



**ADDIS ABABA UNIVERSITY**

**ADDIS ABABA INSTITUTE OF TECHNOLOGY**

**DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING**

Design and Simulation of Front End 3-in-1 EEG, ECG, EMG Bio-Potential Signal  
Acquisition System

A thesis submitted to School of Graduate Studies and Research in Partial Fulfillment of  
the Requirement for the Master's Degree

By: Yonas Worede Legesse

June, 2020

## Declaration

I, the undersigned, declare that this thesis work is my original work, has not been presented for a degree in this or any other universities, and all sources of materials used for the thesis work have been fully acknowledged.

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## **Abstract**

The last couple of years have given birth to meticulously mapped and innovative solutions in regards to product as well as research of medical analysis tools and diagnostic equipment. The industry has shown a major transformation on the general process of diagnosis tools providing flexibility and enhanced accuracy. However, despite the astonishing progress of the bio-medical industry, the status of medical provision is still a concern in third world countries. The inaccessibility and unaffordability of medical equipment in such countries needs immediate attention as many people fall prey to this problem which can be solved through the provision of a supplementary solution that can aid the process of preliminary diagnosis.

In this thesis, the design of a front-end system for EEG, ECG and EMG signal acquisition is done. The design addresses the problem of medical provision in under developed nations by providing a supplementary hardware that is portable making it cost-efficient and readily available. Moreover, it extends the research aspect in the area through the combination of a 3-in-1 signal acquisition hardware and optimizing the design in regards to performance, complexity and scalability.

Owing to the fact that the signals operated by the hardware are very weak in nature, the utilization of low noise amplifiers with very high common-mode rejection ratio and gain adjustment is critical. Moreover, the implementation of analog-to-digital conversion needs a thorough analysis in regards to the architecture, resolution and area of application. Accordingly, the design in this thesis is specifically done so as to improve the performance in regards to noise cancellation, minimization of filter circuitry, number of channels and overall circuit complexity.

Verification of the design is done with the co-simulation of PSPICE and SIMULINK. The simulation is carried out for individual cases of EEG, EMG and ECG application by using physiological signals of patients from PhysioNet.org through the addition of noise signals to mimic actual physical application of the hardware. Furthermore, the output is analyzed and compared with existing products and previous researches in the area which yielded a 21% improvement in common-mode rejection ratio and a 33% increase in channel capacity.

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## List of Acronyms

ADC	Analog to digital converter
A/D	Analog / Digital
BCI	Brain Computer Interface – used to describe applications for the detection, recording and analysis of brain wave
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CLK	Clock – used for interface and data communication clock signals
CMRR	Common Mode Rejection Ratio
CS	Chip Select – signal for initiating device for data communication
DIN	Data in – port used for receiving digital signal
DOUT	Data out – port used for transmitting digital signal
DRDY	Data Ready – output signal that transition from high to low indicating new conversion data are ready
DSP	Digital Signal Processor
ECG	Electrocardiogram – diagnostic tool for assessment of electrical and muscular function of the heart
EEG	Electroencephalography – a diagnostic procedure to detect abnormalities in brain waves
EMG	Electromyogram – diagnostic procedure to detect muscular abnormalities
edf	European Data Format – used for storing time series data
GPO	General Purpose Output – pin used for general purpose of digital input and/or output
GUI	Graphic User Interface
HPF	High Pass Filter
IC	Integrated Circuit
IFCN	International Federation of Clinical Neurophysiology – reference for set of standards in brain-computer applications
INA	Instrumentation amplifier
LNA	Low Noise Amplifier
LPF	Low Pass Filter

MISO	Master In Slave Out
MOSI	Master Out Slave In
MUX	Multiplexer
OSR	Over Sampling Ratio – design parameter for sigma delta converters
PCB	Printed Circuit Board
SCLK	Serial Clock
sEMG	Surface Electromyogram
SNR	Signal to noise ratio
SOC	System on chip
SPI	Serial Peripheral Interface - a full-duplex synchronous serial interface for connecting low-/medium-bandwidth external devices using four wires
SPICE	Simulation Program with Integrated Circuit Emphasis

# Chapter 1

## Introduction

### 1.1 Overview

Bio-potentials signals originate from the human body as occurrence of potential differences between compartments [1]. These signals are generated due to the electrochemical activity of certain class of cells that are components of the nervous, muscular or glandular tissue. The electrical activity of each cell is described by the ion exchange through the cell membrane. These signals possess various properties and characteristics that contribute to their diagnostic value. The available bio-signals are grouped into two major categories which are: bio-electric signals (i.e. ECG, EEG and EMG) and bio-acoustic signals (i.e. lung sounds, hears sounds). These signals are tiny carriers of information that provide crucial data about the bodily functions and are accurate indicators of the physiological and neurological state of human beings.

In a nutshell, an EEG, EMG and ECG are the physical measurements of the signals generated by the human body, human muscle and human heart respectively [2]. These organs are filled with mobile ions such as calcium and potassium which constantly flow through the body. Through accurate and highly sensitive detection mechanism, these signals can be retrieved and interpreted. These signals, if interpreted correctly, can give extensive explanation to the physical functioning state of the body, which is very crucial in the diagnosis of illnesses related to the organs.

The weakness of these signals in amplitude and frequency have put enormous challenges in designing systems that accurately measure them. Some of the most predominant challenges faced in designing such systems are: Power line interference, Instrumental Imprecisions, DC bias voltage, Gain adjustability, Digital System consideration and circuit complexity [2].

In the last few decades, consumer grade bio-medical electronics have gone through numerous changes. Initially, these devices were to be operated only by licensed physicians under certain protocols. However, the advancement in research within this area has paved the way for the public to put their hands on such devices. These devices usually take the form of a portable hardware such as a headset or an armband, and usually have the means of not just processing the data but to send it over some form of communication channels. These bio-medical electronics provide a diverse range of functionality from detection of brain signals and heart rate, to digital storage and

interactions through mobile applications as well as web interfaces. However, these electronic devices cannot be utilized for medical diagnosis purposes as they do not meet international biomedical standards.

The aim of this thesis is to provide a solution to the critical problems pertaining to noise cancellation, digital filtering, circuit complexity, availability and affordability by designing a data acquisition hardware that can be used for the acquisition of EEG, ECG and EMG signals that meets international medical standards. The project proposes a step by step approach of bio-signal processing from detection through to data communication under clearly defined stages of signal conditioning, analog to digital conversion and data communication.

## **1.2 Theoretical background and design principles**

### **1.2.1 Signal characteristics**

EEG, ECG and EMG signals have broad classification independently with very similar characteristics to each other which is discussed in the coming sections. However, the property that is most common to these signals is the fact that they are very weak in amplitude and low in frequency. This property makes these signals highly susceptible to noise interference which have numerous sources but can be generally categorized as [3]: personal-related and technical. Personal-related noise sources refer to artefacts that arise from bodily movement of individual under study, sweating, breathing and so on. Technical artefacts refer to artefacts such as AC power line noise, fluorescent lighting, electrical machinery and computers.

#### **A. EEG signals**

Different mind states lead to different EEG displays. The four main mind states—alertness, rest, sleep, and dreaming—have associated brain waves named beta, alpha, theta, and delta respectively [4]. Aside from providing crucial information in regards to the state of the mind, these signals are key indicators of any illness or abnormality in regards to the brain. The brain wave patterns are classified according to their frequency which is described in table 1.1.

Table 1.1: Frequency characteristics of EEG signals

No.	Signal Name	Frequency (Hz)
1	Delta	< 4
2	Theta	4 - 7
3	Alpha	8 - 15
4	Beta	16 - 31
5	Gamma	> 32
6	Mu	8 - 12

### B. ECG signals

Relatively speaking, ECG signals are much stronger than EEG signals and hence require less amplification. The useful frequency band of ECG signals range from 0.5 – 100Hz. One cardiac cycle of ECG signal consists of the P wave, QRS complex along with T waves [6]. P wave represents depolarization and the QRS represents ventricular depolarization. T wave represents rapid repolarization of the ventricles. The signal representation under normal scenario is shown in the figure 1.1.

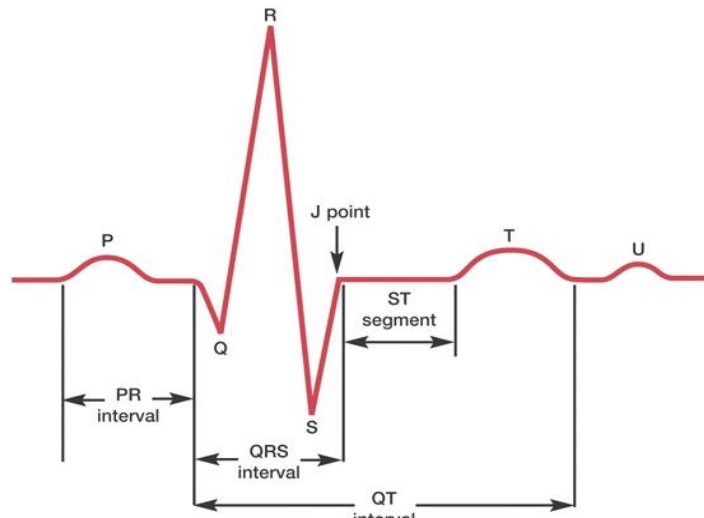


Figure 1.1: Processed display of an ECG signal [5]

The dynamic range in amplitude of the segments vary from each other as given in table 1.2 [5]

Table 1.2: Average amplitudes of independent ECG waves

No.	Wave	Amplitude
1	P wave	0.25 mV
2	R wave	1.6 mV
3	Q wave	25% of R wave
4	T wave	0.1 – 0.5 mV

### C. EMG signals

EMG signals refers to the recording of the potential difference resulting from muscle movement [3]. Relatively speaking, EMG signals possess stronger amplitude and wider bandwidth compared to EEG and ECG signals. The amplitude of EMG signal is stochastic (random) and can be reasonable represented by a Gaussian distribution function. The amplitude can range from 0 to 10 mv (peak-to-peak) or 0 to 1.5 mv (rms).

The power density spectrum of the EMG signal ranges from zero to four hundred Hertz for many muscles [3]. Above this frequency, the amplitude of the signal is less than  $1\mu\text{V}$  rms and are no longer distinguishable from the noise of the detection and recording system. There are some exceptions, such as the masseter muscle, where the frequency distribution reaches up to 600 Hz. As can be inferred from figure 1.2, the dominant energy of EMG signal lies in the range of 0 – 200 Hz. More specifically, the frequency range of 0 – 150 is one that is the most usable for preliminary diagnosis purposes.

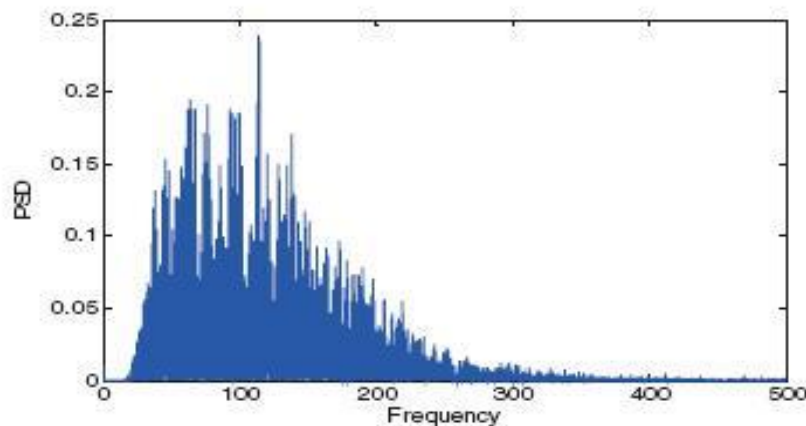


Figure 1.2: Power spectral plot of EMG signal [7]

## 1.2.2 Signal measurement type and standards

### 1.2.2.1 Measurement type

When considering measurement types in clinical EEG, EMG and ECG measurement, there are two general categories that are employed: invasive and non-invasive [3]. Invasive EEG, ECG and EMG recordings refer to measurements that require surgery. This type of measurement requires highly trained physicians under specially equipped laboratories and centers. It requires the surgical penetration of the scalp, heart and muscle of the understudy and has to be done with the utmost care and expertise. On the other hand, there is the non-invasive method of bio-potential signal measurement which requires no surgical procedure and is done through the use of surface electrodes. The measurement type proposed in this work is a non-invasive type carried out with pre-gelled gold-plated electrodes.

### 1.2.2.2 Measurement standards

EEG, ECG and EMG signals have different types of measurement standards. When selecting which type of standard to employ to use for various types of bio-potential signals, the critical point to consider is the expected detail of the recording required. For the measurement of brain waves, the widely accepted standard electrode placement is known as the 10-20 system which is a method to describe and apply the location of scalp electrodes in the context of an EEG exam, polysomnography sleep study, or voluntary lab research [6]. This type of electrode placement is depicted in figure 1.3.

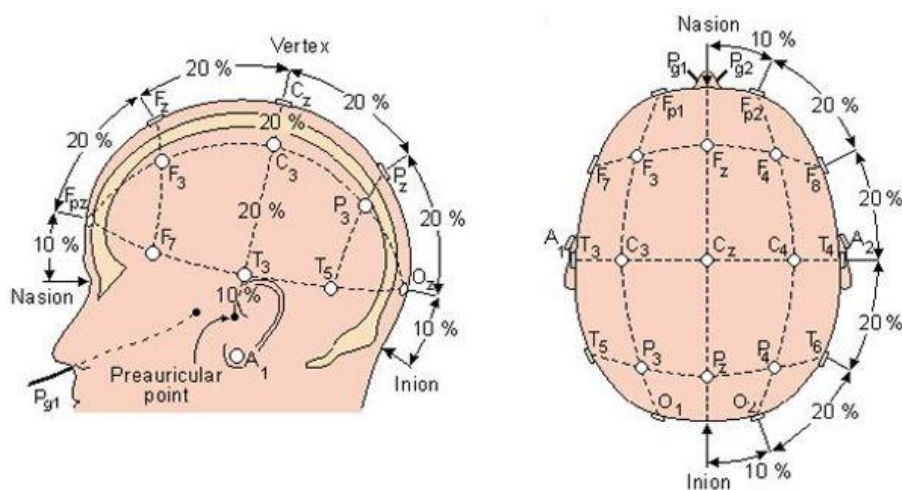


Figure 1.3 10-20 standard for electrode placement in EEG measurement [11]

For the measurement of EMG signals, the placement of electrodes depends on the type of application required. Generally, there will be more than one measurement electrode placed on the muscle area under inspection [20]-[21]. One of the electrodes will be used as a reference so that the measurement starts from zero. Other electrodes will be used for the measurement of the muscle potential between the muscle ends of placement. Sample placements is shown figure 1.4.

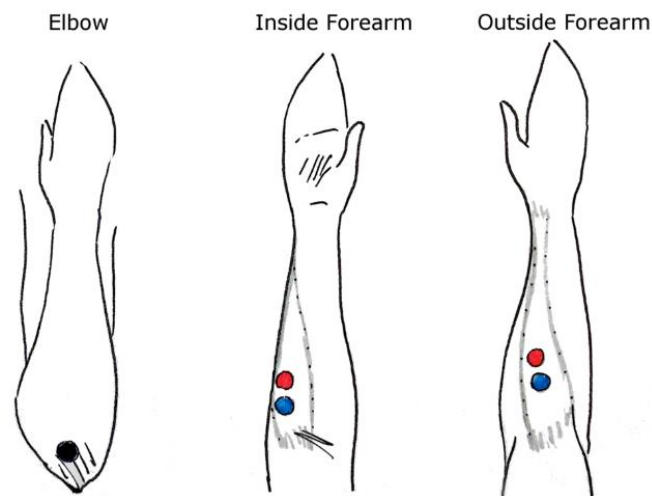


Figure 1.4 Standard electrode placement for EMG measurement [10]

In regards to ECG measurement, the scheme that yields detailed information is known as the 12-lead ECG [5]. It is composed of twelve signals or 'leads' measured from the limbs and six positions on the chest called precordial. The precordial (1/2 of the signals) are measured as the potential difference between each exploring electrode located on the chest, and an assumed constructed 'zero' reference. This 'zero' reference was introduced by F. N. Wilson in 1931 and named after him as Wilson's Central Terminal (WCT). The placement of the electrodes is given in the table 1.3.

Table 1.3 Standard electrode placement for a 12-lead ECG measurement

Electrode name	Electrode Placement
RA	Right arm
LA	Left arm
RL	Right leg
LL	Left leg
V1	Right of the sternum (between ribs 4 and 5)
V2	Left of the sternum (between ribs 4 and 5)
V3	Between leads V2 and V4
V4	Mid-clavicular line
V5	Left anterior axillary line
V6	Mid-axillary line

### 1.2.3 Data acquisition system architecture

When designing bio-potential data acquisition systems, engineers take diversified approaches in regards to sensing mechanisms, noise cancellation, filter designs as well as digital system development. The approaches taken in designing such systems is made in regards to what type of optimization is required. However, the general design process of bio-potential signal acquisition system can be generalized through a high-level system architecture given in figure 1.5.

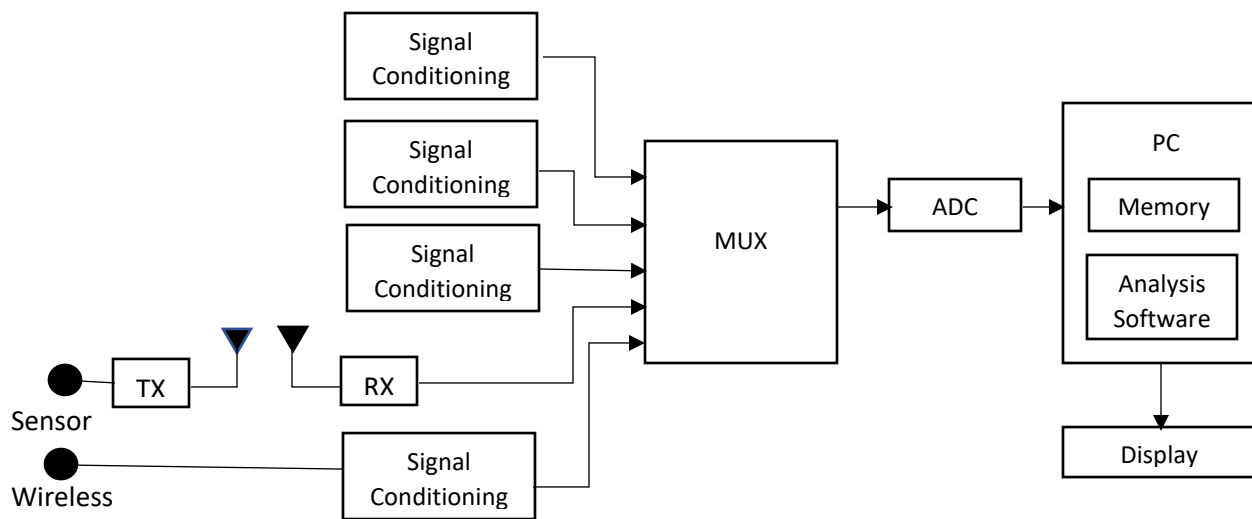


Figure 1.5 Generalized architecture of a bio-potential signal acquisition system design [22]

The main components of a DAQ are shown in figure 3.5. The inputs are from sensors that are usually connected by cables to signal conditioning circuits to prepare their outputs to be digitized. Signal conditioning includes amplification, filtering for noise, level shifting, or other corrections. In some applications the sensor may be far from the DAQ system in which case a wireless link can be established using Wi-Fi or other wireless technology [22].

The processed sensor signals then go to a multiplexer (MUX) that selects the sensor to be digitized and passes the signal along to an analog-to-digital converter (ADC) that samples the analog signal from the sensor and converts it to a stream of binary values. Sampling rates are usually low, from several samples per hour to 1 MS/s. The resulting data words are then sent to a PC and stored in a file. The data can then be analyzed by software, used in analysis or converted into appropriate displays or graphs [22].

#### **1.2.4 Safety and standard**

Medical devices are subject to strict general controls and procedural regulations [3]. The development and use of standards are vital to ensuring the safety and efficacy of medical devices. Numerous regulatory agencies and standards organizations collaborate to establish the accepted standards for medical equipment. Standard-setting activities include the development of performance characteristics, characterization and testing methodologies, manufacturing practices, product standards, scientific protocols, compliance criteria, ingredient specifications, labeling, or other technical or policy criteria. However, it should be noted that the type of standard to be followed is defined by the target market of the equipment as the standards are required to be met based on a country basis.

