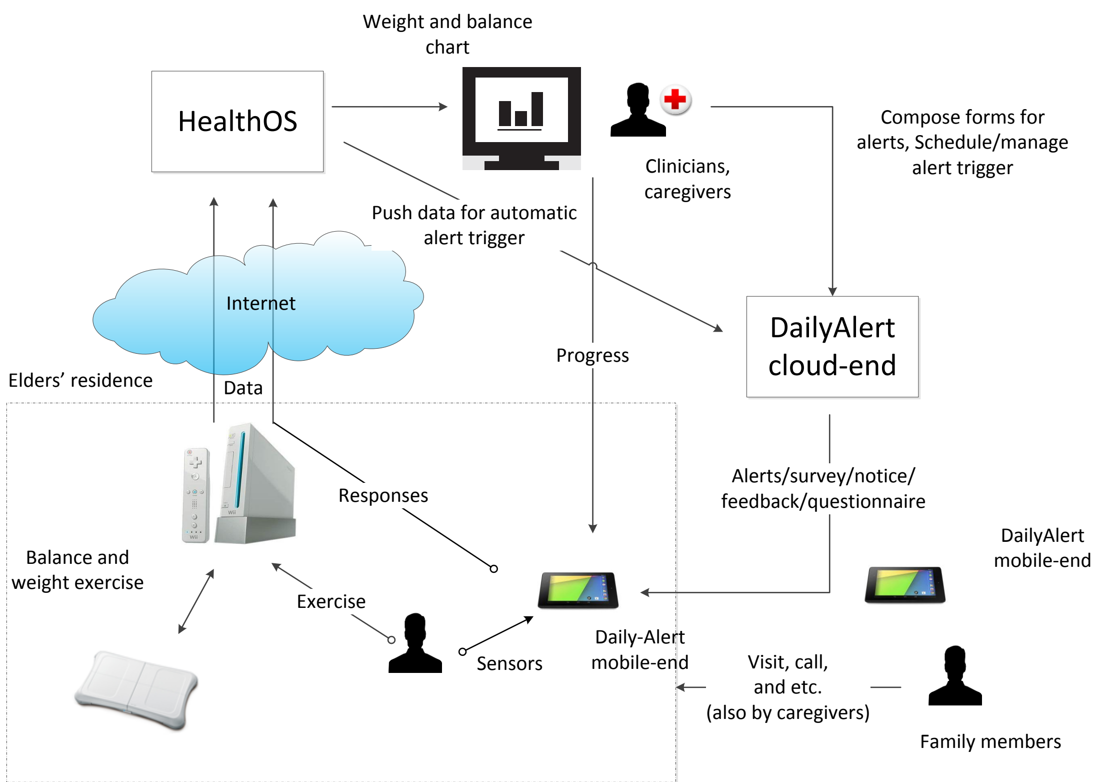

Figure 4.20. Health OS System

CHAPTER FIVE

Summary and Future Work

5.1 Summary

In this thesis work, we developed methods of signal acquisition and processing for biomedical vital signs. The application areas are in the ubiquitous healthcare, especially for the global aging population. We discussed the biomedical vital signs that include SpO2, ECG and blood pressure and focused on the analysis of stethoscope signals and ECG signals. Real ECG data are used for digital signal processing through MATLAB programming. We chose the Bluetooth Low Energy as the technology for signal delivery and networking for the ubiquitous healthcare applications. A demo system was developed based on Texas Instrument CC2540 development boards to implement the Bluetooth Low Energy technology for E-Health.

5.2 Future Work

In our future work, multiple types of biomedical vital signs will be sensed, acquired, and analyzed. We will advance the signal processing methods to filter noise caused by patient movement or ambient EM sources. We will collect data, build database, and statistically relate multiple vital signs to various medical symptoms. Signals classification will be developed for disease diagnose. We will build hardware for real-time signal acquisition and transferring to a smartphone through Bluetooth Low Energy. The sensed biomedical vital signs will be pre-processed, pattern recognized, and transferred to the smartphone and continued onto the cloud server.

BIBLIOGRAPHY

[1] "Number of older americans." [Online]. Available: http://www.census.gov/

[2] United Nations, *World population aging, 1950-2050.* New York: United Nations, 2002.

[3] W. Chen, "The trend of China propulation:2005–2050." Population Research, 2006, pp. 93–95.

