Article

Removal of electromyography noise from ECG for high performance biomedical systems

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Abstract
This paper presents the review of the biomedical system which consists of an energy source, signal processing, signal conditioning and signal transmission. These blocks are designed by various optimization techniques to achieve high operating speed, compressed area and minimum energy consumption. These techniques are mainly divided in to four aspects: (a) increasing the longevity of device using energy harvesting approaches; (b) reducing the delay to enhance the operating frequency; (c) reducing the data storage using data compression; (d) increasing the data rate transmission with reduced power consumption. This review paper briefly summarizes the various techniques and device performance achieved by these techniques. To attain these high performance systems input played a vital role. This paper also presents the different low pass IIR filter approximation method techniques to remove Electromyography noise from ECG input signal. For this purpose, we have taken MIT-BIH Arrhythmia database. We have calculated signal to noise ratio and power spectral density. On comparing their performance parameters of different low pass IIR filters, Elliptic filter has found best suited to remove this type of noise.

Keywords energy harvesting; implantable devices; inductive coupling; SNR; PSD; ECG; IIR.

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1 Introduction

For the last sixty years, biomedical implantable devices are available for consumers. In 1957, for the first time Earl Bakken included transistor in biomedical implantable device for cardiac pacemaker (Rhees, 2009). These transistors enable biomedical devices to monitor and diagnose different types of signals such as electroretiuogram (ERG), electrocardiogram (ECG) and electromyography (EMG) of human body (Dogra et al., 2018; Zhang, 2018). The main focus of research is on patient safety and comfort in recent years. Therefore, the main aim of the research is to ensure efficient energy transfer and to the implanted device to reduce the power consumption (Amandeep et al., 2017; Jain et al., 2015; Jain, 2016).

With the advancement in integrated circuits (IC) technology and revolution in circuit design technique replicates the complex biomedical operations such as speech spectral analysis, image processing and digital filtering etc which enhance the device performances (Chandrakasan et al., 2008; Wong et al., 2004, and Paradiso et al., 2005). In Electronic Biomedical Devices, reduction in power consumption can be achieved by continued device scaling and integration. For example, an implanted medical device comprises of low-power general purpose processor which consumes almost 10 mW of energy having 3 days of battery operation. Alternately, a dedicated solution is obtained by implementing a specialized low power technique, which consumes approximately (Wise et al., 2004; Mishra et al., 2016). Generally, implanted devices were powered by batteries, but limited life time of batteries can lead to many challenges. Such issues are resolved by wireless–telemetry bio devices (WTB) which have been powered by radio frequency (RF) signals. In WTB, transmission of power has been performed via inductive coupling coil which is converted to DC voltage. Many other energy harvesting sources has been utilized to power the implanted devices such as knee implants that use the vibration of piezoelectric materials or body motion (Chen et al., 2009; Mishra et al., 2016; Zeng et al., 2011).

For biomedical devices a system level approach is needed which reduces the power consumption to µW (Jain, 2017). Advanced architecture and circuits for biomedical applications should be used to lessen the energy dissipation. This review focuses on the different specialized techniques which lead to the design to be compatible for high performance biomedical applications that require reduced power consumption, compress chip area and speed up operating frequency (Gyselinckx et al., 2005; Cadei et al., 2014).

Different Infinite impulse response (IIR) and Finite impulse response (FIR) filters are used to remove the noise from input ECG signal. FIR filters are simplest filter as they do not require any feedback system. These non–recursive filters are characterized by equation

$$y(m) = \sum_{k=1}^{N} ak\ y(m-K) + \sum_{k=o}^{M} bk\ x(m-K) \quad (1)$$

IIR filters are known as recursive filters as their output depends on past inputs and past outputs. These filters are designed by using different approximation methods like Butterworth, Chebyshev I and Elliptic. IIR filters are determined by equation

$$\mathrm{y[n]} = \sum_{k=0}^{N-1} \mathrm{h(k).X(n-k)} \quad (2)$$

In this paper, high frequency noise from ECG signal has been removed by designing different low pass IIR filter using Butterworth, Chebyshev I and Elliptic approximation methods.