Aside from general standards, patient safety is also a critical component of the design process. As EEG, ECG and EMG components are directly attached to the subject under test, the system design should be done with special emphasis on the power circuitry and protection options.

Moreover, for the case of EEG data acquisition design, the International Federation of Clinical Neurophysiology (IFCN) published a set of recommended practices for EEG recording [9]. Here a Workgroup of IFCN experts presents unanimous recommendations on the following procedures

relevant for the topographic and frequency analysis of resting state EEGs in clinical research defined as neurophysiological experimental studies carried out in neurological and psychiatric patients:

- Recording of resting state EEGs (environmental conditions and instructions to participants; montage of the EEG electrodes; recording settings);
- Digital storage of resting state EEG and control data;
- Computerized visualization of resting state EEGs and control data (identification of artifacts and neuropathological resting state EEG waveforms);
- Extraction of "synchronization" features based on frequency analysis (band-pass filtering and computation of resting state EEG amplitude/power density spectrum);
- Extraction of "connectivity" features based on frequency analysis (linear and nonlinear measures);
- Extraction of "topographic" features (topographic mapping; cortical source mapping; estimation of scalp current density and dura surface potential; cortical connectivity mapping)
- Statistical analysis and neurophysiological interpretation of those resting state EEG features

### **1.2.4 Summary**

EEG, ECG and EMG signals are bio-potentials that possess very weak amplitude and narrow frequency. The proper acquisition, recording and analysis of these signals yields crucial diagnostic information of subjects and can be the basis of further studies in regards to bodily functions. There are different types of methods that can be employed for the measurement of these signals. However, some of the widely applied measurement standards are: 10-20 system for EEG measurement; 12-lead for ECG recording; differential placement for EMG. The measurement standards employed are dependent on the required accuracy and diagnostic detail.

Consequently, in the design of data acquisition systems for bio-potential signals, modularizing the entire approach for better understanding of the architecture is necessary. Accordingly, the major sections of the systems can be broken down as sensing, conditioning, analog-to-digital conversion

and digital signal processing. Hence, the design of EEG, ECG and EMG data acquisition systems involve critical consideration: sensing methodology; signal amplification; noise removal; analog-to-digital conversion architecture as well as mechanisms involved; digital signal processing requirements and specifications. Moreover, study of general patient safety requirements, regulations as well as useful recommendations as well as standards should be thoroughly understood and utilized.

### **1.3 Problem statement**

In the current medical provision of low-income countries, getting a brain scan, a thorough heart examination, a physiotherapy, or related diagnoses have become a luxury for reasons such as:

- Cost of examination
- Shortage of equipped medical centers
- Large queues
- Length of appointment
- Shortage of qualified physicians equipped with the diagnostic knowledge of scans
- Absence of cost-effective supplementary solutions.

Bio-medical equipment manufacturers across the globe come out with new products that minimize human error whilst providing impeccable performance and patient safety. However, the costs of these equipment are very high and their functionality is mainly limited to a single bio-potential signal application. Aside from the product spectrum of bio-medical equipment, research institutes are also actively involved in the improvement of circuit design of such systems in regards to noise, circuit complexity and digital filtering. Moreover, there are numerous ongoing BCI researches that are aimed at advancing the field in regards to flexibility and accuracy.

Evidently, Researchers tend to provide special emphasis on the development and advancement of BCI which mainly revolves around the human brain while products are restricted to single bio-potential signal applications. However, when carefully studying the signal characteristics of the brain, heart and muscles of the human body, it becomes evident that these signals possess highly similar traits in regards to signal amplitude as well as frequency. Hence, this thesis provides a supplementary solution by designing a hardware capable of data acquisition of EEG, ECG and EMG signals with optimization in regards to complexity and performance.

## **1.4 Objectives**

### **1.4.1 General objective**

The main objective of this research is to design a hardware for the measurement of EEG, ECG and EMG bio-potential signals.

### **1.4.2 Specific objectives**

- Design of a bio-medical electronic circuit with optimized circuit complexity, performance and modularity for application in a 3-in-1 EEG, ECG and EMG bio-potential data acquisition
- Carry out a detailed market research in integrated circuits manufactured for medical instrumentation
- Develop a simulation environment that mimics real world application scenario and carry out verification via simulation
- Analyze, interpret and provide valid conclusions and recommendation for future studies as well as adaptation into a feasible product

## **1.5 Scope of the study**

The scope of this thesis is focused on the design and simulation of a data acquisition hardware for EEG, ECG and EMG signal application. Although highly accurate simulation models and tools are used, due to limitation in resource and time, experimental verification of the design isn't carried out. Moreover, the thesis is strictly concerned with the hardware part of the data acquisition and doesn't account for the software counterpart of the design.

## **1.6 Significance of the study**

The ultimate outcome of this study has impacts in regards to both research and product development. The final design of the PCB is done so as to allow actual manufacturing which tackles the major problem of medical provision in low-income countries by acting as a supplementary solution. Furthermore, the digital counterpart can be developed simultaneously and scaled up to a nation-wide repository for medical data storage, remote monitoring and diagnosis.

Moreover, the study also contributes to previous researches that have worked on optimization in regards to complexity and overall performance. It also extends the concept of a single bio-potential

data acquisition hardware being used for multiple purposes, which has been suggested by previous studies, by designing a bio-potential data acquisition hardware that can be used for three distinct purposes i.e. EEG, ECG and EMG.

## **1.7 Thesis outline**

Included in this research is the design, simulation and analysis of a hardware system for EEG, ECG and EMG signal acquisition. Accordingly, the thesis is organized with five distinct chapters outlined as follows.

Chapter one provides a brief outline in regards to bio-potential signals, their significance as well as current stages of bio-medical equipment design. Problems residing in the area of study is discussed along with the objectives of the research. Finally, the scope of the study along with the significance in regards to research as well as product is provided.

Chapter two provides a literature review related to the research at hand. The review is done so as to provide a seamless continuation of concepts by initially providing reviews in regards to signal characteristics of the bio-potential signals followed up by previous researches in the area of bio-potential data acquisition hardware design. Finally, review in regards to common design methodologies and patterns is carried out.

Chapter three deals with the methodology employed in the research by describing the methods employed, tools utilized and research process flowchart. This chapter is meant to provide a detailed analysis of the steps followed in data collection, design, simulation and analysis used in the research.

Chapter four goes through the entire circuit design in detail through the application of the concepts discussed in chapter three through an in-depth circuit design and simulation. Once the design is verified through simulation, the PCB design is also carried out after which, results and discussions are carried out.

Finally, chapter five provides a conclusion based on analysis of discussion carried out in chapter four. Moreover, it contains what the future holds for this research as well as shortcomings that need improvement in its future endeavors.

## Chapter 2

### Literature review

#### 2.1 Bio-potential signals and measurement practices

Wim V. Dronghen [1] describes biopotentials as signals of the body that originate within biological tissue as potential differences occurring between compartments. Generally, the compartments are separated by a (bio)membrane that maintains concentration gradients of certain ions via an active mechanism (e.g., the Na<sup>+</sup>/K<sup>+</sup> pump). Moreover, John W. Clark Jr [2] sets out in detail the origin of bio-potentials commencing from a discussion at the cellular level. In his work, he identifies a class of cells known as excitable cells that are components of nervous, muscular or glandular tissue. Electrically, they exhibit resting potential and when properly stimulated, an action potential.

Measurement of biopotential signals through the utilization of specialized electrodes is discussed in [3]. The function of recording electrodes is described as the coupling of the ionic potentials generated inside the body to an electronic instrument. Furthermore, the classification of biopotential electrodes is done as noninvasive (skin surface) or invasive (e.g., microelectrodes or wire electrodes). Invasive bio-potential signal recordings refer to measurements that require surgery. This type of measurement requires highly trained physicians under specially equipped laboratories and centers. It requires the surgical penetration of the scalp, heart and muscle of the understudy and has to be done with the utmost care and expertise. On the other hand, there is the non-invasive method of bio-potential signal measurement which requires no surgical procedure and is done through the use of surface electrodes.

Biopotential measurements must be carried out using high-quality electrodes to minimize motion artifacts and ensure that the measured signal is accurate, stable, and undistorted. Body fluids are very corrosive to metals, so not all metals are acceptable for biopotential sensing. Furthermore, some materials are toxic to living tissues. For implantable applications, we typically use relatively strong metal electrodes made, for example, from stainless steel or noble materials such as gold, or from various alloys such as platinum-tungsten, platinum-iridium, titanium-nitride, or iridium-oxide. These electrodes do not react chemically with tissue electrolytes and therefore minimize tissue toxicity. Unfortunately, they give rise to large interface impedances and unstable potentials.

External monitoring electrodes can use nonnoble materials such as silver with lesser concerns of biocompatibility, but they must address the large skin interface impedance and the unstable biopotential. Other considerations in the design and selection of biopotential electrodes are cost, shelf life, and mechanical characteristics [3].

## **2.2 Electroencephalogram**

Electroencephalogram (EEG) is the recording of electrical activity along the scalp [3]. It further elaborates the recording as the measures of voltage fluctuations resulting from ionic current flows within the neurons of the brain. In clinical contexts, EEG refers to the recording of the brain's spontaneous electrical activity over a short period of time, usually 20-40 minutes, as recorded from multiple electrodes placed on the scalp. Diagnostic applications generally focus on the spectral content of EEG which refers to the type of neural oscillations that can be observed in EEG signals.

EEG is most often used to diagnose epilepsy, which causes obvious abnormalities in EEG readings. It is also used to diagnose sleep disorders, coma, encephalopathy, and brain death. EEG is used as a first-line method of diagnosis for tumors, stroke and other focal brain disorders, but this use has decreased with the advent of high-resolution anatomical imaging techniques such as MRI and CT. despite limited spatial resolution, EEG continues to be a valuable tool for research and diagnosis, especially when millisecond-range temporal resolution (not possible with CT or MRI) is required [3].

The system of EEG measurement involves hooking up several pairs of electrodes on a patients' head. These electrodes are disks that conduct electrical activity, capture it from the brain and convey it out through a wire to a machine that amplifies the signal. Electrodes attached in pairs on the head, measure the difference in voltage between the pairs. The measured electrical activity of brain waves is correlated to a persons' state of mind and the brain patterns form wave shapes that resemble sinusoids. Usually, they are measured from peak to peak and normally range from 0.5 to 100 $\mu$ V in amplitude [4].

## **2.3 Electrocardiogram**

The registration of the ECG signal Known as electrocardiogram, represents the recording of the electrical potential of the heart. Physicians record ECG signal easily and noninvasively by attaching small electrodes to the human body. Electrocardiogram is the standard tool to diagnose

the heart disease. While diagnosis the different artifacts get introduced in the ECG signal like Electrode contact noise, motion artifacts, base line drift electrosurgical noise, and power line interference [4].

Relatively speaking, ECG signals are much stronger than EEG signals and hence require less amplification. The useful frequency band of ECG signals range from 0.5 – 100Hz. One cardiac cycle of ECG signal consists of the P wave, QRS complex along with T waves [5]. P wave represents depolarization and the QRS represents ventricular depolarization. T wave represents rapid repolarization of the ventricles.

Pertaining to signal measurement, the ECG measurement scheme that yields detailed information is known as the 12-lead ECG [5]. It is composed of twelve signals or ‘leads’ measured from the limbs and six positions on the chest called precordial. The precordial (1/2 of the signals) are measured as the potential difference between each exploring electrode located on the chest, and an assumed constructed ‘zero’ reference. This ‘zero’ reference was introduced by F. N. Wilson in 1931 and named after him as Wilson’s Central Terminal (WCT).

## **2.4 Electromyogram**

An electromyogram (EMG), is a graphical recording of electrical activity within muscles. Activation of muscles by nerves results in changes in ion flow across cell membranes, which generates electrical activity. This can be measured using surface electrodes placed on the skin over the muscle of interest [1].

The EMG signal is the electrical manifestation of the neuromuscular activation associated with a contracting muscle. It is an exceedingly complicated signal which is affected by the anatomical and physiological properties of muscles, the control scheme of the peripheral nervous system, as well as the characteristics of the instrumentation that is used to detect and observe it. Most of the relationships between the EMG signal and the properties of a contracting muscle which are presently employed have evolved serendipitously. The lack of a proper description of the EMG signal is probably the greatest single factor which has hampered the development of electromyography into a precise discipline [39].

Measurement of surface EMG is dependent on a number of factors and amplitude as the surface EMG signal varies from the microvolts to the low millivolts range. The amplitude and time and frequency domain properties of the EMG signal are dependent on factors such as [3]: Timing and intensity of muscle contraction; Distance of the electrode from the active muscle area; Properties of the overlying tissue; Electrode and amplifier properties; Quality of electrode – skin contact.

If properly integrated, EMGs can be used to detect abnormal electrical activity of muscle that can occur in many diseases and conditions, including muscular dystrophy, inflammation of muscles, pinched nerves, peripheral nerve damage (damage to nerves in the arms and legs), amyotrophic lateral sclerosis (ALS), myasthenia gravis, disc herniation, and others [3].

## **2.5 Related works**

There are numerous works pertaining to EEG, ECG and EMG applications. Even though the majority of these researches are restricted to single signal applications and tend to push boundaries in regards to technological advancements, the considerations taken in regards to the design is extremely helpful for any designs that share the scope of application

In regards to equipment design pertaining to EEG, ECG and EMG signal acquisition. the primary focus of biomedical signal processing was on filtering signals to remove noise [4]. These sources of noise include the interference from power lines, instrumental imprecisions and more. Hence, the major objective during these days was to implement powerful noise cancellation mechanisms specifically designed for medical applications. The widely used method is through the use of frequency suppression while the other method is through statistical signal processing.

There are abundant researches done in the area of bio potential signal acquisition system that approach the idea from a diversified point of view. Some of the works include: multichannel data acquisition for brain control interface [14], Brain-computer interfaces for communication and control [40], past, present and future of BCI [41] and more. However, most researches are restricted to detection and analysis of a single type of bio potential signal acquisition and restricted to non-clinical applications.

A detailed multichannel signal acquisition system is designed in [14] where a successful design of a 32 channel EEG system is developed for the purpose of brain control interface application. The

research takes into account existing standardization in regards to brain wave applications and provides a portable hardware with a design that improves single-power AC-coupled circuit, which effectively reduces the DC bias and improves the error caused by the effects of part errors. The work also provides the software counterpart for the display.

Design considerations for mixed signal application systems which includes grounding, choice of power supply, power supply filters, low pass filters for ADC to remove wideband noise and after DACs for the reconstruction of the required analog signals is put forth in [34]. These considerations have considerable utility when physical prototypes are built.

In [16] and [17], signal acquisition system for the application in the area of surface electromyogram is carried out. These works present a detailed topology for the detection of muscle signals based on an SOC specifically designed for bio-potential signal applications. The works present a four-to-eight channel data acquisition system with variable sample rate for the application in surface electromyogram and electroencephalogram.

Another emerging, important need in a number of biomedical experiments is classification. In clinics, the goal of classification is to distinguish pathology from normal [41]. For instance, monitoring physiological recordings, clinicians judge if patients suffer from illness; watching cardiac MRI scans, cardiologists identify which region the myocardium experiences failure; analyzing gene sequences of a family, geneticists infer the likelihood that the children inherit disease from their parents. The rigorous research field of biomedical engineering is in great demand of the integration of bio-medical devices with statistical generation and artificial intelligence.

In [31], one of the first multi-person non-invasive direct brain-to-brain interface for collaborative problem solving is designed. The interface combines EEG to record brain signals and transcranial magnetic stimulation to deliver information noninvasively to the brain. The design is carried out through the use of a commercial EEG machine along with Arduino boards to carry out customized tasks. The interface allows three human subjects to collaborate and solve a task using direct brain-to-brain communication. The design also incorporates careful consideration of typical server-client TCP protocol to transmit information between computers for the purposes of record, analysis and display.

An experiment utilizing OPENBCI board for the collection of data from hand gestures for the purpose of gesture identification is done in [32]. EMG signal is collected through the use of three individual electrodes placed on the forearm of the subject and transferred through a single channel. Butterworth bandpass filter is used to extract the signal of choice after which an algorithm based on the Hilbert transform is used for identifying the dynamic threshold and find the action segment.

In regards to the benefit of BCI technological advancements in clinical applications, the prospect of improving the lives of countless disabled individuals through a combination of BCI technologies is carried out in [35]. In doing so, four application areas where disabled individuals could greatly benefit from advancement in the area are identified as: communication and control, motor substitution, entertainment and motor recovery. Moreover, existing state of the art equipment and future development are assessed whilst discussing the main research issues in the identified spectrum.

Furthermore, in [33] – [37], diversified researches based on ADS1299 are carried out. These researches span the areas of EEG, ECG and EMG application for numerous purposes that take advantage of the fact that the integrated circuit has been specifically designed for clinical application that require specific performances in regards to low signal applications.

## **2.7 Summary**

EEG, ECG and EMG signals are bio-potential signals whose measurement and analysis yields critical information in regards to bodily function. Measurement of these signals can be done through an invasive method which requires surgery or through a non-invasive method through the use of highly sensitive surface electrodes is widely used. The type of electrode placement depends on the diagnostic required measurement detail as well as expected analysis.

Moreover, through the analysis of the literatures discussed, it becomes evident that most of the researches are concerned with the design of signal acquisition intended for single bio-potential signal application. Moreover, researches in the area of EEG application are focused on the extension of BCI applications and lack the clinical application for basic medical provision. Furthermore, the literatures focused on the signal analysis and description are proof that EEG, ECG and EMG signals possess highly similar qualities in regards to their amplitude as well as frequency. Hence, designing a 3-in-1 system for multipurpose application is not farfetched.

## Chapter 3 Methodology

### 3.1 Design and implementation procedure

The approach devised for this research is shown in figure 3.1. It involves seven stages which are subsequently brought together to meet the objectives of the research.