[4] Z. Xiaoyi and K. Fisher, "Evaluating the elderly care community services in shanghai," in *2011 International Conference on Management and Service Science (MASS)*, Aug. 2011, pp. 1–8.

[5] "International programs - totalization agreement with Japan," DCDISP.OIP. [Online]. Available: http://www.socialsecurity.gov/international/Agreement Pamphlets/japan.html

[6] "Social security programs throughout the world: Asia and the pacific, 2004 – Japan," U. S. Social Security Administration, Office of Retirement and Disability Policy. [Online]. Available: http://www.socialsecurity.gov/policy/docs/progdesc/ssptw/2004-2005/asia/japan.html

[7] "Germany's aging population." [Online]. Available: http://www.aicgs.org/2012/11/germanys-aging-population/

[8] A. Borsch-Supan, "Aging in Germany and the United States: International comparisons," National Bureau of Economic Research, Working Paper 4530, Nov. 1993. [Online]. Available: http://www.nber.org/papers/w4530

[9] "Aging gracefully: Germans grow gray together." [Online]. Available: http://www.cnn.com/2013/06/19/world/europe/german-senior-citizens/index.html

[10] N. V. Daniilidou, C. Economou, D. Zavras, J. Kyriopoulos, and E. Georgoussi, "Health and social care in aging population: an integrated care institution for the elderly in Greece," *International Journal of Integrated Care*, vol. 3, Oct. 2003, PMID: 16900264 PMCID: PMC1483938. [Online]. Available: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1483938/

[11] "Greece is facing huge problem with aging population." [Online]. Available: http://www.topix.com/forum/world/cyprus/TDR5S4CG586POQ7O8

[12] "Smart and connected health," National Science Foundation. [Online]. Available: http://www.nsf.gov/pubs/2013/nsf13543/nsf13543.htm

[13] J. A. Blaya, H. S. F. Fraser, and B. Holt, “E-health technologies show promise in developing countries,” *Health Affairs*, vol. 29, no. 2, pp. 244–251, Feb. 2010, PMID: 20348068.

[14] “Implementing ehealth in developing countriesl,” ICT Applications and Cybersecurity Division, Policies and Strategies Department,ITU Telecommunication Development Sector. [Online]. Available: http://www.itu.int/ITU-D/cyb/app/docs/e-Healthprefinal15092008.PDF

[15] I. Troshani and N. Wickramasinghe, “e-health trends,” in *Pervasive Health Knowledge Management*, ser. Healthcare Delivery in the Information Age, R. Bali, I. Troshani, S. Goldberg, and N. Wickramasinghe, Eds. Springer New York, Jan. 2013, pp. 57–66.

[16] J. Smith and R. Roberts, *Vital signs for nurses an introduction to clinical observations*. Chichester, West Sussex, U.K.: Wiley-Blackwell, 2011.

[17] “Application note an092,” Texas Instruments. [Online]. Available: http://www.ti.com/lit/an/swra347a/swra347a.pdf

[18] “Spo pulse ox wrist oximeter reference design,” Texas Instruments. [Online]. Available: http://www.ti.com/lit/ug/tidu124/tidu124.pdf

[19] “Integrated analog front-end for pulse oximeters,” Texas Instruments. [Online]. Available: http://www.ti.com/lit/ds/symlink/afe4490.pdf

[20] Z. Gao, J. Wu, J. Zhou, W. Jiang, and L. Feng, “Design of ECG signal acquisition and processing system,” in *2012 International Conference on Biomedical Engineering and Biotechnology (iCBEB)*, May 2012, pp. 762–764.

[21] J. Silva, J. Caldera, and G. Passariello, “DSP application for QRS detection, alignment and averaging in ECG signals,” in *, Proceedings of the 1995 First IEEE International Caracas Conference on Devices, Circuits and Systems, 1995*, Dec. 1995, pp. 149–153.

[22] “Ultra low power, 18 bit precision ecg data acquisition system,” Texas Instruments. [Online]. Available: http://www.ti.com/lit/ug/slau516/slau516.pdf

[23] “Freescale solutions for electrocardiograph and heart rate monito applications,” Freescale Semiconductor. [Online]. Available: http://cache.freescale.com/files/analog/doc/app note/AN4323.pdf

[24] L. A. Geddes, “Birth of the stethoscope,” *IEEE Engineering in Medicine and Biology Magazine*, vol. 24, no. 1, pp. 84–86, Jan. 2005.