2 Electronic Biomedical System

The generic biomedical system is shown in Fig. 1. The main components of this biomedical system includes energy source, sensors/transducers; signal conditioning, data storage, data transmission, control system and display equipment. A reliable biomedical system has been obtained by optimizing each and every block.

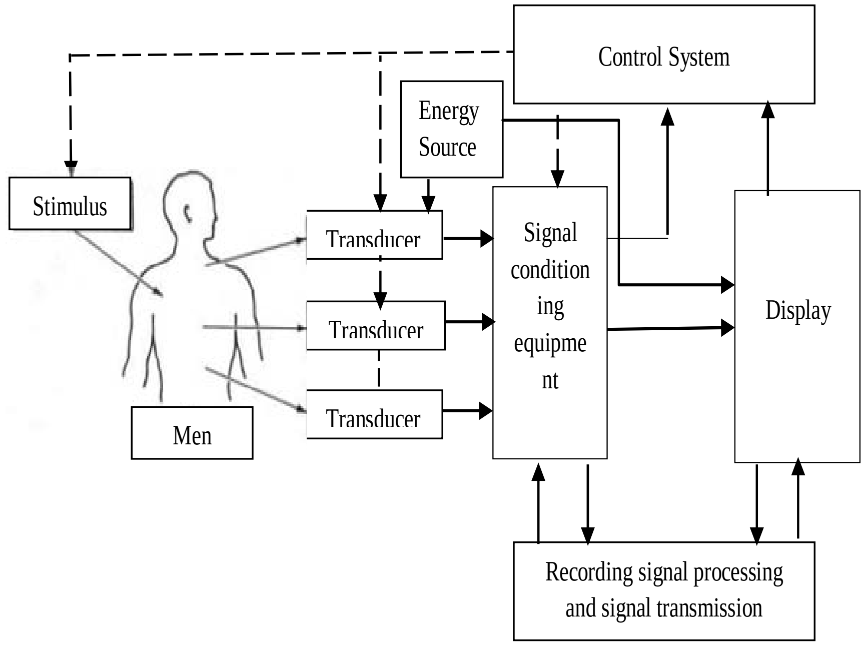


Fig. 1 Generic block diagram of Biomedical System (Cromwell, 2004).

Few existing biomedical devices such as pacemaker, hearing-aid, analog cochlear processor, retinal stimulator, neural recording and body-area monitoring with their performance parameters are shown in Table 1 (Chandrakasan et al., 2008).

Table 1 Review of existing applications of Biomedical Devices (Chandrakasan, 2008).

Energy Source	Power	Processors	Application
10 year lifetime battery	<10μW	1 KHz DSP	Pacemaker
1-week lifetime rechargeable battery	100-2000 μW	32 kHz-1MHzDSP	Hearing-Aid
1-week lifetime rechargeable battery	200 μW	Analog DSP	Analog cochlear processor
Inductive Power	$25X10^4$μW	No embedded DSP	Retinal stimulator
Inductive Power	(1 $X10^3$-$10X10^3$μW	-	Neural recording
Battery	140 μW	<10 MHz DSP	Body-area Monitoring

The reviews of the various components of Biomedical System are discussed in the following sections:

2.1 Energy source

In biomedical devices, the main source of energy is battery. Batteries can be easily replaced in non-implanted device but in case of implanted devices that cannot be possible without surgery. Therefore, an energy harvesting techniques has been introduced that provide continuous power to implanted devices. Paradiso et al.