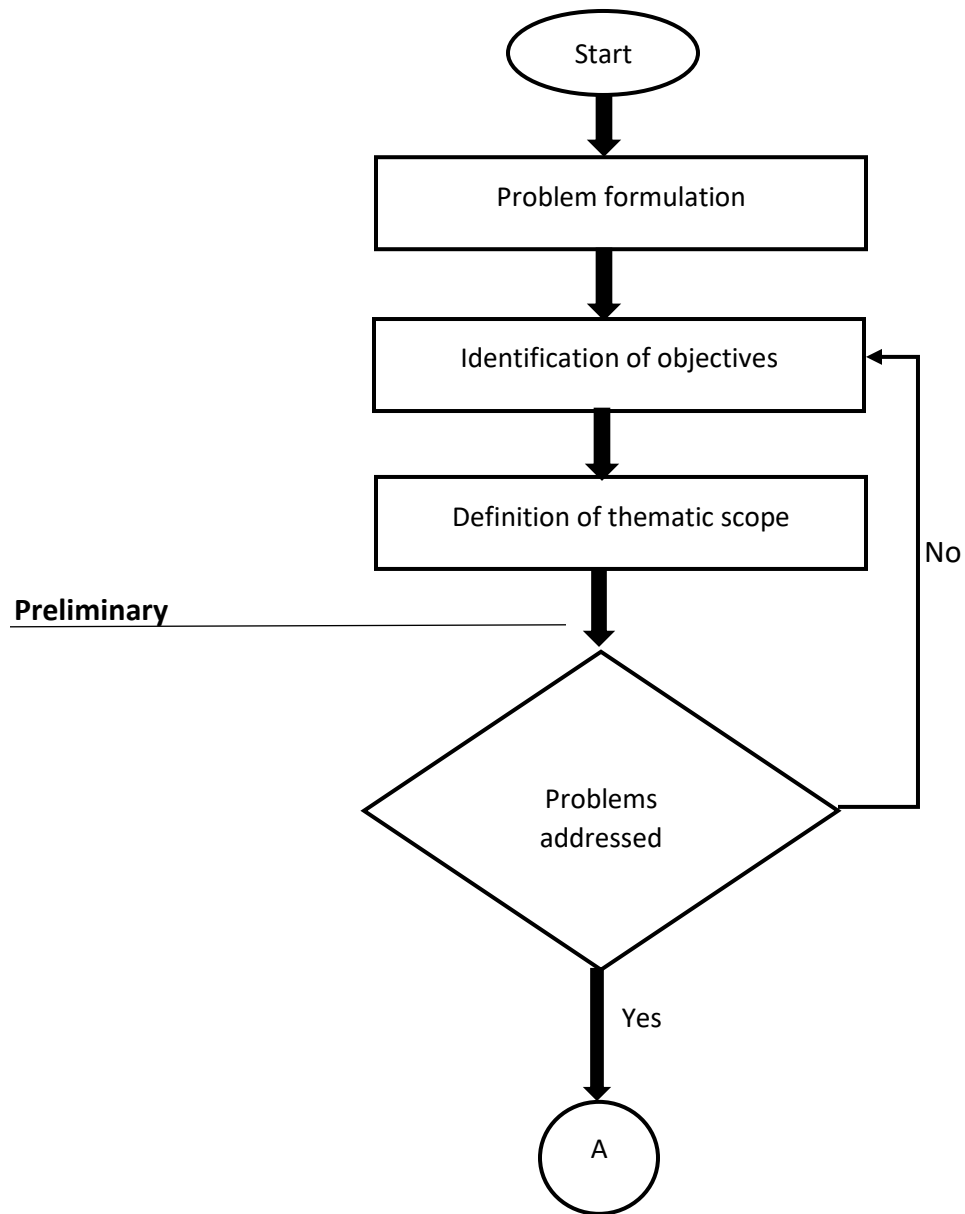


Figure 3.1 Flow chart of methodology

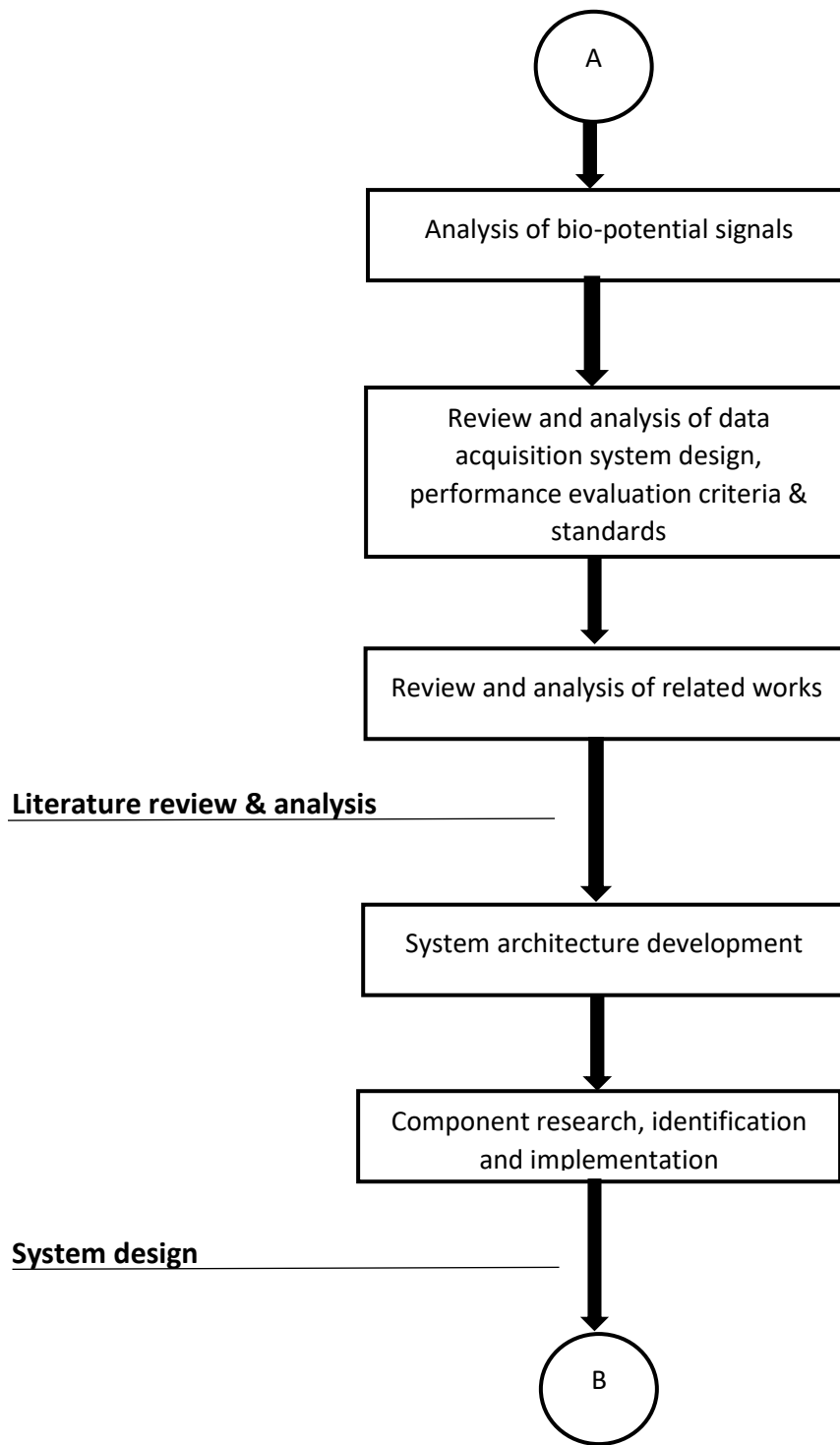


Figure 3.1 (continued)

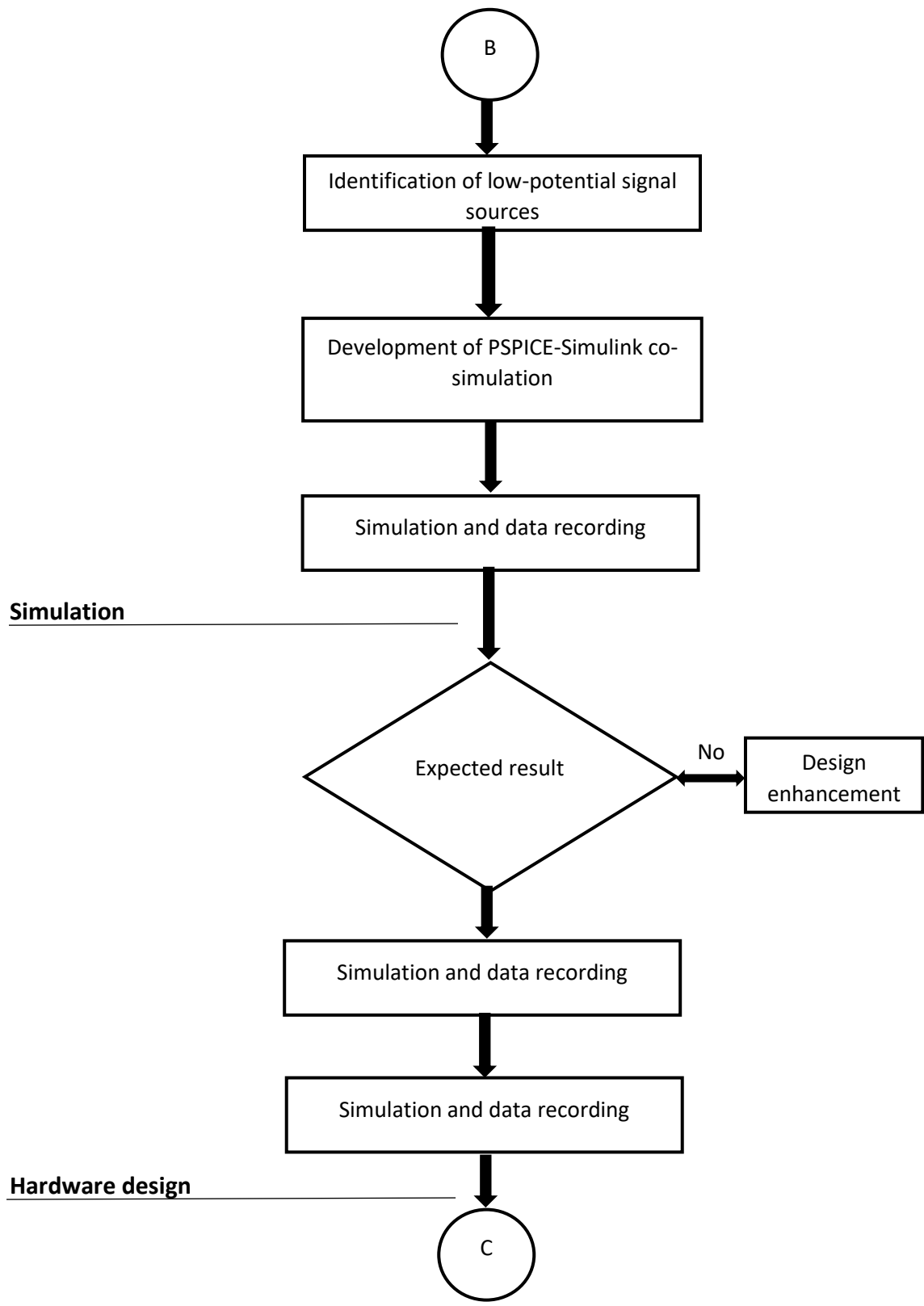


Figure 3.1 (continued)

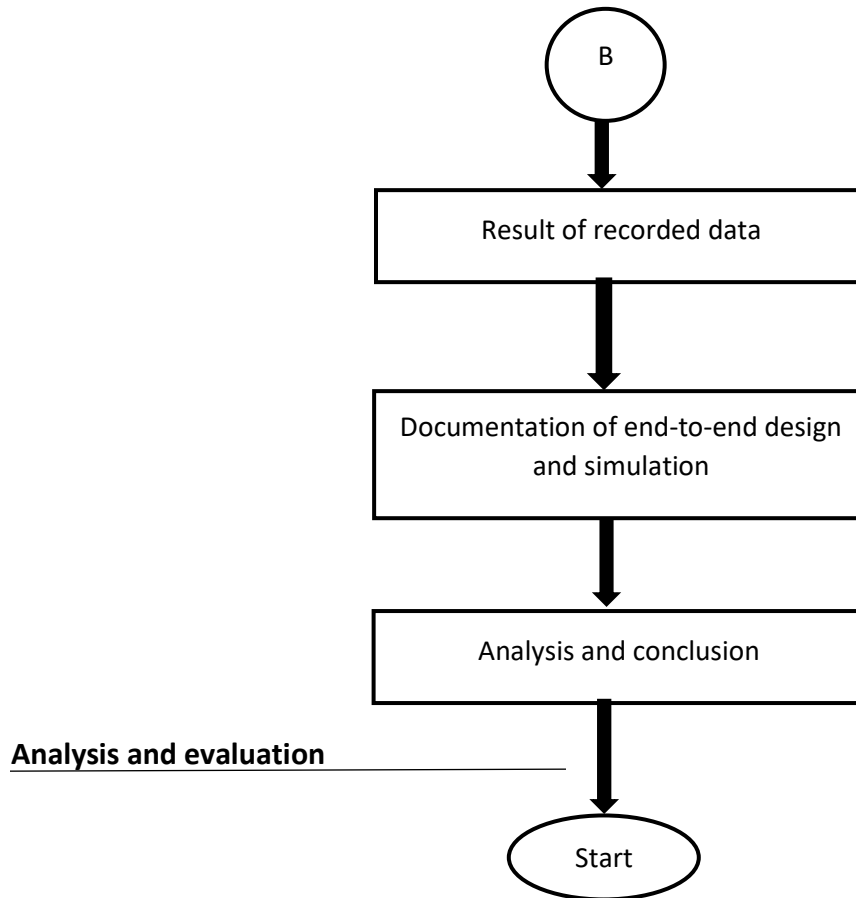


Figure 3.1 (continued)

### 3.1.1 Preliminary

The preliminary stage of the methodology is concerned with the identification of residing problems of the thematic area in regards to both research as well as product. It lays the foundation of the research by clearly defining the objectives which are meant to solve residing issues in the area. Moreover, the scope of the research is discussed which defines the overall expectation of the end output.

### 3.1.2 Literature review and analysis

This phase is concerned with the review of publications related to the research at hand for the purposes of better understanding and conception of the research topic as well as determine further information. The extraction is made through the use of books, articles, journals, conference papers, online portals and more. Furthermore, the use of literature review and analysis is done through the

definition of two distinct stages: Study and analysis of bio-potential signals; Common practices in data acquisition system design.

During the first phase of literature review and analysis, an in-depth study and analysis of bio-potential signals is carried out. The study addresses the signal characteristics of EEG, EMG and ECG signals in regards to their amplitude, frequency, diagnostic behavior, measurement measures etc. Furthermore, comparative analysis of the signals in regards to their similarities and differences are carried out.

The second phase is concerned with the study of data acquisition system design which includes the study and analysis of diversified approaches of previous researches in the thematic area. Moreover, the identification of critical performance criteria mentioned in previous researches as well as standards and practices are taken into consideration for the purpose of drafting optimized metrics for this research.

### **3.1.3 System design**

The system design phase of the research is done through two distinct stages which are: system architecture development; component identification and implementation. In the system architecture development, the identification of system blocks which is concerned with undertaking a block level analysis of the system from signal sensing through to digital output. Moreover, performance requirement development is done in order to set the goal and metrics of the end design through the aid of analysis carried out on previous researches.

Once the system architecture development is complete, the second stage deals with the identification of circuit components based on a pre-defined selection metrics. The circuit components are selected based on the criteria through an intensive market search from IC manufacturers extensive database. Moreover, a component survey record is also done for the purpose of future reference.

### **3.1.4 Simulation**

This phase is concerned with the development of a simulation environment for the purposes of design evaluation, correction, validation and analysis. The simulation is done with a PSpice – SIMULINK co-simulation through which the data acquisition system designed is tested end-to-

end. Furthermore, the output of the simulation is thoroughly analyzed through the reconstruction of the digital output stream. The simulation is inclusive of the following:

- Actual bio-potential records from online database as signal sources
- IC models from manufactures for individual design blocks
- Performance evaluation of critical components through the additions of noise

### **3.1.5 Hardware design**

In the hardware design phase, the PCB development of the validated design is carried out. The design is carried out with the aid of CAE tools and includes the following:

- Circuit schematic
- PCB design
- Routing and simulation

### **3.1.6 Analysis and evaluation**

In this phase, an in-depth assessment of simulation results is carried out. Moreover, a comparative analysis of the overall design against previous researches as well as existing product is done. The analysis is done against the following key points:

- Existing open source product
- Application areas
- Hardware property
- General performance

### **3.1.7 Conclusion**

The last phase is concerned with providing a conclusion based on discussions in previous phases, obtained results and overall output. Moreover, suggestion in regards to the future of the research along with its limitation is carried out.

## **3.2 Tools and signal resources**

For the purpose of overall circuit design, simulation and analysis, carefully selected Computer aided engineering (CAE) tools are utilized. For the entirety of the project, the tools employed with their scopes are outlined below:

- Cadence OrCAD V16.3 CAE software package is used to design the electrical schematic, PCB layout and routing
- PSpice AD V16.3 is used for the simulation of the LNA stage of the design. Moreover, it is used detailed analysis and comparison in regards to variable amplification, CMRR and PSRR
- MATLAB R2018a is used to generate a script for the purpose of creating a user setting for data supply to GUI based simulation done on Simulink
- Simulink is used for the simulation and analysis of the analog-to-digital conversion stage. Furthermore, the simulation of data transmission through SPI and the reconstruction is done.
- DSToolbox is used parameter settings such as: OSR, NTF synthesis and coefficient mapping
- SIMSIDES is used to add non-idealities to ADC simulation block such as: clock jitter, op-amp saturation and switch non-linearity
- Physionet.org is used as the source for bio-potential signals. Physionet.org provides decades of actual records of patients across the globe. The fact that bio-potential signals resemble low amplitude noises makes it very hard for result analysis. However, the utilization of actual records contributes to the analysis and authenticity.

## Chapter 4

### Proposed circuit architecture and implementation

#### 4.1 Overview

There are three distinct signals that are pertinent in this work: EEG, ECG, EMG. Careful analysis of the individual signals makes the similarity in regards to amplitude and frequency evident. Hence, the methods employed in regards to the design of the hardware takes into consideration critical factors such as noise cancellation, amplification, analog-to-digital conversion and digital signal processing.

The approach gives special attention for the elimination of power line interference, gain adjustment, anti-aliasing filter requirement, circuit complexity and extended functionality. The issue of noise cancellation involves the use of high performance LNAs that provide stable common mode rejection for application specific band of frequency. The selection of an LNA that best fits the aimed performance is meticulously done through a comparison matrix: Number of channels, available gain, supply voltage, minimum CMRR, bandwidth and specific application area.

Circuit complexity optimization is done through the integration of a state-of-the-art analog to digital converter provided by Texas Instruments which eliminates the use of anti-aliasing filters resulting in the significant reduction of circuit complexity whilst significantly contributing to a boost in performance.

The hierarchical circuit design is validated through an integrated circuit simulation that takes into account all non-idealities for employed circuit components such as input referred noise, jitter noise and component saturation whilst providing a general simulation model for future inferences and continuations in the sector through a parameter setting environment allowing users to check all the dynamic variables that are essential for performance evaluation of like systems.

#### 4.2 System design

The circuit topology of the bio-potential signal acquisition system can be categorized into two as analog sub-system and digital sub-system. The analog sub-system is concerned with the extraction of the usable band of frequency and amplification of the signals to an operable point. In a circuit that has an integration of numerous passive elements, the consideration of noise is a very critical issue. The issue of noise can be further classified into three classes: Power line interference and

sources from operation environment; Thermal noise generated by the resistive property of electrodes; Flicker noise due to components intrinsic behavior. In order to get rid of information loss due to the presence of these sources of noise, one must come up with an effective method of noise cancellation. Moreover, the amplification of the signals should be adjustable as the amplitude vary and component saturation should be avoided.

The digital sub-system on the other hand is concerned with the conversion of the analog signal to its digital equivalent and transmission of the signals for further processing and display. The key component in this sub-system is the ADC. When considering the selection of the ADC, the key points to consider include architecture, resolution, anti-aliasing filter design and signal selection which have a direct impact on circuit complexity as well as performance.

#### 4.2.1 Goals and Metrics

This research aims at providing an optimized design for bio-potential signal acquisition in regards to noise cancellation, circuit complexity and standardization. There are several standards that must be met when designing circuits for bio-medical applications. Specific to this work, there are standards that must be met respective to the signal under consideration. However, when studying the properties of the signal, it becomes apparent that the weakest in amplitude and frequency are EEG signals. Accordingly, this work proposes to use the IFCN standards as the design metrics in regards to standardization. The IFCN has put forth standards to be met in designing such systems.

Table 4.1 Design consideration in regards to IFCN standards

No.	Term	IFCN Standard
1	CMRR (dB)	$\geq 110$
2	LPF (Hz)	$\geq 70$
3	Sample Rate	$\geq 200$
4	Bits	$\geq 12$
5	Channel	$\geq 24$

In section 1.2.2, the measurement standards for ECG, EMG and EEG have been discussed which is set as the second metric in this work. Previous works in this area have provided meticulously mapped solutions for individual measurement of bio-potential signals. However, this research

takes the measurement type one step forward and provides a detailed measurement practice for all three types of signal. Accordingly, the hardware tends to provide a detailed 32-channel EEG reading, 12-lead ECG reading as well as dynamic EMG reading.

#### **4.2.2 Bio-potential signal conditioning**

As discussed in section 1.2.3, the high-level architecture of bio-potential signal acquisition is usually built using a pre-amplifier followed by an LPF and HPF. However, this work proposes the implementation of an LNA that can be used specifically for bio-potential signal amplification with high and stable CMRR. This approach tends to eliminate the use of higher order filters of various topologies to get rid of surrounding noise. Generally, the noise one should be concerned with when designing such systems are 50/60 Hz power line interference, fluorescent lighting (depending on the environment of operation), and miscellaneous noises (i.e. computers, machinery etc.).

To find an LNA that can carry out this operation for the intended purpose efficiently, a component research is carried out. This research has its own measurement grids which are discussed below.

##### **4.2.2.1 Gain adjustment**

The circuit is intended to operate for three types of signals that are different in amplitude and frequency. The critical issue to consider in this case is the concept of IC saturation. If the signals are amplified by the same gain factor,  $G$ , then the output of amplified EEG and EMG for instance will have different implications. EEG signals are in the range of microvolts which after amplification becomes millivolts. However, the amplitude of EMG signals is in the range of millivolts. Hence, when EMG signals are amplified more than 100 times, the ADC which follows in the next stage should be given consideration of the DC bias threshold. Exceeding the threshold will result in signal distortion. Accordingly, the LNA is required to have an adjustable gain with a single external resistor that should not exceed 1 component per channel. This will aid the circuit in the reduction of circuit complexity and additive noise. Additionally, the IC is expected to have a wider range of gain so as to incorporate the smallest amplitudes

Moreover, component selection should consider overall circuit performance. One of the issues that results in performance degradation is additive noise from components. Hence, for the purpose of performance maximization, the LNA IC used must have a very low input referred noise so as to avoid noise contribution.