[25] N. Jatupaiboon, S. Pan-ngum, and P. Israsena, “Electronic stethoscope prototype with adaptive noise cancellation,” in *Knowledge Engineering, 2010 8th International Conference on ICT and*, Nov. 2010, pp. 32–36.

[26] "Blood pressure monitor using flexis qe128." [Online]. Available: http://cache.freescale.com/files/microcontrollers/doc/appnote/AN3500.pdf

[27] V. K. Ingle and J. G. Proakis, *Digital signal processing using MATLAB*. Stamford, Conn.: Cengage Learning, 2012.

[28] B. P. Lathi, *Signal processing and linear systems*. New York: Oxford University Press, 1998.

[29] Z. Lianyi and Z. Chongxun, "A new method to monitor depth of anesthesia based on the autocorrelation EEG signals," in *2005 First International Conference on Neural Interface and Control, 2005. Proceedings*, May 2005, pp. 123–126.

[30] B. Ninness, "Spectral analysis using the fft," University of Newcastle, Australia.OW.

[31] G. Moody and R. Mark, "The MIT-BIH arrhythmia database on CD-ROM and software for use with it," in *Computers in Cardiology 1990, Proceedings.*, Sep. 1990, pp. 185–188.

[32] S. Chernenko, "Ecg processing r-peaks detection," LIBROW. [Online]. Available: http://www.librow.com/cases/case-2

[33] B.-Y. Shiu, S.-W. Wang, Y.-S. Chu, and T.-H. Tsai, "Low-power low-noise ECG acquisition system with dsp for heart disease identification," in *2013 IEEE Biomedical Circuits and Systems Conference (BioCAS)*, Oct. 2013, pp. 21–24.

[34] W. Omar and A. Taleb-Bendiab, "E-health support services based on service-oriented architecture," *IT Professional*, vol. 8, no. 2, pp. 35–41, 2006.

[35] "IEEE standard for local and metropolitan area networksPart 15.4: Low-rate wireless personal area networks (LR-WPANs)," *IEEE Std 802.15.4-2011 (Revision of IEEE Std 802.15.4-2006)*, pp. 1–314, Sep. 2011.

[36] A. Helal, D. J. Cook, and M. Schmalz, "Smart home-based health platform for behavioral monitoring and alteration of diabetes patients," *Journal of diabetes science and technology*, vol. 3, no. 1, pp. 141–148, Jan. 2009, PMID: 20046657.

[37] A. Aragues, J. Escayola, I. Martnez, P. del Valle, P. Munoz, J. Trigo, and J. Garcia, "Trends and challenges of the emerging technologies toward interoperability and standardization in e-health communications," *IEEE Communications Magazine*, vol. 49, no. 11, pp. 182–188, 2011.

[38] D. Barakah and M. Ammad-uddin, "A survey of challenges and applications of wireless body area network (WBAN) and role of a virtual doctor server in existing architecture," in *2012 Third International Conference on Intelligent Systems, Modelling and Simulation (ISMS)*, Feb. 2012, pp. 214–219.

[39] I. Akyildiz and K. Bernhardt, "ATM local area networks: a survey of requirements, architectures, and standards," *IEEE Communications Magazine*, vol. 35, no. 7, pp. 72–80, Jul. 1997.

[40] S. Adibi, "Link technologies and BlackBerry mobile health (mHealth) solutions: A review," *IEEE Transactions on Information Technology in Biomedicine*, vol. 16, no. 4, pp. 586–597, Jul. 2012.

[41] C. Tachtatzis, F. Di Franco, D. Tracey, N. Timmons, and J. Morrison, "An energy analysis of IEEE 802.15.6 scheduled access modes," in *2010 IEEE GLOBECOM Workshops (GC Wkshps)*, Dec. 2010, pp. 1270–1275.

[42] K.-S. Kwak, S. Ullah, and N. Ullah, "An overview of IEEE 802.15.6 standard," in *2010 3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL)*, Nov. 2010, pp. 1–6.