(2005) described various energy harvesting sources such as thermoelectric, light, vibration, piezoelectric, electrostatic generators, near-field inductive energy transfer, far-field electromagnetic energy transfer. Cadei et al. (2014) explained thermoelectric generators that generate few hundred μ watts by creating temperature difference between outer and inner parts. Cascading of large thermocouples has been done to raise the output power. Glynne et al. (2001) and Kim et al. (2011) discussed the phenomenon of conversion of kinetic energy in to electric energy in piezoelectric generators to generate the power in mW. However, requirement of bulky movement made it not suitable for many implant devices. Kymissis et al. (1998) explained a piezoelectric transducer that produced the output power of 1W while attached to the shoe heel. Cheng et al. (1989) explained electrostatic energy harvesting based on the interference of coulomb forces. Wireless electromagnetic energy transfer is most efficient technique to impart energy to implanted biomedical devices. These techniques involve transmission of electromagnetic energy in to the body and gather the same through coil and antenna. Weiland et al. (2005) and Huang et al. (1998) explained low-frequency energy transfer using near-field electromagnetic induction process for many biomedical applications like radio-frequency identification (RFID), retinal prosthetics and neuro stimulators. To transfer the energy at far distance, Kurs et al. (2007) and Karthaus et al. (2003) presented a quantitative model of non-radiative power transfer over distances up to 8 times the radius of coil via strongly coupled magnetic resonances. High frequencies above hundreds of megahertz are another method to achieve far field communication. However, channel losses and low penetration to the skin are some of the limitations that keep the efficiency low. For implanted devices micro-electronic mechanical system (MEMS) technology has been introduced which fabricate mechanical system in to microchip. Amirtharajah et al. (2000) presented a fabricated MEMS energy harvester for low-power biomedical system. To transfer the energy continuously some other technologies like optical charging, ultrasonic transducers has been introduced which sent the energy through body tissue optically and mechanically (Murakawa et al., 1999). Table 2 shows the energy harvesting approaches for implanted biomedical devices (Amar et al., 2015).

2.2 Biomedical signal processing

Biomedical signal processing includes operation like filtering, data computation and data compression. Digital signal processing is preferred over analog due to its large noise margin and robust to distortion (Sood et al., 2017, Rana et al., 2016a; Bhusri et al., 2016a; Sharma et al. 2017). The limitation of analog circuits is that they require additional hardware for conversion in to digital signals.

Table 2 Energy harvested approaches for implanted biomedical devices (Amar et al., 2015).

Energy Harvesting Approaches	Generated Power (μW)
Thermoelectric	180 $\mu W/cm^2$
Piezoelectricity	0.33 μW
Electrostatic	80 μW
Electromagnetic	400 μW
Optical charging	22×10^3 μW /cm
Ultrasonic transducer	15×10^2 μW /cm^2
Inductive coupling	6150 μW

2.2.1 Filtering

Different methods have been implemented to remove the unwanted signal. Bhusri et al. (2016b), Mohamed (2016), and Rana et al. (2016b) presented least-square finite impulse response filtering technique to the ECG input signal to filter out low frequency noise. Implementation of least-square linear phase FIR filter (LLFE) design on field programmable gate array (FPGA) achieved accuracy of 97.8% with reduction in resource utilization.

2.2.2 Data computation

Biomedical devices required fast computation with greater accuracy and low power consumption along with reduced device area. Pardhu et al. (2014) designed a new hybrid CMOS design for one-bit full adder which operates at low voltage. This adder is then realized in 4-2, 5-2, 5-3, 7-2, 11-2, 15-4, 31-5 compressors which is used in multipliers to reduce the delay but design complexity leads to high power consumption. Ajay and Laurde (2015) designed an efficient booth–encoded wallace tree (BEWT) multiplier architecture for fast computation using fast fourier transform (FFT). In this architecture partial products have been reduced by booth encoder and then added by Wallace tree. Output accuracy can be increased by increasing the significant digits of twiddle factor by compromising with the increased area of circuit .Circuit analyzation gave an accuracy of ± 0.1% for twiddle factor =0.7071. BEWT multiplier architecture consist of five blocks- 2's complement, partial product generator, booth –encoder, Wallace tree and carry look-ahead (CLA) adder as shown in Fig 2.