#### **4.2.2.2 CMRR**

This is the most defining characteristics of the LNA of choice. This feature will be responsible for the noise cancellation due to power line interference and noises from miscellaneous sources. Accordingly, the amplifier is selected based on the level of CMRR.

#### **4.2.2.3 Operating frequency**

The signals handled by the circuit are low frequency signals. Hence, the LNA is expected to have consistent performance in regards to gain and CMRR for the bandwidth of operation without any glitches.

#### **4.2.2.4 Power supply**

The LNA is expected to operate within a wide range supply which allows the circuit design achieve low power dissipation as well as capability of a single power supply to be used by other circuit elements as well.

#### **4.2.2.5 Release/revision dates**

For the purpose of making this research relevant by paving options for future citations and incorporation in related researches, the component should be up-to-date. Accordingly, for the LNA to be considered in this work, two points are considered:

- Product availability on the market
- Cross checking for other products that offer superior performance without major variation in cost, safety and availability

#### **4.2.2.6 Application notes**

The LNA is given higher priority if designated by the manufacturer that it has been specifically designed for application in ECG, EEG, EMG and related low frequency & amplitude applications

In summary, using the research matrices mentioned earlier, extensive research through various IC manufacturers is carried out. Even though the research in regards to manufacturers included numerous leading IC vendors currently on the market, the dominant vendors available that provide high-end products for medical instrumentation are Texas Instruments and Analog Devices. Some of the ICs have been revised through the years through production. However, for the purpose of

research, all ICs are thoroughly reviewed and compared with the aid of the previously mentioned comparison metrics. Table 5 summarizes the findings in accordance with the metric provided.

Accordingly, INA819 is chosen as it provides impeccable noise cancellation for the bandwidth of operation. INA819 is a high-precision instrumentation amplifier that has flexibility in power supply requirement and offers low input offset voltage and current noise. Moreover, this IC satisfies one of the critical goals of this work by providing a high CMRR that exceeds 90dB at minimum gain,  $G=1$ . The amplifier has specific applications in ECG amplifiers and general medical instrumentation. A minified schematic of the LNA is shown in figure 4.1.

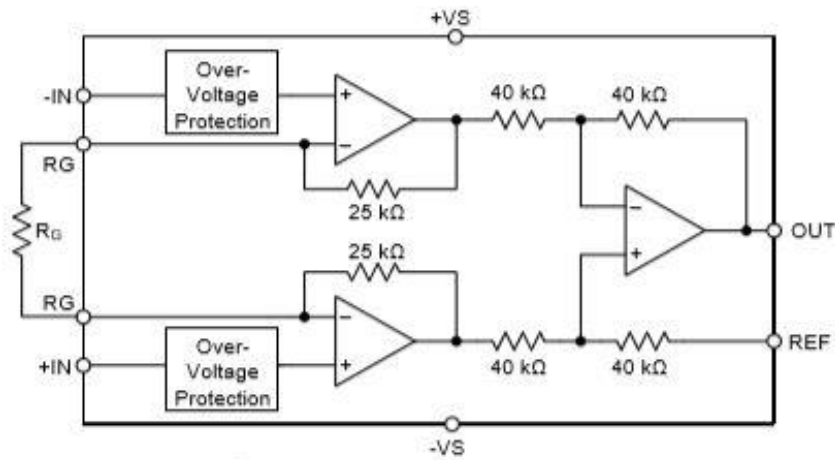


Figure 4.1 Minified internal schematic of INA819 [23]

The gain of the amplifier is set through the use of a single resistor between  $R_G$  ports using the equation given below [23].

$$G = 1 + \frac{50K\Omega}{R_G} \quad (4.1)$$

Table 4.2. Component survey for signal amplification

<b>Part Number</b>	<b>Minimum Gain (V/V)</b>	<b>Maximum Gain (V/V)</b>	<b>Noise at 1KHz (nV/<math>\sqrt{\text{Hz}}</math>)</b>	<b>Supply Voltage Range (Rail-to-Rail)</b>	<b>Minimum CMRR (dB)</b>	<b>Bandwidth (MHz) at <math>G_{\text{min}}</math></b>	<b>Date of Release/Revision</b>	<b>Specifically, Relevant Application Notes</b>
AD8229	1	1000	1	8 - 34	80	15	February, 2012	Harsh environment data acquisition
AD8237	1	1000	68	(+1.8) - (+5.5)	106	0.2	August, 2012	Medical Instrumentation
AD8420	1	1000	55	5.4 - 36	100	0.25	January, 2015	Medical Instrumentation
AD8421	1	1000	3.2	5 - 36	80	10	May, 2012	Medical Instrumentation
AD8422	1	1000	8	4.6 - 36	80	2.2	January, 2015	Medical Instrumentation
AD8429	1	1000	1	8 - 36	90	15	February, 2017	Medical Instrumentation
INA118	1	10000	10	2.7 - 36	107	0.8	January, 2018	Medical Instrumentation
INA128	1	10000	8	4.5 - 36	120	1.3	April, 2019	Medical Instrumentation
INA129	1	10000	8	4.5 - 36	120	1.3	April, 2019	Medical Instrumentation
INA141	10	100	8	4.5 - 36	117	1	April, 2019	Medical Instrumentation
INA333	1	1000	50	4.5 - 36	110	2	December, 2015	Medical Instrumentation
INA818	1	1000	8	4.5 - 36	140	2	April, 2019	Medical Instrumentation
INA819	1	1000	8	4.5 - 36	140	2	December, 2018	Medical Instrumentation
INA821	1	1000	7	4.5 - 36	140	4.7	December, 2018	Medical Instrumentation
INA828	1	1000	7	4.5 - 36	140	2	January, 2018	Medical Instrumentation
INA2141	10	100	8	4.5 - 36	117	1	August, 2018	Medical Instrumentation

### **4.2.3 Analog to digital conversion**

Once the bio-potential signals have gone through the stage of amplification and conditioning, the next step is the conversion of the analog signals to their digital equivalent. To do so, an ADC is incumbent. The ADC is responsible to convert the analog signals to their digital representations without distortion and send the converted data to a DSP through a certain communication protocol. Some of the research angles applied for LNA selection is also applied for the survey and selection of ADC such as input referred noise, CMRR, power supply requirement, release/revision dates and application notes. Moreover, there are additional points that are specific for the ADC which are discussed below.

#### **4.2.3.1 Analog input channels**

In regards to minimization of circuit complexity, the number of analog inputs available by the ADC is very crucial. There are various types of ADCs currently available in the market that provide different analog input channel capacity. However, as the circuit should be capable of handling ECG, EMG and EEG signals, the total number of analog input channels required by the ADC is 32. Hence, the choice of ADC is done with the total number required as per the total input channels available kept in mind.

#### **4.2.3.2 Sample rate**

The IFCN standard (as given in table 4.1) requires the minimum sample rate to be 200. Accordingly, the ADC of choice must meet this standard and provide a sample rate that is greater than the minimum threshold. This sample rate must also satisfy the Nyquist criteria given in equation 4.2 [26].

$$F_s = 2f_{\max} \quad (4.2)$$

#### **4.2.3.3 Resolution**

Similarly, the minimum number of bits required by the IFCN standard must be met by the ADC of choice which refers to the resolution of the ADC. This will also contribute to the signal integrity of the overall circuit.

#### **4.2.3.4 Data rate and CMRR**

Once the standards in regards to sampling and resolution are met, the CMRR performance against variable data rate is also taken into consideration. This is done so as to ensure the flexibility of the ADC for the purpose of scalability.

#### **4.2.3.5 Conversion architecture**

Of all the selection criteria mentioned earlier, the conversion architecture is the most critical in regards to this research. This refers to the type of architecture the ADC implements for the conversion of analog signals to their digital representations. ADCs can be categorized through their conversion schemes: successive approximation, sigma-delta, flash converters, pipelined, and bit-per-stage. This property becomes a defining one due to the direct implication it has on circuit complexity as it comes with pre-requisites in regards to circuit components. For this work, an ADC that employs oversampling principle is the most attractive since it drastically reduces the requirement of anti-aliasing filters and hence significantly reduces circuit complexity as well as noise.

In summary, inferring from the points discussed earlier, the ADC is selected through research from manufacturers. Even though there are not ample choices available as in the case of LNA, there are high precision converters available for the specific work at hand which is described in table 3.6.

Through a thorough analysis of features provided by various ADCs, the ADS1299 is selected for the work at hand. The ADS1299 is a low-noise analog-to-digital converter specifically designed for EEG and bio-potential measurements. One of the most unique features of this converter is the fact that it allows to programmatically switch of analog input channel selection from multiplexed to simultaneous sampling type and vice versa. It utilizes sigma-delta converter which drastically eliminates the requirement of anti-aliasing filters that are required with typical Nyquist ADCs. The converter has an on-board oscillator and programmable gain amplifiers. Moreover, the ADS1299 has been specifically designed for EEG and related bio-potential application which suits the scope of this research.

Table 4.3 Component survey of analog to digital converter

<b>Part Number</b>	<b>Number of Analog Input Channels</b>	<b>Conversion Architecture</b>	<b>CMRR (dB)</b>	<b>Programmable Gain</b>	<b>Supply voltage range</b>	<b>Data Rate</b>	<b>Date of Release / Revision</b>	<b>Relevant Application Notes</b>
AD9249	16	Flash	N/A	Unavailable	1.7 – 1.9	455MSPS	October, 2013	Medical imaging
AD9253	4	Flash	N/A	Unavailable	1.7 – 1.9	125MSPS	January, 2018	Medical ultrasound
AD9257	8	Flash	N/A	Unavailable	1.7 – 1.9	65MSPS	April, 2013	Medical imaging
AD9461	1	Pipeline	N/A	Unavailable	4.75 - 5.25	130MSPS	April, 2006	MRI receivers
ADS1299	8	delta-sigma	110	Available (1, 2, 4, 6, 8,16,24)	4.75 - 5.25	250SPS - 16kSPS	January, 2017	EEG, ECG, Sleep Study Monitoring
ADS1258	16	delta-sigma	N/A	Unavailable	Unipolar (0 - 5) Bipolar (-2.5 - +2.5)	125kSPS	March, 2011	Medical Instrumentation

#### **4.2.4 System design review**

Once components that fulfil the requirement of the designs are selected, a high-level design is constructed representing the general operation mechanism of the signal acquisition system. The design incorporates individual blocks the signals undergo from detection through to conversion and transmission. The high-level block diagram of the acquisition hardware is shown in figure 4.2. The diagram depicts the circuit blocks required in regards to the following key points:

- Safety regulations
- System-level performance requirements
- Signal-specific requirements

In addition to the critical components of the signal acquisition system being the LNA and ADC as discussed in previous sections, the design must incorporate other fine details such as overpower protection circuit, gain adjustment components, power supply requirement, communication protocol etc.

#### **4.3 Simulation**

Implementation of the techniques discussed so far requires setting up a simulation model for bio-potential signal acquisition with all non-idealities that occur in physical application of such systems. The simulation model consists of two distinct stages: analog sub-system, and digital sub-system.

In the analog sub-system, bio-potential signal models acquired from previous researches is used as well as general signals that resemble the amplitude and frequency of such signals. The system is simulated with an addition of noise for the purpose of imitating non-idealities that occur in actual physical applications. The validation is done using the SPICE model provided by the manufacturer with the aid of CAD tools.

In the digital sub-system, a Simulink model for ADS1299 is built with all the properties of the converter put into consideration. The design variable is generate using SIMSIDES, a SIMULINK tool, after which the simulation model is constructed.

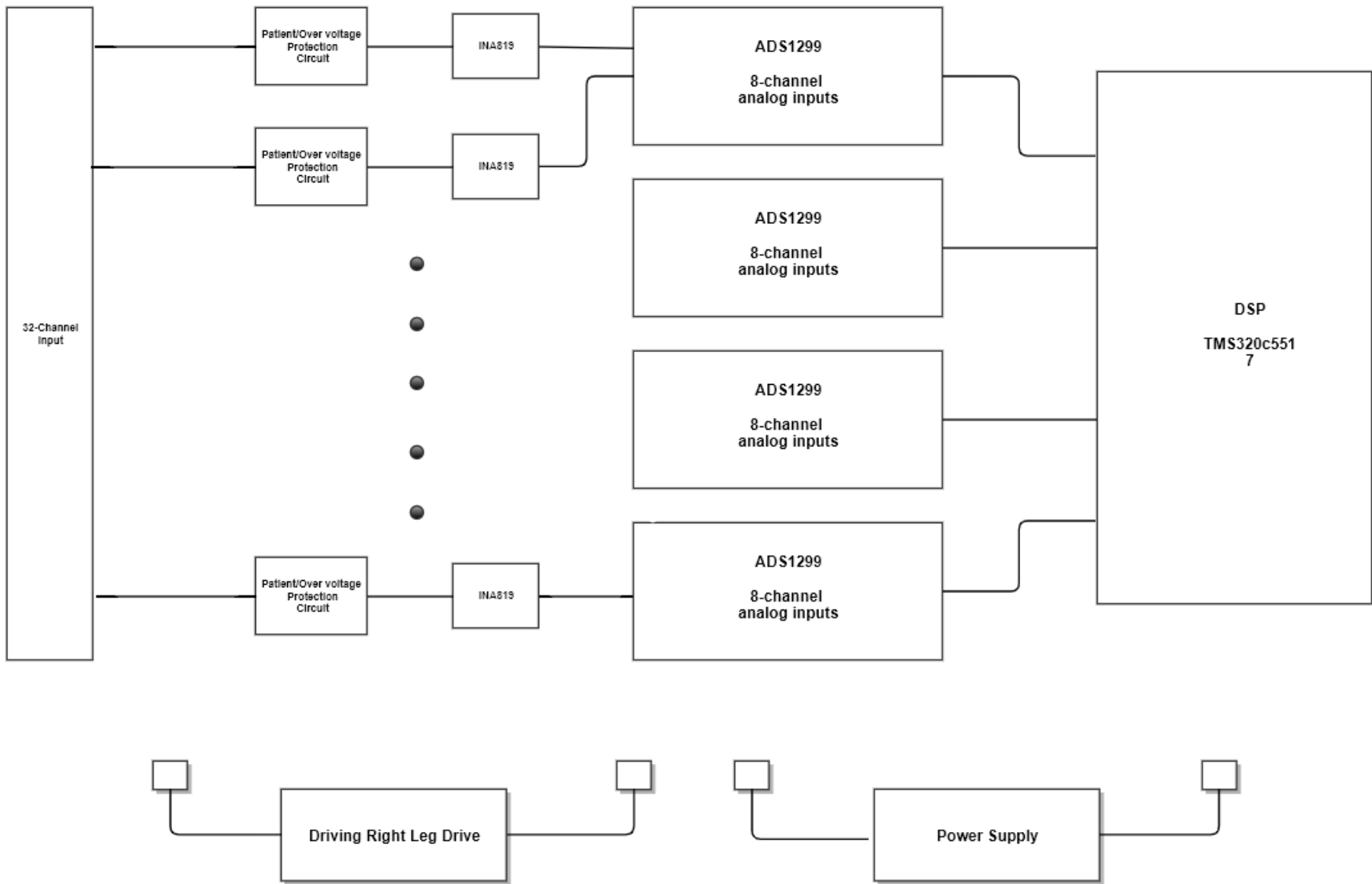


Figure 4.2 High level block diagram

### 4.3.1 Bio-potential signal sources

If analyzed from a non-technical point of view, bio-potential signals, especially EEG signals, resemble a noisy waveform. Hence, it is necessary to familiarize oneself with the waveforms of the signal even though their properties in regards to amplitude and frequency have been mentioned in previous section.

There are numerous models available to accurately model bio-potential signals. However, this research uses Physionet.org, an online database that has a variety of actual records of bio-potential signals of physical subjects made across the globe which are available in. edf format.

The data fetched from the database are converted to a signal source format compatible with PSpice A/D and used for further evaluation. Summarized specification for implemented EEG and EMG sources are given in tables 4.4 and 4.5

Table 4.4 Summary specification of EEG sample

<b>EEG record</b>	<b>Specification</b>
Number of channels	23
Sampling rate	256Hz
Number of seizures in file	0
Total time	1 hour

Table 4.5 Summary specification of EMG sample

<b>EMG record</b>	<b>Specification</b>
Number of channels	23
Sampling rate	4KHz
Sample profiles	<ul style="list-style-type: none"><li>• Healthy</li><li>• Myopathy</li><li>• Neuropathy</li></ul>
Total time	1 hour

In simulating the bio-potential signal source, the two extremes selected are the EEG and EMG signal. The justification used for this is the fact that EEG signals are the weakest amongst the types of signals proposed for this work and EMG signals are the strongest in amplitude and frequency. The time and frequency analysis of the signal sources are presented in Figures 4.3 – 4.6.

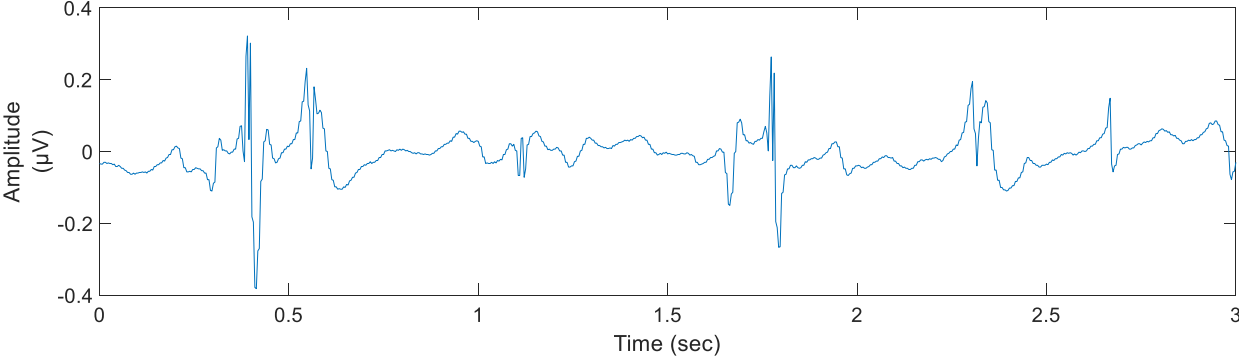


Figure 4.3 Time domain analysis of EEG source

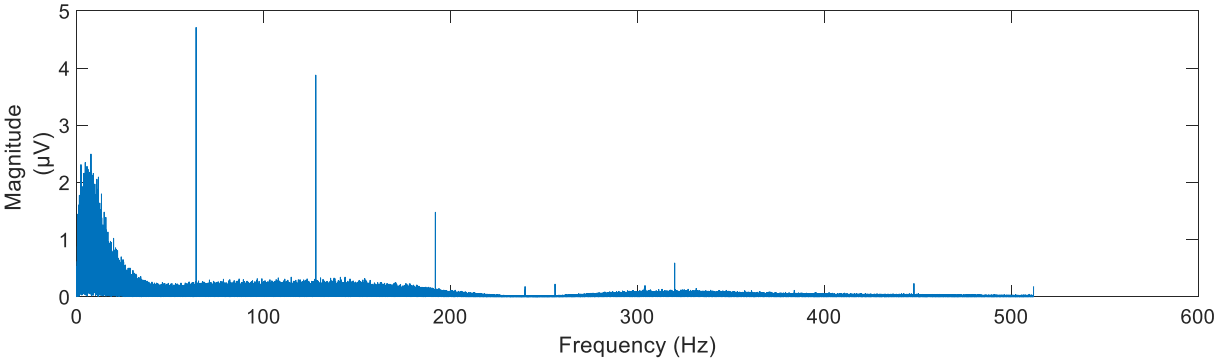


Figure 4.4 Frequency domain analysis of EEG source

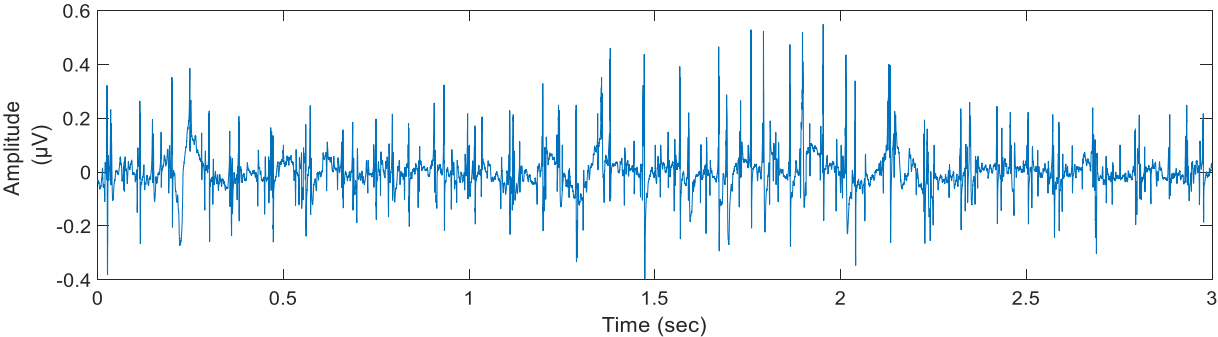


Figure 4.5 Time domain analysis of EMG source

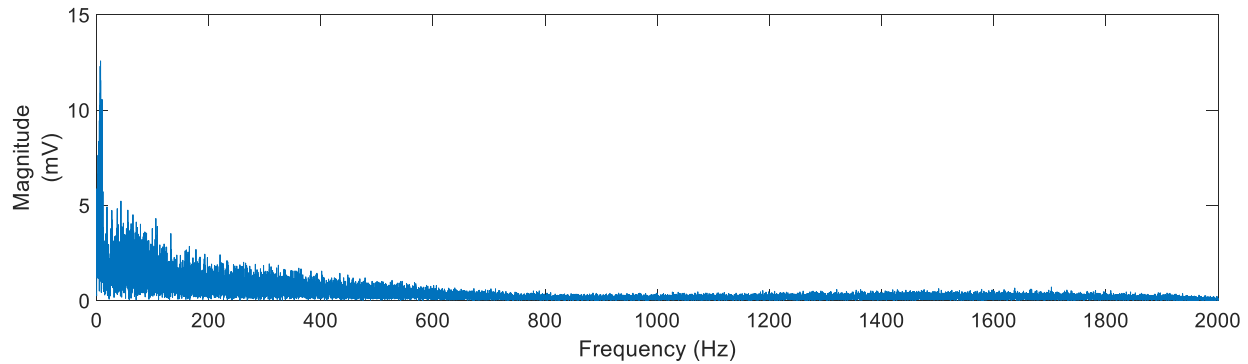


Figure 4.6 Frequency domain analysis of EMG source

### 4.3.2 System simulation models

As discussed in the previous section, the system design is broken down into two major parts as analog sub-system and digital sub-system. In the analog sub-system, the major component is the low noise amplifier selected for the work at hand whereas in the digital sub-section, the major concern of design is the analog-to-digital converter. In order to assess the properties of the selected component, the requirement is an analysis and simulation software to facilitate the Computer aided Engineering (CAE). The CAE has two major elements which are: Computer aided design (CAD) and computer aided manufacturing (CAM). For this specific work, the CAD handles issues related to schematic design, simulation profile, PCB design and analysis. Accordingly, there are two CAE tools utilized in this work: Cadence OrCAD V16.3 CAE software package and MATLAB R2018a.