[43] B. Latr, B. Braem, I. Moerman, C. Blondia, and P. Demeester, "A survey on wireless body area networks," *Wirel. Netw.*, vol. 17, no. 1, p. 118, Jan. 2011. [Online]. Available: http://dx.doi.org/10.1007/s11276-010-0252-4

[44] "Wireless connectivity for medical applications." [Online]. Available: http://www.arrownac.com/events-training/training/pdfs/wireless.pdf

[45] A. C. W. Wong, D. McDonagh, O. Omeni, C. Nunn, M. Hernandez-Silveira, and A. Burdett, "Sensium: an ultra-low-power wireless body sensor network platform: Design and application challenges," in *Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2009. EMBC 2009*, Sep. 2009, pp. 6576–6579.

[46] "Ultra low power smart sensor interface and transceiver platform." [Online]. Available: http://www.all-electronics.de/media/file/18023

[47] P. Carvey, "Technology for the wireless interconnection of wearable personal electronic accessories," in *VLSI Signal Processing, IX, 1996., [Workshop on]*, Oct. 1996, pp. 13–22.

[48] J. Barber, T., P. Carvey, and A. Chandrakasan, "Designing for wireless LAN communications," *IEEE Circuits and Devices Magazine*, vol. 12, no. 4, pp. 29–33, Jul. 1996.

[49] C.-w. Yuan, H.-r. Wang, and J.-y. He, "Remote monitoring system based on MC9S12NE64 and z-WAVE technology," in *2010 International Conference on E-Product E-Service and E-Entertainment (ICEEE)*, Nov. 2010, pp. 1–4.

[50] G. Csernath, L. Szilagyi, G. Fordos, and S. Szilagyi, "A novel ECG telemetry and monitoring system based on z-wave communication," in *30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2008. EMBS 2008*, Aug. 2008, pp. 2361–2364.

[51] "Bluetooth," Feb. 2014, page Version ID: 595117852. [Online]. Available: http://en.wikipedia.org/

[52] J. DeCuir, "Introducing bluetooth smart: Part 1: A look at both classic and new technologies." *IEEE Consumer Electronics Magazine*, vol. 3, no. 1, pp. 12–18, Jan. 2014.

[53] B. Yu, L. Xu, and Y. Li, "Bluetooth low energy (BLE) based mobile electrocardiogram monitoring system," in *2012 International Conference on Information and Automation (ICIA)*, Jun. 2012, pp. 763–767.

[54] J. Liu, C. Chen, Y. Ma, and Y. Xu, "Energy analysis of device discovery for bluetooth low energy," in *Vehicular Technology Conference (VTC Fall), 2013 IEEE 78th*, Sep. 2013, pp. 1–5.

[55] M. Siekkinen, M. Hiienkari, J. Nurminen, and J. Nieminen, "How low energy is bluetooth low energy? comparative measurements with ZigBee/802.15.4," in *2012 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, Apr. 2012, pp. 232–237.

[56] A. Dementyev, S. Hodges, S. Taylor, and J. Smith, "Power consumption analysis of bluetooth low energy, ZigBee and ANT sensor nodes in a cyclic sleep scenario," in *Wireless Symposium (IWS), 2013 IEEE International*, Apr. 2013, pp. 1–4.

[57] "Smartrf protocol packet sniffer," Texas Instruments. [Online]. Available: http://www.ti.com/tool/packet-sniffer

[58] "Bluetooth low energy cc2540/41 mini development kit users guide," Texas Instruments. [Online]. Available: http://www.ti.com/lit/ug/swru270c/swru270c.pdf

[59] "Bluetooth low energy cc2540 development kit cc2541 evaluation module kit users guide," Texas Instruments. [Online]. Available: http://www.ti.com/lit/ug/swru301a/swru301a.pdf

[60] "Texas instruments cc2540/41 bluetooth low energy software developers guide," Texas Instruments. [Online]. Available: http://www.ti.com/lit/ug/swru271f/swru271f.pdf

[61] Z. Lv, F. Xia, G. Wu, L. Yao, and Z. Chen, "iCare: a mobile health monitoring system for the elderly," in *Green Computing and Communications (GreenCom), 2010 IEEE/ACM Int'l Conference on Int'l Conference on Cyber, Physical and Social Computing (CPSCom)*, Dec. 2010, pp. 699–705.

[62] J. H. Lim, A. Zhan, J. Ko, A. Terzis, S. Szanton, and L. Gitlin, "A closed-loop approach for improving the wellness of low-income elders at home using game consoles," *IEEE Communications Magazine*, vol. 50, no. 1, pp. 44–51, Jan. 2012.