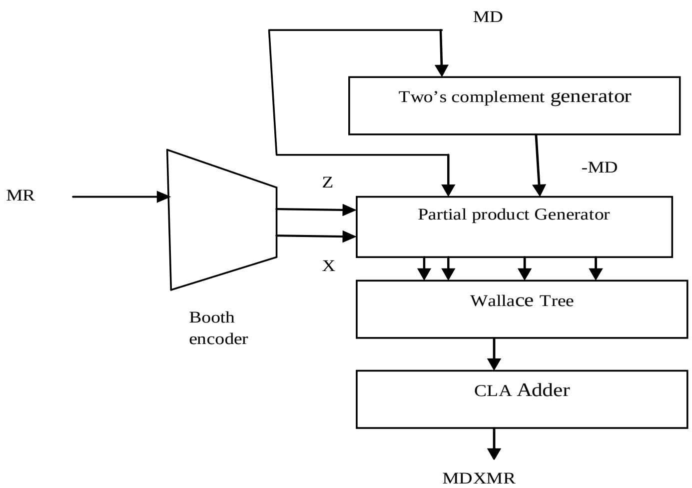


Fig. 2 Architecture of BEWT multiplier (Ajay and Laurde, 2015).

2.2.3 Data compression

In signal processing, data compression encodes the information in fewer bits than its original representation to reduce the storage (Sood et al., 2014). In this context, many new reliable and efficient data compression techniques have been developed by researchers. Ranjith and Muniraj (2012) presented a dictionary based data compression technique for bio signal processors that leads to significant reduction in storage. On reviewing the results this technique showed 28% saving of data storage. Also the previous research challenges such as bitmask selection and don't care resolution of previous test data compression technique has been overcome by dictionary based data compression technique.

2.3 Signal transmission

In implanted biomedical devices, signal transmission has been done through modulation technique. In this technique, carrier variation can be done by Amplitude shift keying (ASK), Frequency shift Keying (FSK) and Phase shift Keying (PSK). Different types of modulation techniques with their performance parameters for bio medical devices are shown in Table 3. These modulation techniques allow high data transmission, low power consumption, intensive data security and greater accuracy (Ziemer et al., 2010; Zhu et al., 2010). ASK modulation also called as on-off keying (OOK) of the simplest technique to be implemented in implanted biomedical devices. However, low data rate, high noise sensitivity, coupling variations have some of the limitations of ASK. To overcome these limitations, two more modulation techniques known as FSK and PSK modulations along with their derivatives have been used that provide high date rate and more immunity to noise and interference but complexity and high power consumptions are some of their issues. To overcome these issues, Trigui et al. (2016) introduced a new technique called quad-width carrier modulation based on pulse width modulation for data transmission that allow high data rate and minimum power consumption with reduced complexity.

Table 3 Performance analysis of different modulation techniques.

Author name and reference no.	Type of modulation	Technology (μm)	Carrier (MHz)	Data rate (Mbps)	Power Consumption (μW)	Supply voltage (V)
Zhu, 2010	FSK	0.35	6.459	0.45	20	2.5
Trigui, 2016	QCWM	0.13	27.12	10.85	35.5	1.2
Kao, 2009	ASK	0.18	2	1	396	1.8
Lee et al., 2011	PSK	0.35	0.250	9.536743e-7	31.5	5
Li et al., 2010	BPSK	0.18	10	2	485.4	3.3
Deng et al., 2006	QPSK	0.18	13.56	4	750	1.8
Lu and Sawan, 2008	OQPSK	0.18	13.56	8	-	1.8
Kiani and Ghovanloo, 2012	PDM	0.35	50	13.56	-	1.8
Kiani and Ghovanloo, 2013	PHM	0.35	66.6	20	-	1.8

3 Response of Different IIR Filters for Denoising ECG Signal

Denoising is the process to reconstruct the signal from noisy one. Its aim to remove noise and preserve useful information. ECG is an important tool to measure health and disease detection. Due to many noise sources, this signal has to be denoised and presented in a clear waveform.ECG signal have frequency range between 0.5 Hz –100 Hz. An electrocardiogram demonstrates the electrical activity in the heart, and may be analyzed in characteristic parts, named P, Q, R, S, and T waves. In ECG Low frequency components are P and T waves, QRS resides at higher frequency. When an ECG is recorded, it would be corrupted with various kinds of noise. These noises are classified as