#### 4.3.2.1 Low noise amplifier

For accurately simulating the circuit behavior of INA819, Cadence OrCAD is used. The amplifier is used to carry out two major tasks; Amplification and common mode signal rejection. In order to simulate the performance of the component, the circuit configuration is set up as shown in figure 4.7. Through reference from the datasheet provided by the manufacturer, the CMRR is given as 110dB at an operating gain,  $G=10$ . However, the gain must be variable as the signals have different amplitudes which will have an effect on the CMRR of the component. In order to test the performance of the signal, a common mode signal of variable amplitude is supplied to the circuit and evaluated at different levels of voltage gain. The variables of the simulation profile are provided in table 4.6.

As provided in table 4.6, the simulation profile takes into account two major elements: Amplitude and frequency variations of ECG, EMG and EEG signals; 50/60 Hz power line interference. Accordingly, the output in regards to variable input is recorded and performance analysis is carried out. Moreover, the CMRR is evaluated with the circuit configuration provided in figure 4.7 using equation 4.3 [25].

$$CMRR = 20\log_{10} \frac{V_{diff}}{V_{cm}} \quad (4.3)$$

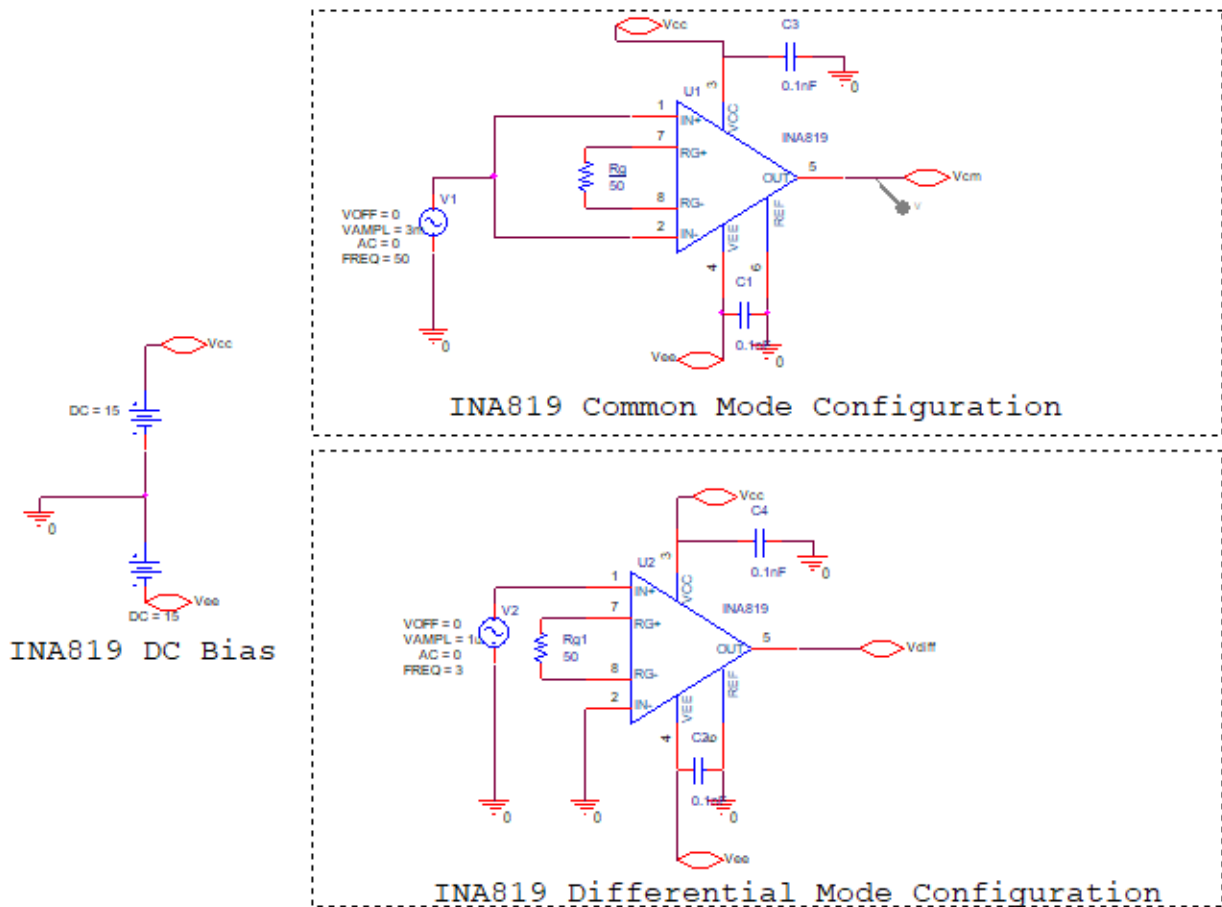


Figure 4.7 Circuit configuration of INA819 [23]

The performance analysis is carried out through amplitude and frequency variation of differential signal input in regards to common mode signal input. Table 4.6 summarizes the input variation of the simulation profile.

Table 4.6 Simulation profile of INA819

Quantity	Variation
Vcm (mV)	3 – 100
Vdiff (mV)	1 – 1000
Fcm (Hz)	50 – 60
Fdiff (Hz)	1 – 200,000
Rg	50 – 50,000
Bias	(±9) – (±18)

#### 4.3.2.2 Sigma-delta ADC

The other defining component of this research is the analog-to-digital converter. Through the comparison chart provided in table 4.3, the ADS1299 is an impeccable choice when it comes to conversion of bio-potential signals of very weak amplitude to their digital counterparts. In order to accurately carry out the simulation of the ADC, a detailed study of previous performance analysis documents as well as the device property is carried out. In doing so, a simulation model of the converter is built using MATLAB R2018a and SIMULINK with the aid of DSToolbox. As shown in figure 4.8, the ADC is comprised of distinctive stages that have diverse functions. However, the critical module that is considered as the defining characteristics of the converter is the  $\Delta\Sigma$  modulator. This modulator is responsible for oversampling the input signals and passing it to the control interface for communication and further processing. The fact that the conversion architecture is a  $\Delta\Sigma$  has large contribution in addressing the anti-aliasing filter design requirement, speed as well as general circuit complexity. A minified depiction of the operation mechanism of the ADC is shown in figure 4.2.

The simulation model for assessing the requirement conformity of the device is accurately constructed using a MATLAB – SIMULINK co-simulation. MATLAB is used to generate the modulator parameters with the aid of DSToolbox through a multi-step process. Once the parameters are successfully generated, SIMULINK is used to put generated parameters into the simulation with the addition of non-idealities that mimic practical applications. Moreover, the digital/decimation filter is constructed providing a simulation model to test the performance of the system altogether.

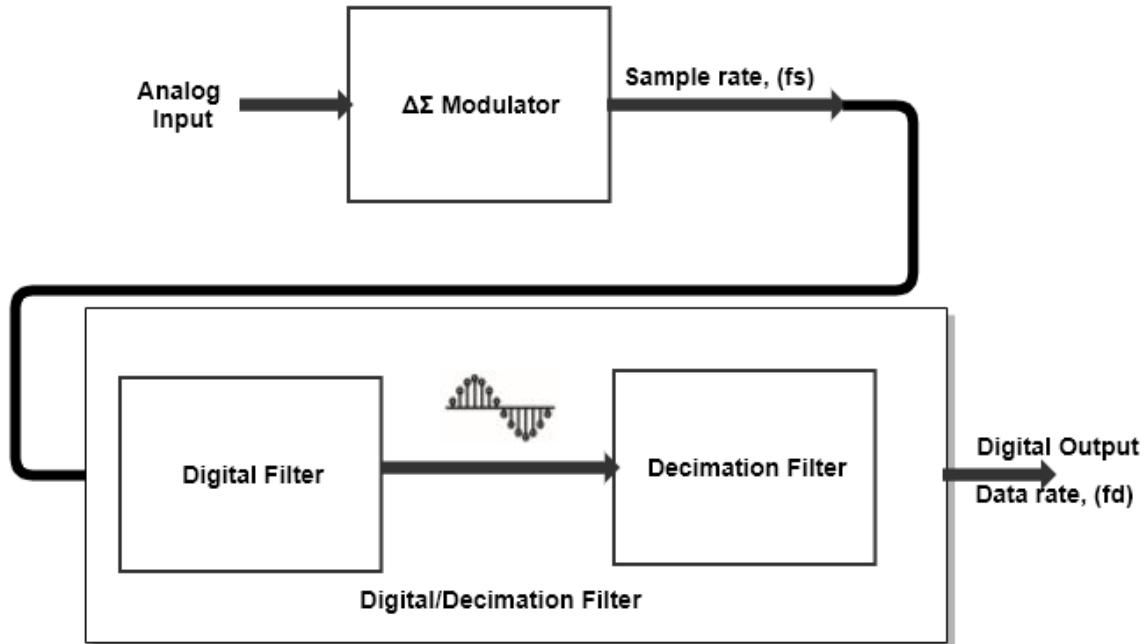


Figure 4.8 Block level analysis of ADS1299

When designing a simulation model for ADS1299 there are numerous determining specifications that are considered. Major design specifications are made through component evaluation which are described in table 4.7.

Table 4.7 Simulation specification for ADS1299

Property	Specification
<b>Modulator</b>	
Order	2 <sup>nd</sup>
Fs	1.024MHz
OSR	2560
Fb	200Hz
Architecture	Feedforward
<b>Digital Filter</b>	
Type	Sync
Order	3 <sup>rd</sup>
Decimation Ratio	64

Once the specifications of the modulator in regards to order, OSR and modulator architecture are identified, DSToolbox is used to generate the parameters and finally add non-idealities to mimic real life applications. The process for system specification generation in MATLAB follows:

1. Determination of modulator order, OSR, quantizer level and modulator type
2. NTF synthesis
3. Realization of [a,b,c,g] coefficient of the modulator
4. Coefficient mapping to internal states ABCD and scaling
5. Realization of coefficient of [a,b,c,g] by ABCD with manual round-off

Once the modulator coefficients are successfully generated, the coefficients are exported to a SIMULINK model which is constructed with non-idealities to mimic practical application. The non-idealities considered in the model are:

- Clock jitter
- Switch non-linearity
- Thermal noise
- Op-amp noise

The simulation output is compared in regards to SNR output for ideal and non-ideal situations. The non-ideal output is taken from the simulation output whereas the ideal is calculated through initial specifications given in table 4.2 using the equation 4.4 [27].

$$\text{SNR} = \left(\frac{3\pi}{2}\right) (2N + 1) \left(\frac{\text{OSR}^{2N+1}}{\pi}\right) \quad (4.4)$$

#### **4.4 Hardware Design**

One of the metrics of this research is to come up with a portable hardware that can be interchangeably used for the detection of ECG, EEG and EMG signals. Accordingly, Cadence OrCAD v16.6 CAE software package is used in regards to circuit schematic, PCB layout, routing and simulation. More specifically, Cadence OrCAD Schematic capture is used for the schematic design and Allegro Expert for the PCB layout, routing and simulation.

The system design can be categorized in the mixed signal application genre as it contains both analog and digital sections. Basically, a PCB design and assembly consist of the bare board,

attached components and connectors which altogether have a significant impact on the process of component placement, product reliability and troubleshoot. Hence, in order to make the hardware meet these specifications, the hardware design is done with two distinct considerations which are: electrical considerations; mechanical and thermal considerations.

However, before diving into the PCB design, all circuit elements with their specifications are clearly defined as per their respective datasheets and required functionality. Moreover, their layout in regards to electrical connectivity is done through individual schematic projects where the blocks are: overvoltage protection; signal amplification; analog-to-digital conversion; digital signal processing. The circuit schematic of all the major blocks are described below.

#### 4.4.1 Overvoltage protection

When comparing the hardware for ECG, EEG and EMG applications, the major concern is against defibrillation which refers to the stimulation of the heart through the use of electrical shock for the purpose of resetting the electrical state and adjust the rhythm [28]. There are numerous approaches one can implement for the protection circuitry. In this research, a neon lamp with large voltage rating along with Zener diodes is used. This configuration is used through comparison of available methods in medical instrumentation guides. The circuit schematic for a single electrode is shown in figure 4.9.

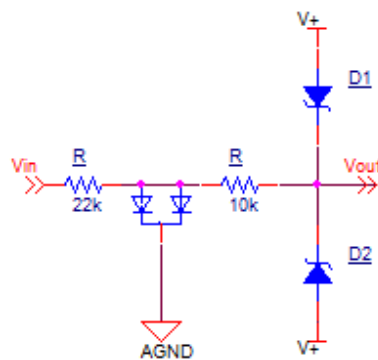


Figure 4.9 Overvoltage protection circuit

The circuit shown in figure 4.9 will only be used for selected pins under ECG applications. The amplitude of applied voltage in defibrillation differs under variable conditions. However, the amplitude can reach up to 5kV in clinical application. However, for EEG and EMG applications, the internal overvoltage protection of the INA819 of 60v is assumed to be sufficient enough.

#### 4.4.2 Signal amplification

As discussed in previous section, the INA819 is used for the amplification of the bio-potential signals and achieve a high level of CMRR. The electrical schematic for connecting the electrodes to the amplifier for a single channel is shown in figure 4.10.

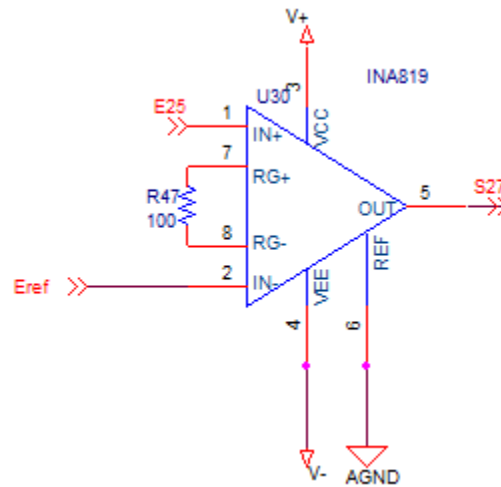


Figure 4.10 INA819 circuit schematic

The major consideration in the signal amplification signal is the difference of reference points for different measurement types. For EEG and EMG measurement, the positive input of the amplifier is taken from different measurement points according to the measurement standards mentioned earlier whereas the negative input is taken from the scalp of the patient for EEG and elbow for EMG. However, for ECG signal amplification, the 12-lead system with the derivation provided in table 1.3 is used in which the signal designated by  $V_{wct}$  is a Wilson central: Signal average of LA (left arm), RA (right arm) and LL (left leg).

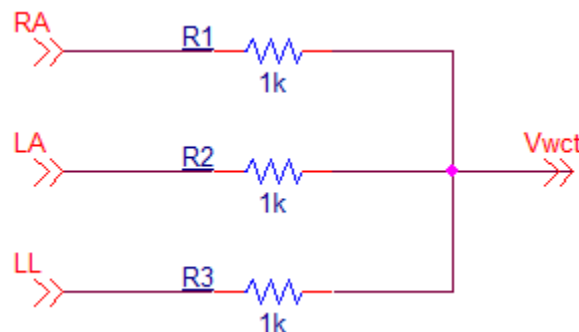


Figure 4.11 Wilson central circuit for referencing voltages of unipolar ECG

As can be inferred from table 1.3, the measurements for lead III, aVR, aVL and aVF are derived from other measurements. Accordingly, this work proposes for the measurement of these signals to be done in the DSP which eliminates the necessity for building circuit for the manipulation of these signals.

#### 4.4.3 Analog to digital conversion

Once signals have gone through the amplification process, the next step is the conversion of the analog signals to a digital form. It has been discussed in the previous section that the ADS1299 analog frontend is proposed for this purpose due to its exceptional performance. However, ADS1299 has 8 inputs whereas the application requires 32 analog channels. Therefore, there must be 4 ADS1299 devices in place to meet the desired specifications.

According to the manufacturer's datasheet, there are two modes to choose from when using more than one device in a single application [24]: cascaded mode; daisy-chain mode. The choice will have a direct impact on the required number of chip-select lines. For this work, the devices are connected in a daisy-chain mode which requires only a single chip-select line. The functional block diagram of the operation is depicted in fig 4.12. However, when operating multiple devices using a daisy-chain mode, the maximum number of devices allowed depends on the data rate at which the devices are operated determined by equation 4.5 [24].

$$N_{\text{devices}} = \frac{f_{\text{sclk}}}{(f_{\text{DR}})(N_{\text{channels}})(N_{\text{bits}}) + 24} \quad (4.5)$$

where  $N_{\text{bits}}$  = device resolution, and

$N_{\text{channels}}$  = number of channels on the device

$f_{\text{sclk}}$  = frequency of serial clock

$f_{\text{DR}}$  = data rate

Hence, using equation 4.5, the minimum required SCLK speed to operate 4 devices with 16kSPS in daisy-chain mode is 3.1MHz. A functional block diagram of the devices connected in daisy-chain mode is shown in figure 4.12.