1. Baseline wanders (low frequency range)
2. Power line interference (Medium frequency range)
3. Electromyography noise (high frequency range)
4. Burst noise
5. Electrode contact noise
6. Muscle contraction
7. Motion artifacts Noise in ECG signal

This paper mainly stresses on the removal of high frequency noise particles called as Electromyography noise by designing different low pass infinite impulse response filters using different approximation methods (Butterworth, Chebyshev I and Elliptic). Taking the input MIT-BIH Arrhythmia from Physio Bank ATM, signal type v5, length 10 sec, 100 Records. We have considered 1454 input samples. The input ECG signal is sampled at sampling frequency f_s= 360Hz.In this input MIT-BIH Arrhythmia are fed to different low pass IIR filters to remove high frequency noise. By implementing these filters, signal time response, frequency response, power spectral density (PSD) and signal to noise ratio (SNR) has been observed. We have considered the cut-off frequency (f_c =100 Hz) for low pass filters. Order of the filter N is 7.

Normalized Frequency (f_n) can be calculated as

$$\omega_n = f_n * f_s \tag{3}$$
$$2\pi(100) = f_n * 360$$
$$f_n = 0.55\pi \text{ rad/sample} \tag{4}$$

4 Results and Discussion

In this section, results of different low pass IIR filters have been analysed through signalTime response, Frequency response and by calculating the value of diffrerentperformance parameters such as SNR and PSD. Signal to noise ratio of a signal determines the signal strength relative to noise. As the signals have wide dynamic range SNR is expressed in Decibles

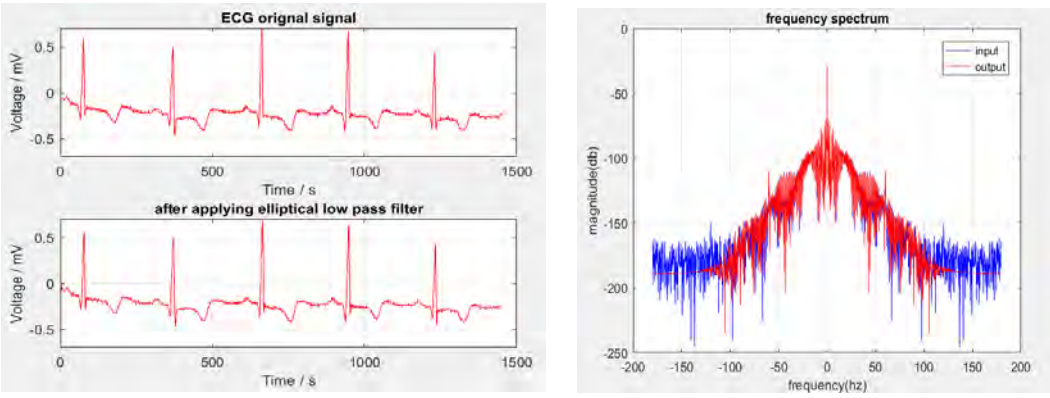
$$SNR_{db} = 10 \log_{10} (P_{signal}) - 10 \log_{10} (P_{noise}) \tag{5}$$

Power spectral density descibes the signal power distribution over the frequency and is expressed in dB/Hz. PSD is determined by equation

$$PSD = \frac{1}{fs\,N} \left| \sum_{n=1}^{N} x_n \, e^{-j\left(\frac{2\pi f}{F}\right)n} \right|^2 \tag{6}$$

PSD has been estimated by Burg's method is an autoregressive power spectral density estimate pxx, of a discrete time signal *x*. Order of autoregressive (AR) model taken is 4. Here, FFT of a signal gave complex numbers for paricular frequency therfore PSD computed for a signal is negative.