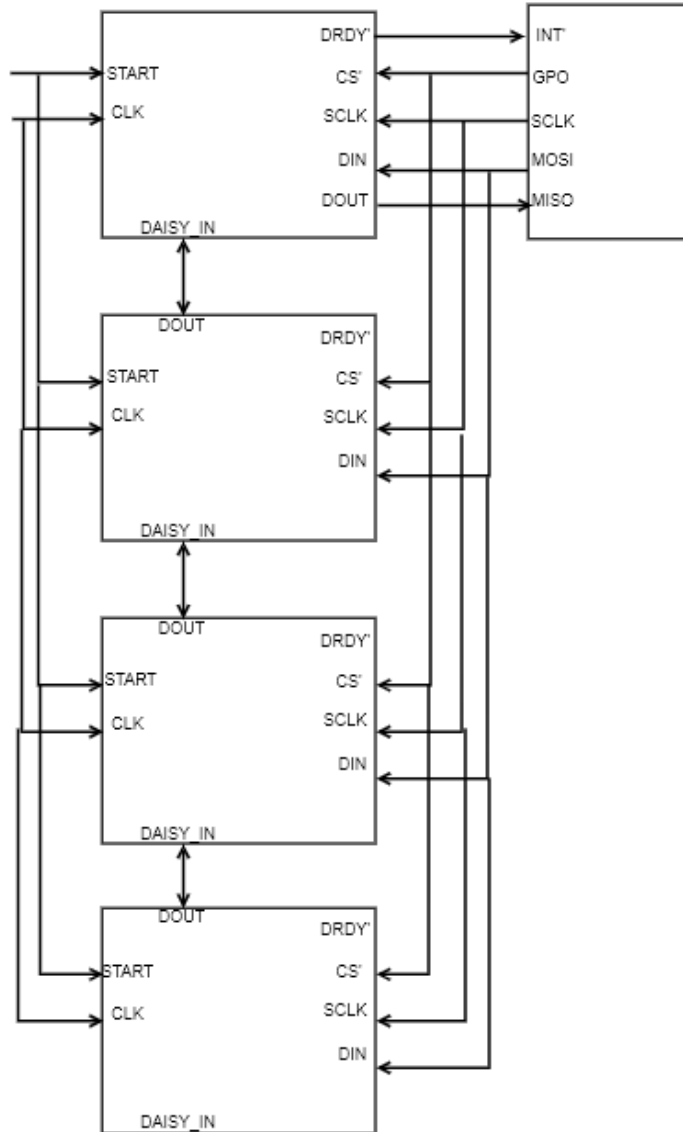


Figure 4.12 Daisy chain configuration for ADS1299

#### 4.4.4. PCB design

The PCB design is inclusive of numerous processes such as electrical schematic, layout and routing. Main considerations taken in regards to the design is layer stack-up, trace width and trace spacing.

The final design of the circuit contains a mixture of both analog and digital circuit components with their respective power requirement and grounding options. Accordingly, the layer stack-up definition is done so as to separate analog and digital components in regards to their power requirements, routing, as well as placement. Critical circuit components along with their specifications is given in table 4.8.

Table 4.8 Power and grounding requirement of core components

<b>Component</b>	<b>Power requirement</b>	<b>Grounding requirement</b>
INA819	Analog	Analog
ADS1299	Mixed	Mixed
TMS320C5514	Mixed	Mixed
TL6012	Analog	Analog
LTC3261	Analog	Analog
LM3480	Analog	Analog

Taking into consideration the type of power and ground required by circuit components, the layer stack-up is defined by taking scalability, placement, routing and spacing into consideration. The PCB is completed in 10 layers whose name and function are provided in table 4.9.

Table 4.9 Summary of layers with functions

<b>No.</b>	<b>Layer name</b>	<b>Layer type</b>
1	TOP	Routing
2	V+	Plane
3	AGND	Plane
4	V-	Plane
5	ABOT	Routing
6	SHLD	Plane
7	DVDD	Plane
8	DGND	Plane
9	AVDD	Plane
10	BOTTOM	Routing

Another crucial property that requires careful analysis is the trace width and spacing used in the design. As can be inferred from table 4.9, the circuit has 6 global power nets which are:

- Analog power (V+, V-) for the circuit elements such as INA819 and LDO regulators;
- Analog and digital grounds;
- Digital and analog supply for digital circuit components of ADS1299 and TMS320C5515.

For the determination of trace width requirement, there are two considerations made for the circuit components: Current handling capability and Impedance. Through a careful study of individual datasheet for each component, the short circuit output current for the devices is determined after individual traces are calculate using equation 4.5 [29].

$$w = \left( \frac{1}{1.4 * h} \right) \left( \frac{I}{k * \Delta T^{0.421}} \right)^{1.379} \quad (4.5)$$

w is the minimum trace width, h is the thickness of the copper cladding, I is the current load of the trace, k = 0.024 for inner layers and 0.048 for outer layers. Hence, the tracing requirement is different from one component to the other whilst being dependent on whether the top/bottom routing layers or the inner routing layer being used.

The other critical component taken into consideration in regards to signal integrity of the circuit is the trace spacing requirement which is dependent on the peak-to-peak voltage of components. This property is very crucial as there is a high density of instrumentational amplifiers used in the system which gives rise for the overall crosstalk. Hence, accurately determining the minimum allowed space between traces will aid the minimization of crosstalk. Once the minimum value is determined, the 3w rule is implemented for the purpose of signal integrity. The standard used is summarized in table 4.10.

Table 4.10 Minimum trace spacing

<b>V<sub>DC</sub> or V<sub>p-p</sub></b>	<b>Internal traces (Mils)</b>	<b>External traces (Mils)</b>
0 – 15	2	4
16 – 30	2	4
31 – 50	4	24
51 - 100	4	24

Table 4.10 is used to determine trace spacing for the entirety of the PCB design. A 3D view of the finished layout is given in the figure below.



Figure 4.13 3D Layout of the PCB design

## 4.5 Simulation results and discussion

### 4.5.1 Signal amplification

The first stage of the circuit is used to amplify low amplitude signals whilst rejecting common mode noise. Accordingly, the simulation is carried out to test these functionalities of the INA819 with a gain of,  $G = 500$ . Once amplified, the output data is studied in regards to its amplitude as well as noise artifact.

Bio-potential signals from a multichannel setup are passed through INA819 operating in differential mode. A common gain of 500 is used for all signals through an external resistor of  $100\Omega$  using the configuration given in figure 4.13. Input-output relation is shown in figures below.

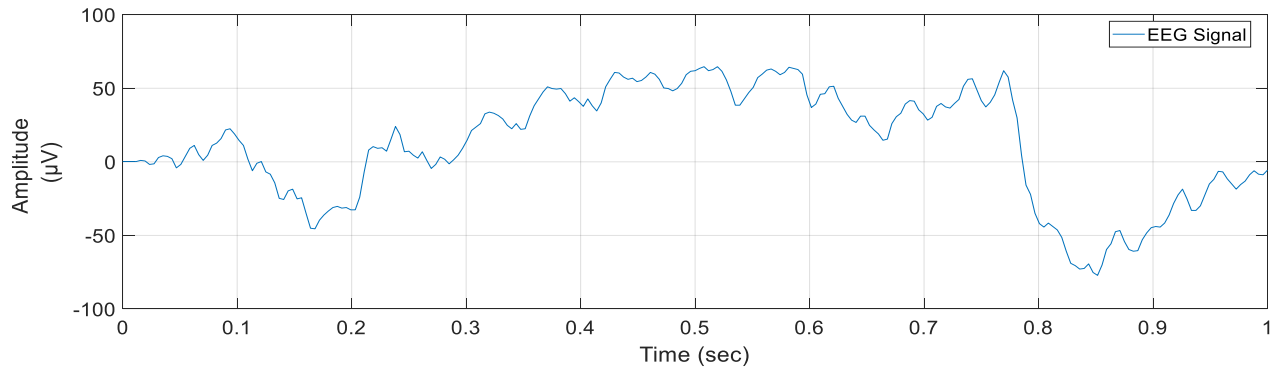


Figure 4.14 Bio-potential signal input

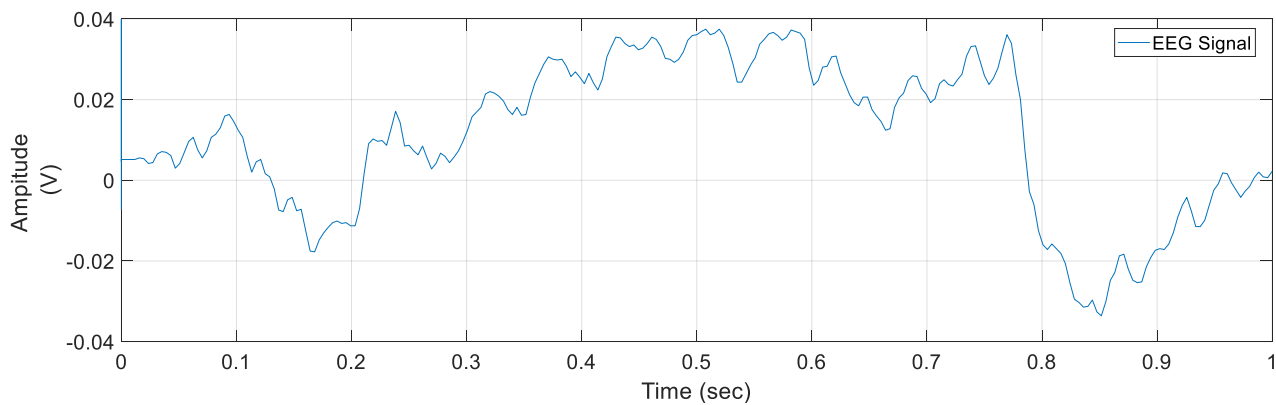


Figure 4.15 Bio-potential signal output

#### 4.5.2 Effects of noise

The amplifier is used to amplify as well as reject common mode noise that are added as artifacts to useful frequency component of the signals. For accurately simulating the effects of noise on the bio-potential signals handled by the system, noise signals are integrated to the bio-potential signal generators. The generated noise signals are meant to cover the wide range of noise interference that occur in physical application. The noises with which the amplifiers CMMR is evaluated against are power line interference noise and white noise [38].

Analysis of power line interference noise is done using a sinusoidal signal of 50Hz frequency and 3mVpp amplitude. On the other hand, white noise meant to account for the miscellaneous noises with variable spectral presence that occur in physical applications is added to the bio-potential signal. These noises include interferences that arise from miscellaneous operating conditions such

as electrical machinery, fluorescent lighting, computer and peripheral accessories, thermal noise etc.

Accordingly, from the three types of bio-potential signals, EEG signals possess the weakest feature in regards to both amplitude and frequency. Hence, the effect of noise is simulated on the EEG signal. Miscellaneous noises mentioned earlier are integrated to the EEG signal generator. Time and frequency domain analysis of the noisy input and achieved output are given in the figures below.

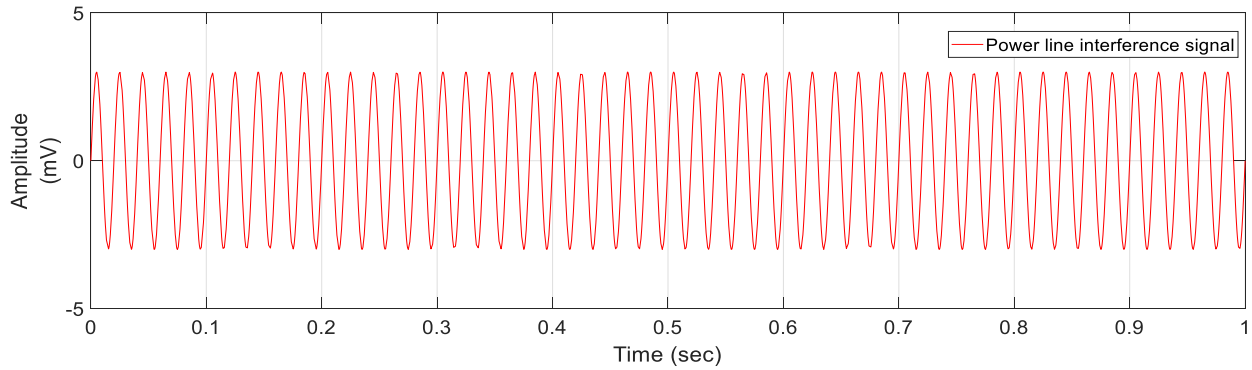


Figure 4.16 Time domain analysis of power line interference noise

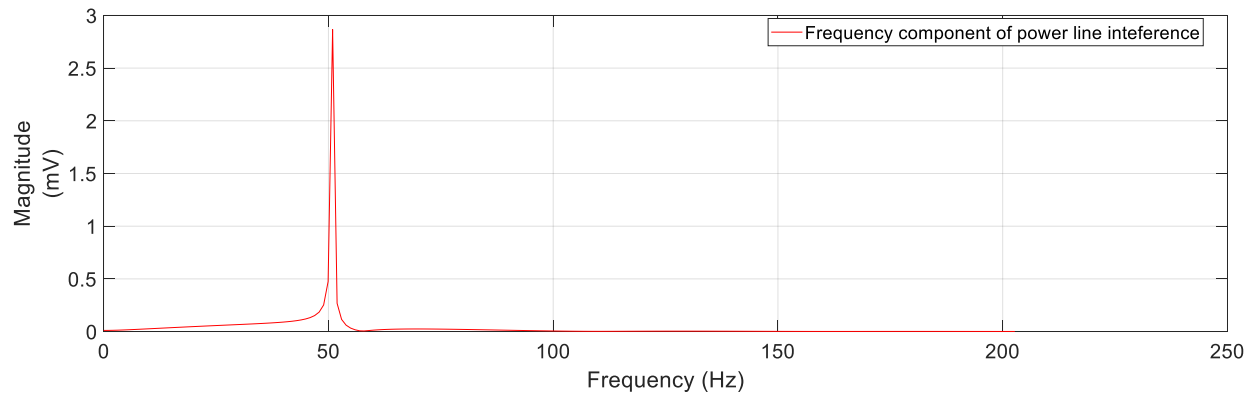


Figure 4.17 Frequency domain analysis of power line interference noise

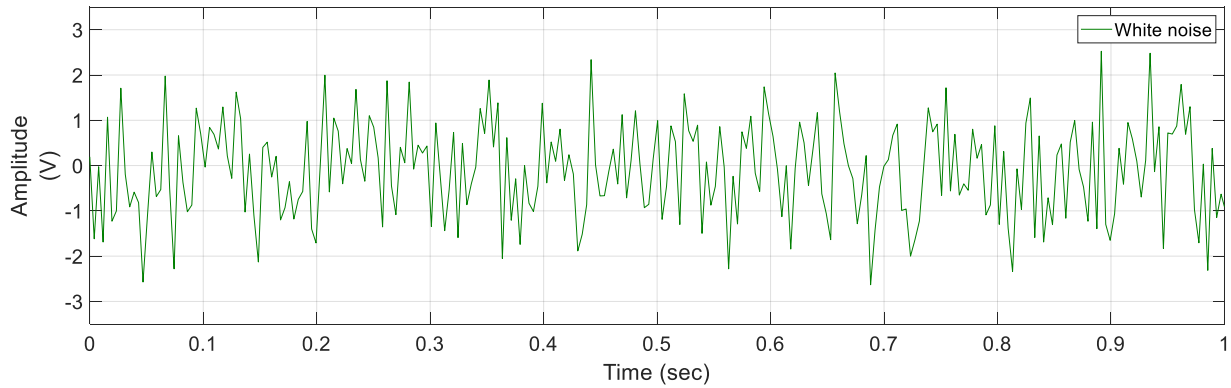


Figure 4.18 Time domain analysis of generated white noise

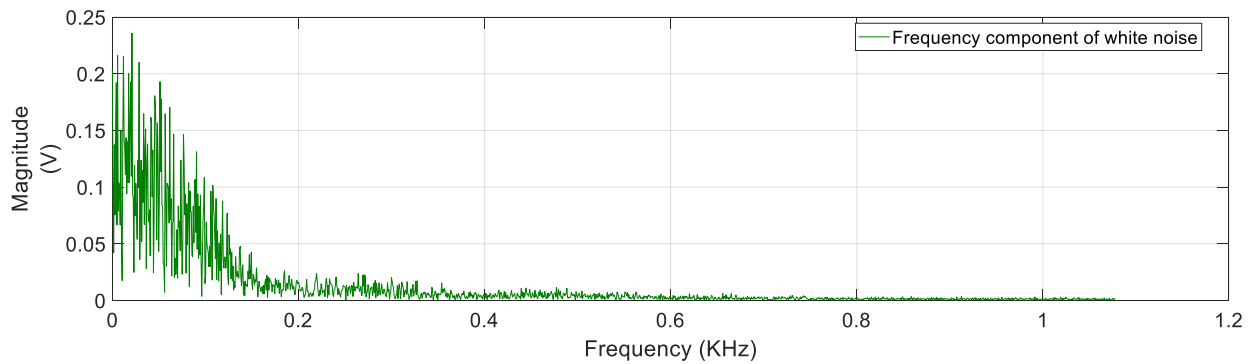


Figure 4.19 Frequency domain analysis of generated white noise

The generated noise signals are added to the bio-signal signal source. The totality is a bio-potential signal that possesses both wanted and unwanted frequency components. This signal is fed into the amplifier operating in differential mode. The input signal with additive noise components and amplified output with common mode signals rejected in its time and frequency domain analysis is shown in the figures 4.19 – 4.22.

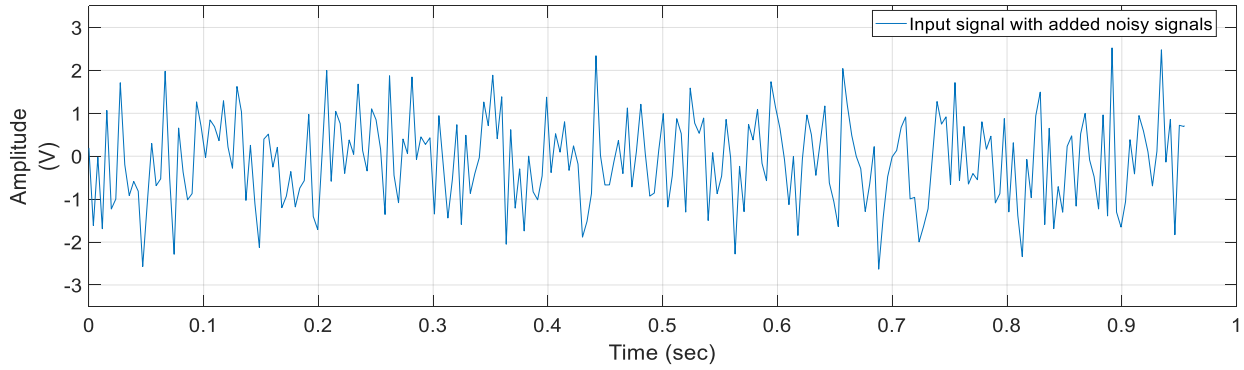


Figure 4.20 Time domain analysis of signal input with added noise signals

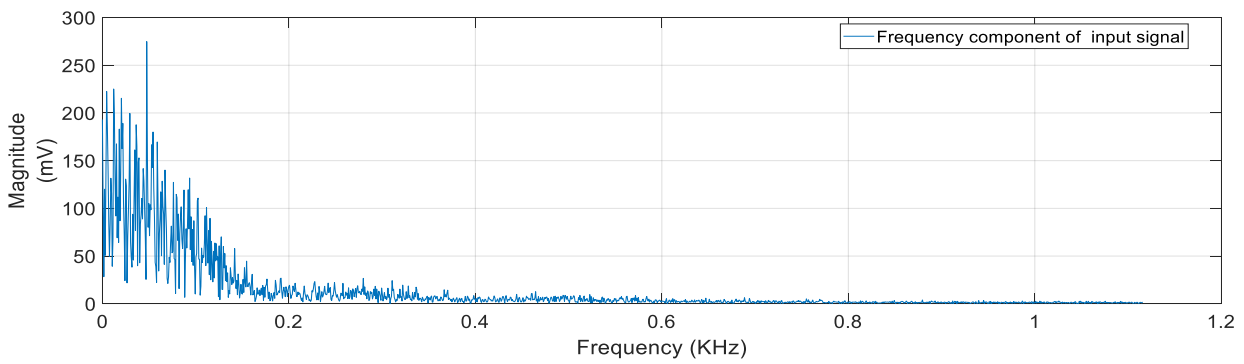


Figure 4.21 Frequency domain analysis of input with added noise signals

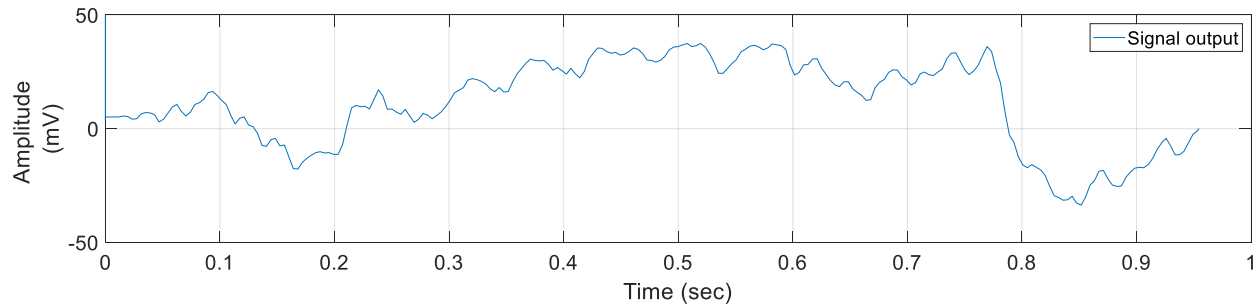


Figure 4.22 Time domain analysis of amplified output

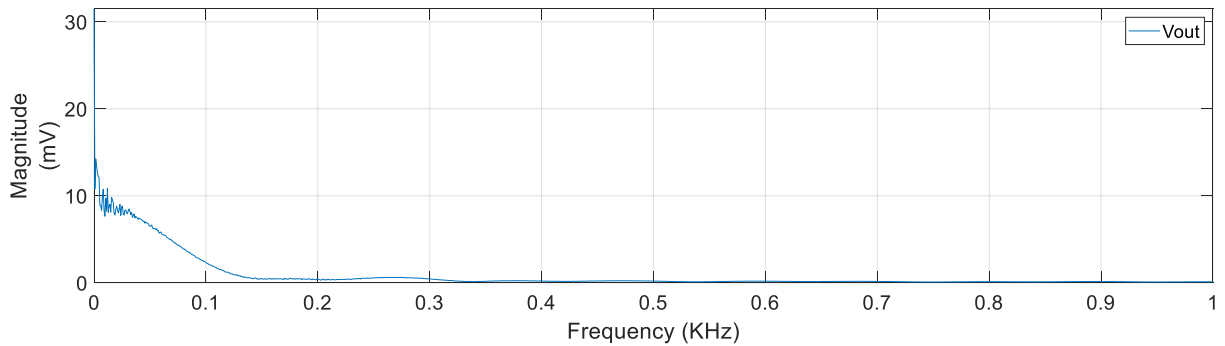


Figure 4.23 Frequency domain analysis of amplified output

### 4.5.3 CMRR analysis

Once the noise cancellation performance of the amplifier is analyzed, the CMRR stability is verified. As one of the metrics of this work is achieving stable CMRR for the bandwidth of the bio-potentials operated by the system, the CMRR for the bandwidth of application is simulated using the same circuit setup in figure 4.7 and analyzed for variable gain conditions whilst applying common mode noise interferences. The CMRR performance for a wide frequency is shown in figure 4.23.

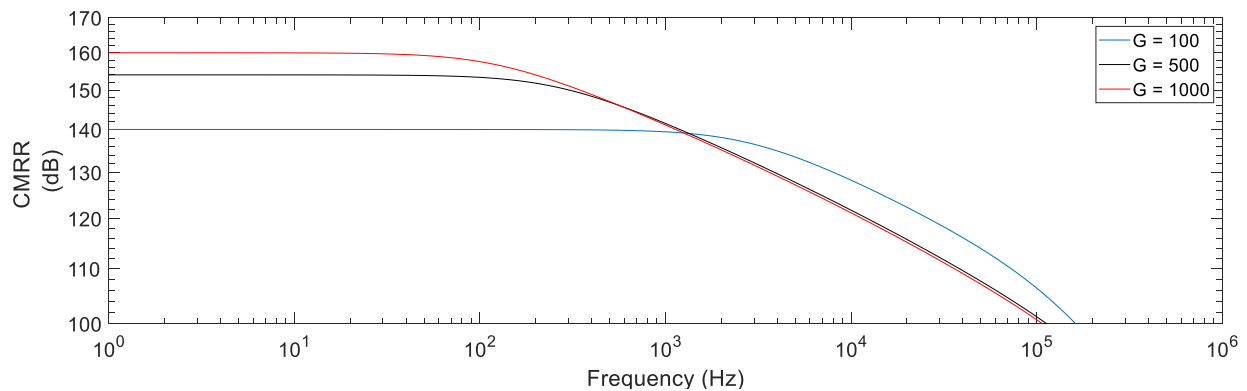


Figure 4.24 CMRR plot of distinct gain levels

### 4.5.4 PSRR analysis

A common performance analysis metric for electronic circuit design is the power supply rejection ratio. The simulation is done up to a maximum of 100 KHz frequency with a source of  $\pm 15V$  with

1Vac for carrying out transient analysis on the circuit. The amplifier is tested for power supply ripple effects at different gain and the result is shown in figure 4.24.

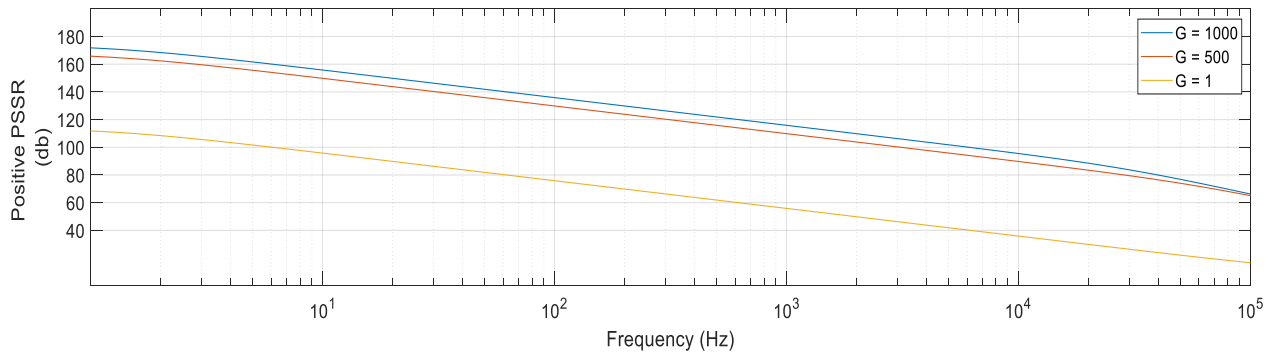


Figure 4.25 PSRR plot for distinct gain levels

#### 4.5.5 Analog to digital conversion

The section for ADC has two critical processes which are oversampling and decimation. Initially, the input signal is oversampled at a given oversampling ratio. Finally, the second stage introduces a tradeoff between signal resolution and data rate by decimating the signal at a certain rate. The simulation profiles used to test the ADC block is taken from table 4.7 with added non linearity described in section 4.3.2.2. The DSToolbox SNR analysis gives an estimate of the ratio to be 156.6dB. However, the signal output in the actual simulation setting with added real-time factors such as op-amp noise, clock jitter and more has yielded an SNR of 113dB. The serial bit stream along with the reconstructed data is shown in the figures 4.25 and 4.26 respectively.

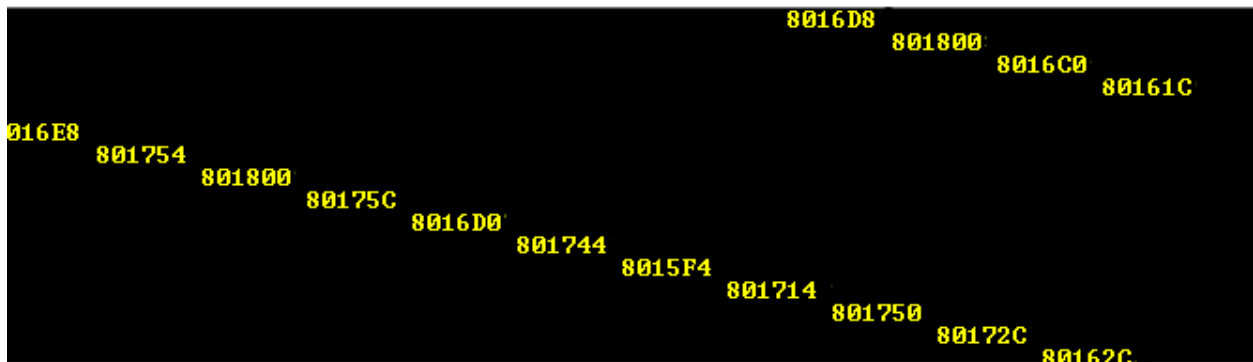


Figure 4.26 Snap shot of serial data captured through a serial monitor

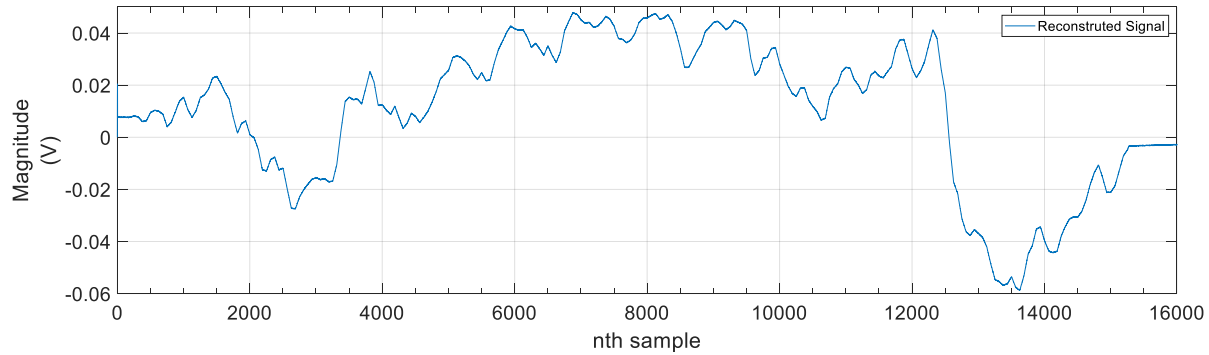


Figure 4.27 Reconstructed serial stream

#### 4.4.6 Performance analysis

The benchmark for performance evaluation and comparison is done in regards to an existing BCI hardware as well as researches published within the past years. Finally, the design is checked against compliance conformity with the IFCN standard.

To analyze the proposed design in regards to the points mentioned above, the open source cyton board by OpenBCI is taken as the bench mark for available products. The cyton board is a hardware manufactured and maintained by researchers in the field of bio-medical research and development. The board has 8 bio potential input channels powered by ADS1299 as the critical circuit component. It has an inbuilt SD storage and wireless communication. However, the board cannot be used for actual clinical purposes. However, there are numerous researches available that are based on this board which mainly span the areas of EEG and EMG applications. A summary of the features of the cyton board is given in table 4.11.

Table 4.11 Feature summary of cyton board

Feature	Value
CMRR (dB)	120
LPF (Hz)	100
Sample rate	500
Bits	24
Channel	8
Main application	EEG signal acquisition

Even though the cyton board cannot be used for clinical purposes, it can be scaled and adjusted for clinical application. Accordingly, there are numerous researches published that are based on the cyton board that are diverse in features as well as application areas. However, the major motive for researchers in the area is not the board by itself. Rather, the critical point of attraction is the ADS1299 SOC. As the SOC is specifically designed for EEG and ECG applications, it has been the focal point of these researches. Table 4.12 summarizes features of sample researches that are based on ADS1299 SOC.

Table 4.12 Summary of ADS1299 based publications

<b>Year of publication</b>	<b>Application</b>	<b>Number of Channels</b>	<b>Resolution</b>	<b>Sample rate</b>
2019 [31]	Brain-to-Brain interface	8	24bits	250Hz
2019 [32]	BCI	16	24bits	125Hz
2019 [33]	sEMG	4	24bits	250Hz
2017 [34]	EMG/EOG	4	24bits	250Hz
2017 [35]	BCI - IOT	8	24bits	250Hz
2016 [36]	Automated brain switch	8	24bits	1KHz
2016 [37]	Robotics	8	24bits	250Hz

Ching-sung wang [14] implemented a thorough design of a 32-channel EEG system for BCI application which follows a general architecture similar to the one described in figure 1.5. The study integrates a mixed signal design and development that supports a software interface to achieve the design goal. For the purpose of noise cancellation, a preamplifier with high CMMR and SNR is integrated and tested. Moreover, the design includes adjustable amplification and filter function meant to be used for different EEG frequency bands. The final design is confirmed to meet IFCN standards and measurement verification conducted to calibrate the accuracy and reliability of the system. The summarized list of features of the output is provided in table 4.13.

Table 4.13 Ching-sung wangs' 32 Channel EEG acquisition system design feature summary

Feature	Value
CMRR (dB)	130
HPF (Hz)	0.16
LPF (Hz)	100
Sample rate	500
Bits	16
Channel	32
Main application	EEG signal acquisition

#### 4.4.6.1 Scope of application

The goal of this research is to design a multipurpose hardware for bio potential signal acquisition. Hence, the portable device should be capable of implementation in EEG, EMG and ECG signal acquisition. When taking a thorough review of the researches and products discussed in the previous section, it is evident that most designs are done for applications in the areas of EEG and sEMG data acquisition. Accordingly, there is a clear absence of ECG specific design functionalities such as a body reference montage i.e. Wilson central. Moreover, most researches aren't meant for clinical application with a few exceptions. On the contrary, this work proposes the hardware to be used for diagnostic purposes in actual clinical applications.

#### 4.4.6.2 Channel capacity

With the exception of Ching-sung wang [14], the researches summarized in table 4.12 provide a maximum of 8 number of analog input channel. However, this design proposed in this research provides a 32 analog input channel which can be utilized for EEG, EMG and ECG applications.

#### 4.4.6.3 Noise reduction

Achieving a high level of CMRR is the focal design parameter in this work. The fact that INA819 is a product released in 2018, there has not been many designs that utilize its high level of noise rejection and medical instrumentation application. Accordingly, the implementation of the LNA in this work has yielded a high CMRR of 145dB for a wide range of frequency application with stability. All the researches summarized in table 4.12 utilize the intrinsic CMRR capability of

ADS1299 has a typical value of -110dB. However, the integration of INA819 as the front end LNA in this work has allowed the analog input to achieve a stable CMRR of 145dB for the frequency band of application. In comparison, this research yields a 21% improvement from Ching-S

#### 4.4.6.4 Analog to digital conversion

The researches summarized in table 4.12 utilize the ADS1299. However, since the maximum number of channels in the researches is limited to 8, there is only a single ADS1299 used in all the designs. However, this work proposes a 32-channel simultaneous sampling montage for the ADS1299 through the use of 4 independent ADS1299 SOCs operating in daisy chain mode whose advantage is twofold. Firstly, the implementation of simultaneous sampling for all 32 available channels provides an ease in regards to visibility for GUI applications. And secondly, using a daisy-chain module rather than cascaded mode has led to a reduced trace runs in the case of the PCB design.

#### 4.4.6.5 Standard compliancy

Even though it cannot be said that the design in this work is in compliant with every standard that exist for bio-medical application development, the initial metric of IFCN standard compliancy is achieved. The compliancy check of the design proposed in this work against major IFCN standard is described in table 4.14.

Table 4.14 Comparison of proposed design with IFCN standards

	<b>IFCN</b>	<b>This research</b>
CMRR	$\geq 110\text{dB}$	145dB
Rin	$\geq 100\text{M}\Omega$	100G $\Omega$
Sample rate	$\geq 200$	16
Resolution	$\geq 12$ bits	24 bits
Channel	$\geq 24$	32

#### 4.4.6.7 Summary

The overall performance analysis is done on both spectrum of the research through product as well as previous works in the area. Accordingly, the analysis shows that the design of the signal acquisition kit possesses enhanced features in regards to channel capacity, noise performance and overall issues of circuit complexity. Table 4.15 presents a summary of the comparison done in regards to both product and research.

Table 4.15 Summary of comparison in product, research and standard

	<b>Open BCI</b>	<b>Ching-sung Wang [14]</b>	<b>This research</b>
CMRR (dB)	110	130	145
Sample rate	1.024M	500	1.024M
ADC Resolution	24	24	24
Channels	8	32	32
Circuit complexity	Highly optimized	Less optimized	Better optimized
Scope of application	EEG	Mainly EEG but suggest ECG usage as well	EEG/ECG/EMG
IFCN compliancy	Does not comply	Complies	Complies

Analyzing table 4.15, the comparison yields a 21% improvement in common mode rejection ratio from previous researches and existing BCI products. Moreover, the analog input channel capacity is boosted by 33% in comparison to the cyton board of Open BCI. Additionally, the diagnostic capability of the data acquisition system is enhanced due to the capability of utilizing EEG, ECG and EMG detection on the same device.

## **Chapter 5**

### **Conclusion and future work**

#### **5.1 Conclusion**

The front-end design proposed in this research presents a generic approach for designing bio-potential signal acquisition devices that can be implemented as a multi-purpose portable hardware. The design takes into account research of recently manufactured ICs and SOCs specifically designed for the purposes of medical instrumentation. Aside from the specific objectives, a generic simulation model for a sigma delta modulator with non-idealities is availed for future inferences.

In this research, a detailed research and simulation-based verification for low noise amplifiers is done with the major criteria being high common mode rejection ratio with stability over a wide range of frequency application. The amplification capability along with noise cancellation and common mode rejection stability is verified through the use of actual bio potential signals acquired from international bio physical signal databases. The overall performance is evaluated in ideal scenarios with the absence of noise signals as well as through the application of power line interference and white noise. The critical feature of the digital section of the design is considered to be the sigma delta modulation ADC with simultaneous simulation. For the purpose of design and validation, a standard simulation model of an analog to digital converter with sigma delta modulation architecture is built and tested in ideal and non-ideal scenarios. The hardware is designed for the purpose of implementing a 32-channel bio-potential signal detection through careful consideration of electrical and mechanical constraints.

The obtained simulation results are compared with selected researches as well as commercially available products in regards to application areas, noise cancellation and digital design performance metrics. The evaluation of the implemented low noise amplifier yielded an average of 21% improvement in common mode rejection ratio in comparison to previous researches and existing BCI products. A 33% improvement in analog input channel capacity is achieved whilst broadening the application to a multi-purpose portable hardware capable of being used for EEG, EMG and EEG application. Moreover, standard compliancy in regards to the IFCN standard is carried out.

## **5.2 Limitations**

The design proposed in this work has several limitations which must be taken into account when utilizing the results as well as design. Although the simulation models used in this work are highly accurate and well maintained by the manufacturers, it doesn't account for the fact that experimental verification has not been done. The main reason for this is the availability of the products on the local market and allocated budget. As the thesis work is done through self-sponsorship, funding has been a very critical drawback in verifying the design experimentally.

The other core limitation is that the design might be considered as lacking in regards to circuit optimization as it uses a large number of low noise amplifiers which can also be considered as redundant since the ADS1299 also provides excellent noise cancellation scheme. However, the fact that the implemented low noise amplifier offers a significant improvement in noise cancellation makes up for the increased size of hardware. Moreover, noise cancellation can be improved through the use of a right-leg drive circuit which is available on the existing component but left unused due to the choice of design.

## **5.3 Future work**

The ultimate objective of this work is to design a multi-purpose signal acquisition device that can be used for EEG, EMG and ECG applications. The design can be further optimized in regards to complexity and cost in order to simplify the medical provision for people in low-income countries. The hardware kit can be distributed to health centers across the countries which will have a significant contribution in cutting-back time and money spent by patients and institution.

Moreover, the digital design can be further extended to have a data syncing protocol to a remote repository (database) that allows patient's data review by medical professionals that reside outside of the patient's locale. This is very helpful in scenarios where a professional opinion is required for further scans and treatment which created a foundation for online collaborative diagnosis. Furthermore, the online repository can be used for the purposes of statistical data generation.