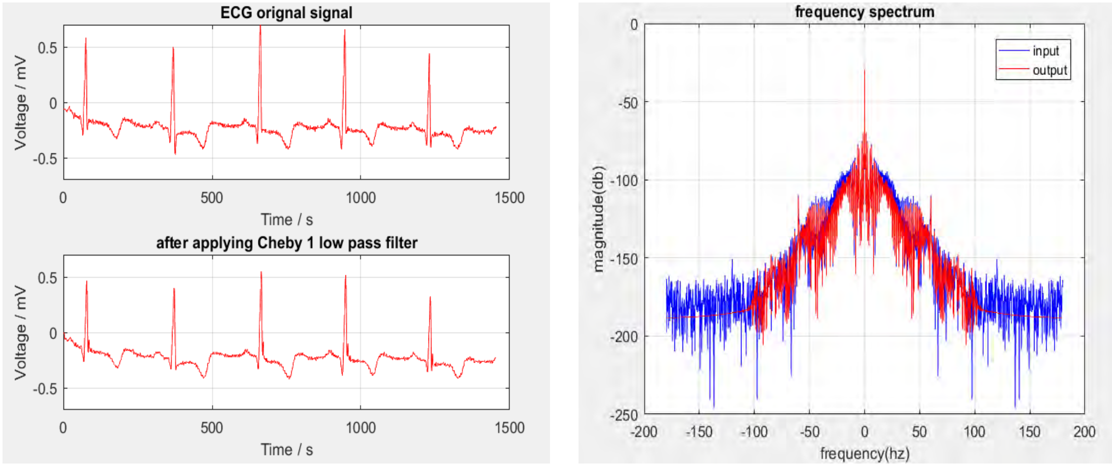
Time domain output waveform of ECG signal filtered by IIR Low Pass filter using Butterworth approximation method is shown in Fig. 3(a) and corresponding Frequency spectrum of an ECG filtered signal is shown in Fig. 3(b).



(a) (b)

Fig. 3 (*a*) Time domain analysis of ECG signal filtered by IIR filter using Butterworth approximation. (*b*) Frequency spectrum of an ECG signal filtered by IIR filter using Butterworth approximation.

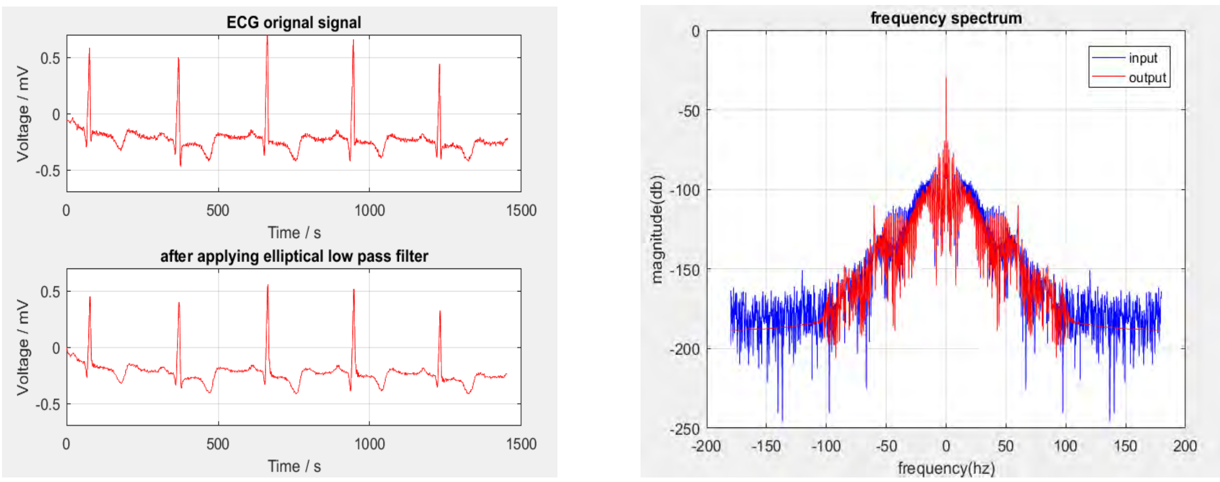
Time domain output waveform of ECG signal filtered by IIR Low Pass filter using Chebyshev I approximation method is shown in Fig. 4(a) and corresponding Frequency spectrum of an ECG filtered signal is shown in Fig. 4(b).