## References

- [1] W. Van Drongelen, "Signal Processing for Neuroscientists". San Diego: Elsevier Science & Technology Books, 2010.
- [2] C. W. John, "Medical Instrumentation: Application and Design (edited by John G. Webster)", Fourth edition, John Wiley and Sons Ltd, 2010.
- [3] J. Enderle and J. Bronzino, "Introduction to biomedical engineering". Amsterdam: Elsevier/Academic Press, 2012.
- [4] S. Sanei and J. Chambers., "EEG Signal Processing". John Wiley & Sons, 2011.
- [5] E. Ashley and J. Niebauer, "Cardiology explained". London: Remedica, 2004.
- [6] "10-20 system (EEG)", En.wikipedia.org, 2019. [Online]. Available: [https://en.wikipedia.org/wiki/10%E2%80%9320\\_system\\_\(EEG\)](https://en.wikipedia.org/wiki/10%E2%80%9320_system_(EEG)) [Accessed: 06- Aug- 2019]
- [7] F. Port., "Finding Power Spectrum of EMG Signal Acquired through Serial Port.", Forums.ni.com, 2020. [Online]. Available: <https://forums.ni.com/t5/Biomedical-User-Group/Finding-Power-Spectrum-of-EMG-Signal-Acquired-through-Serial-Port/td-p/3443060?profile.language=en>. [Accessed: 03- Jul- 2019].
- [8] A. Ra, U. Mahadev and M. Gaikwad, "Design of ECG instrumentation and implementation of digital filter for noise reduction", 2013
- [9] "Clinical Neurophysiology". [Online]. Available: <https://www.journals.elsevier.com/clinical-neurophysiology/view-for-free/guidelines-of-the-ifcn-2nd-ed-published-1999>. [Accessed: 17- Feb- 2019].
- [10] "Muscle Control V1.1 — Open Bionics", Open Bionics, 2020. [Online]. Available: <https://openbionicslabs.com/obtutorials/artichoke-muscle-control>. [Accessed: 06- May- 2019].
- [11] J. Malmivuo and R. Plonsey, "Bioelectromagnetism". New York: Oxford University Press, 1995
- [12] N. B. Robert, "Analysis and Application of Analog Electronic to Biomedical Application", CRC Press LLC, 2003.

- [13] D. Prutchi, M. Norris, “Design and Development of Medical Electronic Instrumentation”, First edition, John Wiley and Sons Ltd, 2005.
- [14] C. Wang, “Design of a 32-Channel EEG System for Brain Control Interface Applications”, 2012
- [15] J. G. Webster, “Encyclopedia of Medical Devices and Instrumentation”, Second edition, John Wiley and Sons Ltd, 2006
- [16] Sarmiento, J. F.; Bastos, T. F.; Botti, A. B.; Elias, A.; Fri16z[]era, A.; Hubner, M.; Silva, I. V. Characterization and diagnosis of fibromyalgia based on fatigue analysis with sEMG signals. In *2012 ISSNIP Bio signals and Bio robotics Conference: Bio signals and Robotics for Better and Safer Living (BRC)*; 2012; pp. 1–4.
- [17] P. Palmes, W. T. Ang, F. Widjaja, L. C. Tan, W. L. , “Pattern Mining of Multichannel sEMG for Tremor Classification”. *IEEE Trans. Biomed. Eng.* 2010, 57, 2795–2805, doi:10.1109/TBME.2010.2076810.
- [18] Gutiérrez, S. J.; Cardiel, E.; Hernández, P. R. A muscle fatigue monitor based on the surface Electromyography signals and frequency analysis. In *2016 Global Medical Engineering Physics Exchanges/Pan American Health Care Exchanges (GMEPE/PAHCE)*; 2016; pp. 1–6.
- [19] N. Hazarika, A. C. Tsoi, and A. A. Sergejew, “Nonlinear considerations in EEG signal classification,” *IEEE Transactions on Signal Processing*, vol. 45, pp. 829–836, April 1997.
- [20] H.-H. Chang, J. M. F. Moura, Y. L. Wu, and C. Ho, “Automatic detection of regional heart rejection in USPIO-enhanced MRI,” to appear *IEEE Transactions on Medical Imaging*.
- [21] B. S. Carter, T. H. Beaty, G. D. Steinberg, B. Childs, and P. C. Walsh, “Mendelian inheritance of familial prostate cancer,” *Proceedings of the National Academy of Sciences of the United States of America*, vol. 89, pp. 3367–3371, April 1992.
- [22] L. Frenzel, *Electronics explained*. Kidlington, Oxford, United Kingdom: Newnes, 2018, pp. 291-324.
- [23] Texas Instruments, “Low-Power Precision Amplifier”, INA819 datasheet, Dec. 2018
- [24] Texas Instruments, “Analog-to-Digital Converter for EEG and Biopotential Measurements”, ADS1299 datasheet, July 2012 [Revised Jan. 2017]

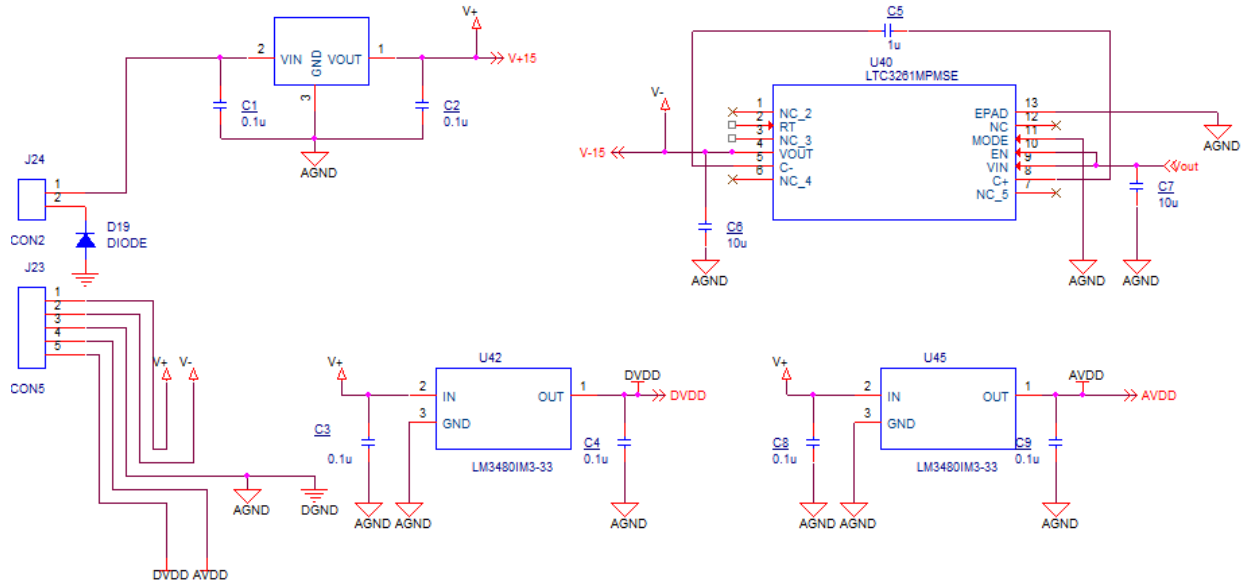
- [25] “Common-Mode Rejection Ratio (CMRR) – NI Digital Multimeters Documentation”, Documentation help, 2020 [Online]. Available: <https://documentation.help/NI-Digital-Multimeters/cmrr.html>. [Accessed: 16- Jan-2019]
- [26] “Nyquist-Shannon sampling theorem”, En.wikipedia.org, 2019. [Online]. Available: [https://en.wikipedia.org/wiki/Nyquist%E2%80%93Shannon\\_sampling\\_theorem](https://en.wikipedia.org/wiki/Nyquist%E2%80%93Shannon_sampling_theorem). [Accessed: 21- Jan-2019]
- [27] X. Xing, P. Zhu and G. Gielen, Design of power-efficient highly digital analog-to-digital converters for next-generation wireless communication systems. Springer, pp. 40 – 41, 2018.
- [28] “Defibrillation”, En.wikipedia.org, 2019. [Online]. Available: <https://en.wikipedia.org/wiki/Defibrillation>. [Accessed: 14- Oct-2019]
- [29] K. Mitzner, B. Doe, A. Akulin, A. Suponin and D. Muller, “Complete PCB Design Using OrCAD Capture and PCB Editor”, 2nd Edition, 2018
- [30] S. Chen and Y. Chen, "Hardware Design and Implementation of a Wavelet De-Noising Procedure for Medical Signal Preprocessing", *Sensors*, vol. 15, no. 10, pp. 26396-26414, 2015
- [31] Jiang, L., Stocco, A., Losey, D.M. et al. BrainNet: A Multi-Person Brain-to-Brain Interface for Direct Collaboration Between Brains. *Sci Rep* 9, 6115 (2019). <https://doi.org/10.1038/s41598-019-41895-7>
- [32] Julia, M., Ryan, P., Stephanie L, et al. “Embodiment improves performance on an immersive brain computer interface in head-mounted virtual reality”. (2019). <https://doi.org/10.1101/578682>
- [33] Cao, J. , Tian, Z. and Wang, Z., “Hand Gestures Recognition Based on One-Channel Surface EMG Signal”. *Journal of Software Engineering and Applications*, 12, 383-392. (2019) doi: 10.4236/jsea.2019.129023.
- [34] Micholaj, B. and Marcin, J., “Project and evaluation of EMG/EOG Human-Computer interface”. Article in *Przegląd Elektrotechniczny*, 93, 128-130. (2017) doi: 10.4236/jsea.2019.129023.

- [35] Aries, T., Mauricio, C., Marcus, E. et al. "Using Brain-Computer Interface and Internet of Things to Improve Healthcare for Wheelchair Users". *The Eleventh International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies* (2017)
- [36] R. V. Sastry, R. Aravind, G. Panwar, S. Indrapriyadarsini and A. G. Ramakrishnan, "Automatic user customized brain switch," *IEEE Annual India Conference (INDICON)*, Bangalore, 2016, pp. 1-5.
- [37] C. J. Perera, I. Naotunna, C. Sadaruwan, R. A. R. C. Gopura and T. D. Lalitharatne, "SSVEP based BMI for a meal assistance robot," *IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, Budapest, 2016, pp. 002295-002300.
- [38] A. Velayudhan and S. Peter, "Noise Analysis and Different Denoising Techniques of ECG Signal – A Survey, International Conference on Emerging Trends in Engineering & Management", 2016, pp. 40-44.
- [39] Neuman R. Michael, "Medical Instrumentation: Application and Design (edited by John G. Webster) ", Fourth edition, John Wiley and Sons Ltd, 2010.
- [40] J.R. Wolpaw, N. Birbaumer, D.J. McFarland, G. Pfurtscheller, and T.M. Vaughan, "Brain-computer interfaces for communication and control". *Clinical Neurophysiology*, 113, 6, 767–791, (2002).
- [41] M.A. Lebedev and M.A.L. Nicolelis, "Brain-machine interfaces: past, present and future". *Trends in Neuroscience*, 29(9), 536–546, (2006).
- [42] H. Chang, J. M. F. Moura, "Biomedical Signal Processing," ed. Myer Kutz, in *Biomedical Engineering and Design Handbook*, 2nd Edition, Volume 1, McGraw Hill. 2010, pp. 559-579.

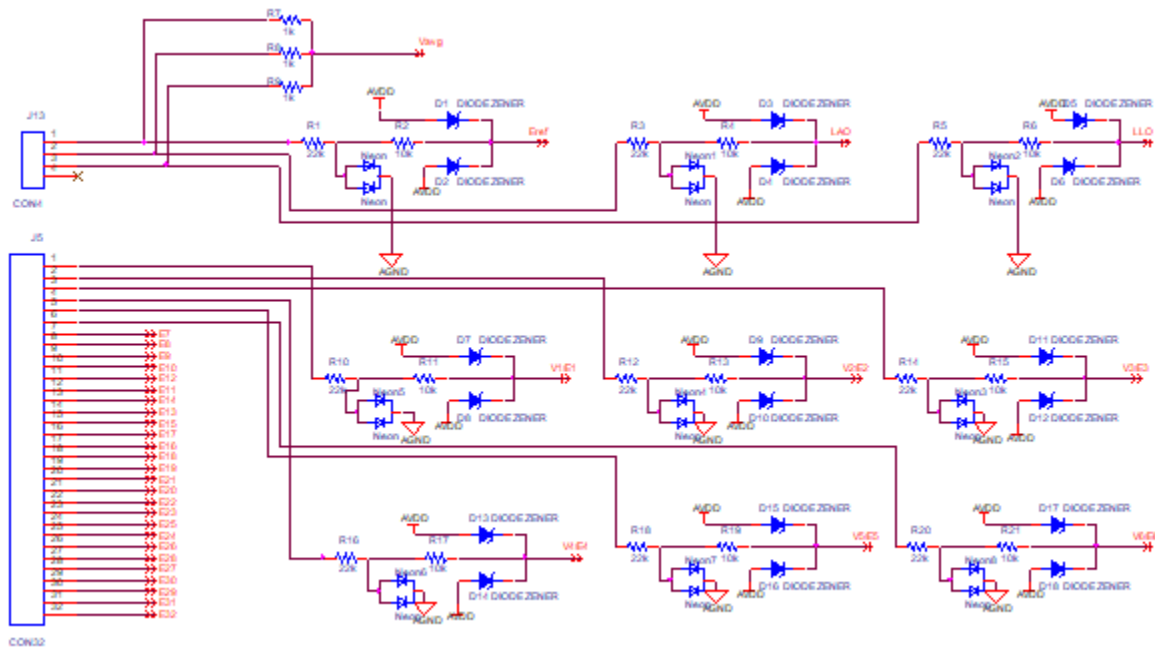
# Appendix

## Circuit schematics

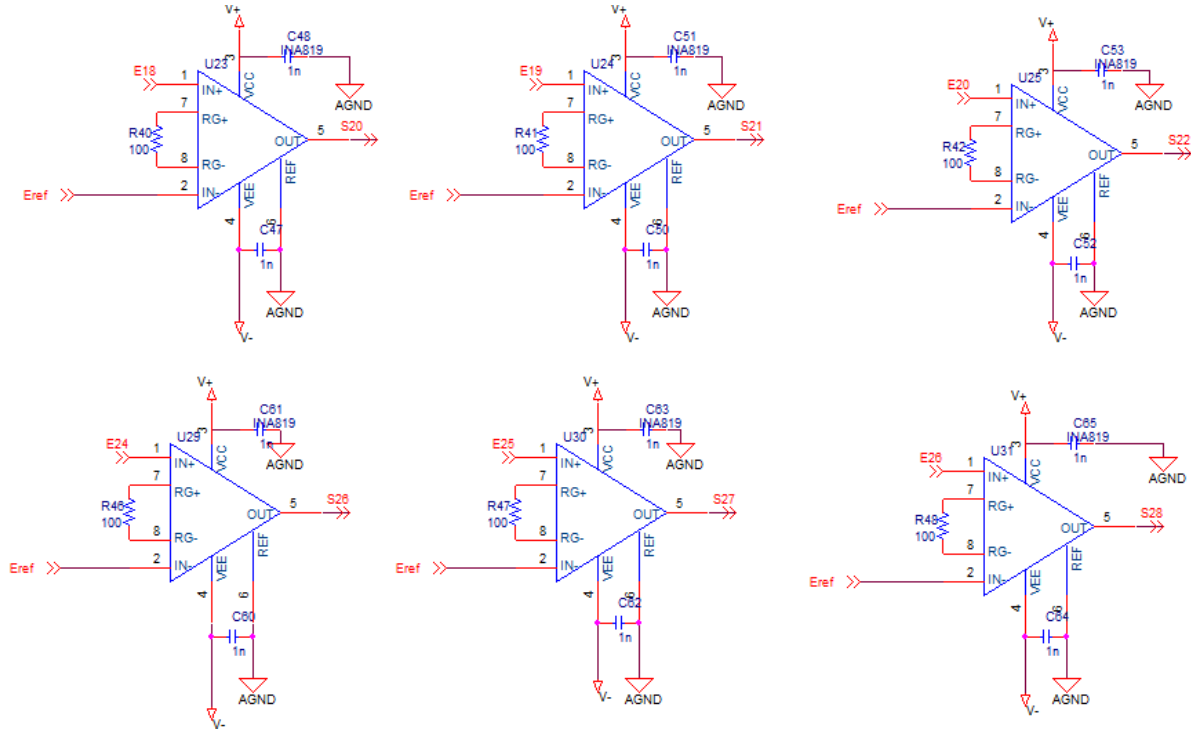
### Power supply



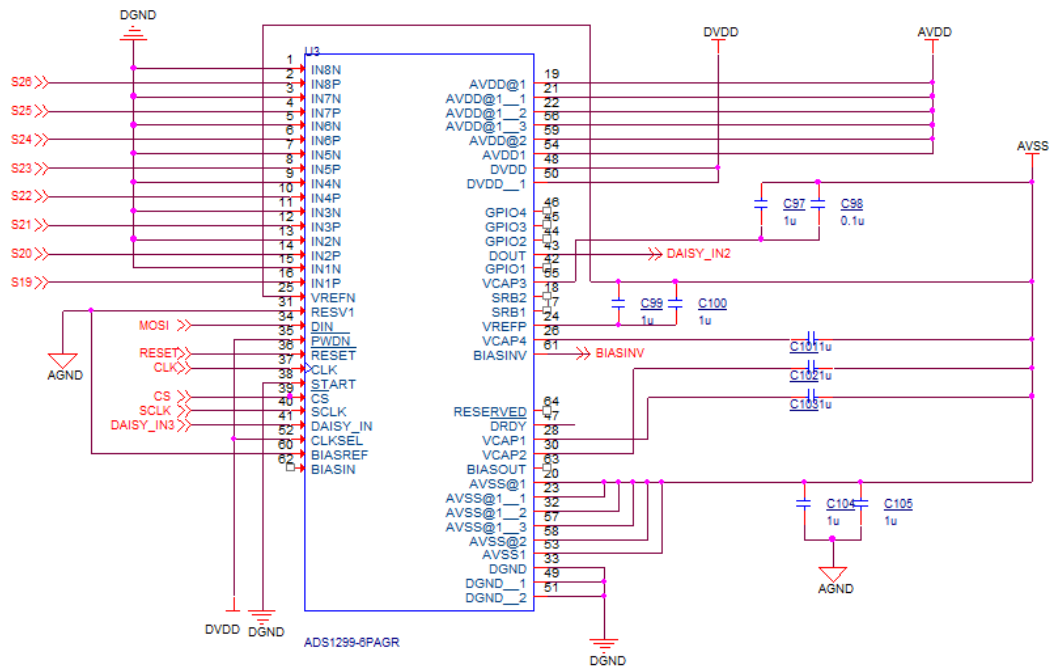
### Electrode wiring



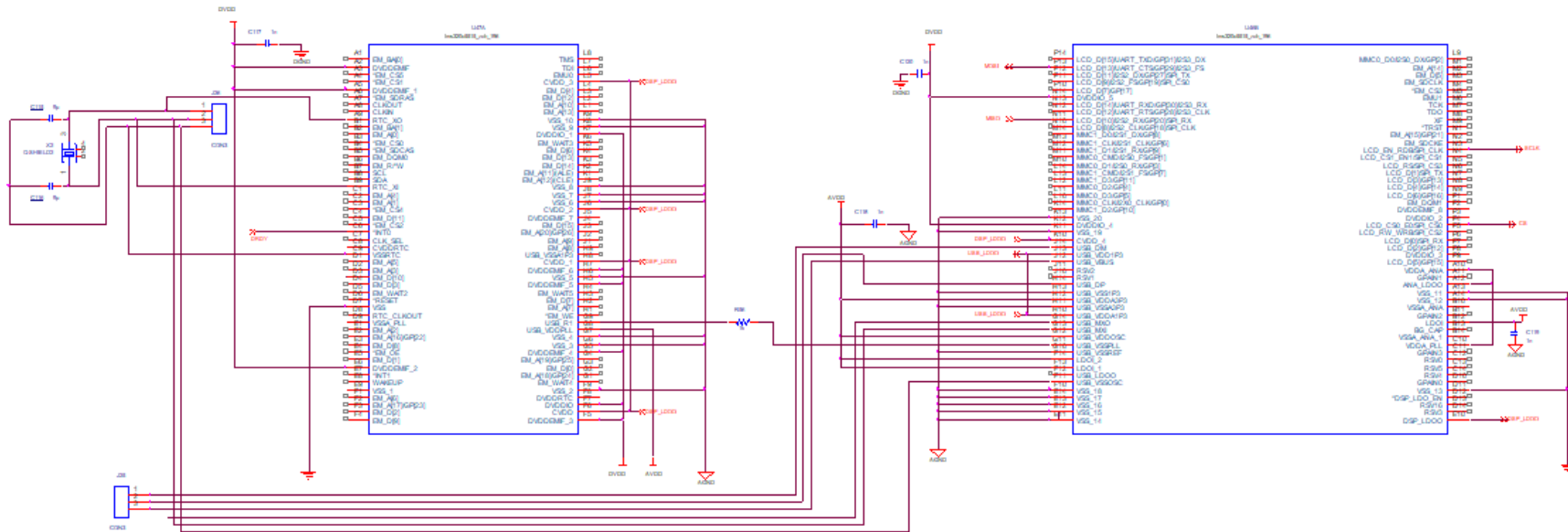
## Amplifier array sample



## ADC wiring for 8-channel input



## DSP connection setup



**N.B. The schematic model is built using two individual blocks for the sake of clarity and doesn't represents two devices.**