(a) (b)

Fig. 4 (*a*) Time domain analysis of ECG signal filtered by IIR filter using Chebyshev I approximation. (*b*) Frequency spectrum of an ECG signal filtered by IIR filter using Chebyshev I approximation.

Time domain output waveform of ECG signal filtered by IIR Low Pass filter using Elliptic approximation method is shown in Fig 5(a) and corresponding Frequency spectrum of an ECG filtered signal is shown in Fig 5 (b).



(a) (b)

Fig. 5 (*a*) Time domain analysis of ECG signal filtered by IIR filter using Elliptic approximation. (*b*) Frequency spectrum of an ECG signal filtered by IIR filter using Elliptic approximation.

4.1 Comparison of different low pass IIR filters

Comparison between different low pass IIR filters has been done on the basis of the performance metric of SNR and PSD. Filter with greater SNR and reduced PSD is well suited for removing the noise from ECG signal.

SNR and PSD of input ECG signal before filtering and after filtering by digital low pass IIR filter with specified approximation method has been calculated and shown in Table 4 and Table 5 respectively.

Table 4 SNR comparison of different low pass IIR filters.

IIR Filter with Approximation Method	SNR before filtering(dB)	SNR after filtering(dB)
Butter worth Filter	-5.5313	11.8139
Chebyshev I Filter	-5.5313	9.0951
Elliptic Filter	-5.5313	12.2930

Table 5 PSD comparison of different low pass IIR filters.

IIR Filter with Approximation Method	PSD before filtering (dB/Hz)	PSD after filtering (dB/Hz)
Butter worth Filter	-54.8834	-68.5366
Chebyshev I Filter	-54.8834	-70.3884
Elliptic Filter	-54.8834	-70.9543

4.2 Comparison of proposed work with previous reference paper

Comparison of proposed work with previous reference papers has been done. For proper comparative analysis of proposed work, we have chosen the orders of different filter same as mentioned in previous reference papers. Comparison of proposed work with previous reference paper is shown in Table 6.

Table 6 Comparison of proposed work with previous Reference papers.

Type of Filter	Order of filter	Author name	SNR after filtering [Existing work]	SNR after filtering [Proposed work]	PSD after filtering [Existing work]	PSD after filtering [Proposed work]
Butterworth Filter	5	(Singh et al., 2013)	-	-	-56.0660	-68.4152
Butterworth Filter	1	(Sarvankumar et al., 2015)	5.70	24.38	-	-
Chebyshev 1 Filter	2	(Sarvankumar et al., 2015)	5.37	7.61	-	-
Elliptic Filter	3	(Sarvankumar et al., 2015)	5.37	13.90	-	-
Butterworth Filter	10	(Bhogeshwar et al., 2014)	1.12	9.39	-	-
Chebyshev 1 Filter	10	(Bhogeshwar et al., 2014)	1.10	3.58	-	-
Elliptic Filter	10	(Bhogeshwar et al., 2014)	1.73	2.10	-	-
Butterworth Filter	4	(Mishra and Mehra, 2014)	-	-	-81	-68.2
Chebyshev 1 Filter	4	(Mishra and Mehra, 2014)	-	-	-82	-70.10

5 Conclusion

This paper presents the review of various existing techniques and their characteristics to develop a reliable Biomedical System. It has been observed that reliability of these devices depend on energy harvesting, signal filtering, data compression and modulation techniques. However, researchers have initial challenge to denoised the biomedical signals. In context to this problem, different low pass IIR filter has been designed to remove the high frequency noise artifacts from an ECG signal. On comparing their performance parameters of different low pass IIR filters, Elliptic filter has found best suited to remove this type of noise.

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