Design and Performance Analysis of Cascade Digital Filter for ECG Signal Processing

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Abstract: ***The present paper is based on study carried out with an objective of denoising and improving the quality of an ECG signal. In the study four sets of filters were used which are High pass FIR Filter, Adaptive Filter, Notch Filter and Low pass IIR Filter. High pass FIR Filter was designed by different windowing techniques in which Blackman technique was found more effective, Adaptive Filter was designed by LMS and NLMS algorithms in which NLMS algorithm was found to be more suitable and low pass IIR filter was designed by using various approximation methods in which Elliptic approximation method was found more potent. Comparisons of physical parameters like signal to noise ratio and power spectral density has been done by observing the signal before and after applying filter. All these high performance filters were cascaded along with notch filter. Results were compared with the existing papers and our results of experiment showed high SNR improvement after filtering as 7.75dB and low PSD minimization as -35.21 dB/Hz.***

Index Terms*: *Electrocardiogram, signal to noise ratio, power spectral density, digital filters.

I. INTRODUCTION

Electrocardiogram (ECG) depicts the electrical activity of heart by attaching the electrodes to the surface of the skin [1], [2]. ECG signal measure the electrical responses produced by polarization and depolarization phenomenon of cardiac tissue and transform it in to waveform [3],[4].These signals get contaminated due to noises that are not acceptable in various Biomedical Applications [6]. ECG signals are mainly affected by:

1) Base line Wander noise (low frequency range) –This type of noise result due to variations in electrode-skin impedance and patient's movement and breathe. The range of frequency in which baseline wander is dominant is typically less than 1.0 Hz [7].
2) Power line interference noise (Medium frequency range) –occurs due to electromagnetic interference of supply lines contributed by capacitive and inductive coupling.
3) Burst noise - classified as instrumentation noise and white Gaussian noise (WGN). The frequency ranges for the burst noise are not well defined.
4) Electromyography noise (High frequency noise)- occurs due to the contraction of muscles. Amplitude of this noise is random in nature and is modeled by Gaussian distribution function.

Different digital filters have been used to remove these artifacts and interferences from ECG signal [8].These digital filters have ability to refine its frequency response at any time which made them compatible for many biomedical signal processing applications [9]. As ECG signal is a varying signal, it is hard to utilize the different digital filters with fixed coefficients [10], [11]. Many researchers have used digital filters to remove the noise from ECG signal. Author in [12] proposed a cascaded adaptive filter which was used to remove base line drift. A digital notch filter based on an integer coefficient filter technique has been designed [13]. Author designed Elliptical Infinite Impulse Response (IIR) filter for three sets of filter consisting low pass filter (LPF), high pass filter (HPF), and band pass filter (BPF) for optimal order that gave stable response [14]. To filter out high frequency and low frequency artifacts, a low pass and high pass Butterworth filter has been designed [15]. Author in [16] designed a Golay filter which smoothen the signal without damaging its original properties. A comparative analysis of different filters using Butterworth and Chebyshev approximations are presented for ECG noise filtration [17].
Later in this paper different digital filters are explained, section III explains the different steps of implementation and lastly the results are discussed.

II. DIGITAL FILTERS

Digital filters are designed to filter the discrete time signals using both present and past output. Digital filters are composed of IIR filter, Finite Impulse Response (FIR) filter, adaptive filters and notch filter [18].

IIR filter: IIR filters are recursive filters as it requires feedback system i.e. output depend on past inputs and past output.IIR filters are determined by standard equation

$$H(z)=\frac{a_o+a_1 z^{-1}+a_2 z^{-2}+a_3 z^{-3}\text{...........}+a_n z^{-n}}{1-b_1 z^{-1}+b_2 z^{-2}+b_3 z^{-3}\text{...........}+b_n z^{-n}} \quad (1)$$

where $a_{0,}\, a_{1,\ldots\ldots}\, a_n$ and $b_{0,}\, b_{1,\ldots\ldots} b_n$ are filter coefficients.
Digital IIR filter has been designed by using different approximation methods like Chebyshev I, Butterworth, and Elliptic filter.

FIR filter: FIR filters are non-recursive filter as it does not require feedback system [19]. FIR filters are characterized by equation (2).

$$H(z) = b_0 + b_1 z^{-1} + b_2 z^{-2} + \ldots\ldots + b_n z^{-n} \quad (2)$$

FIR filters are implemented using window method. In window method, infinite impulse response has been cropped by multiplying it with finite length window function. The various functions are Rectangular window, Kaiser Window, Hanning window, Hamming window, and Blackman window [20].

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a. Rectangular window(RW): In this window function the filter have finite values with in a definite interval ranging from $-M$ to M. RW function is given by

$$w(n) = 1, |n| < M$$
$$= 0, \text{otherwise} \quad (3)$$

b. Kaiser window (KW): The side lobe level of this window can be controlled by varying the parameter α with respect to main lobe peak. KW function is given by

$$w(n) = \frac{I_o\left(\pi\alpha\sqrt{1-\left(\frac{2n}{N-1}-1\right)^2}\right)}{\mathrm{Io}(\pi\alpha)} \quad 0 < n < N\text{-}1 \quad (4)$$
$$= 0 \quad \text{Otherwise}$$

c. Hamming window (HW): HW function is used to minimize the maximum side lobe. The window function is given by

$$w(n) = \alpha\text{-}\beta \cos(2\pi n/(N\text{-}1)) \quad (5)$$

d. Hanning window (HaW): HaW function is defined as

$$w(n) = 0.5[1\text{-}(\cos(2\pi n)/(N\text{-}1))] \quad (6)$$

e. Blackman window(BW) :BW exhibits wider main lobe width than that of HW and is given b

$$w(n)= 0.42\text{-}0.5 \cos(2\pi n/(N\text{-}1))+0.08 \cos(4\pi n/(N\text{-}1)) \quad (7)$$

Adaptive filter: Fixed filters require the prior knowledge of signal and noise characteristics. Therefore, fixed filters are not effective for unknown environment. This drawback has been overcome by implementation of Adaptive filter. An adaptive filter is a self-modifying digital filter that automatically adjusts the filter parameters to achieve optimal filtering [21], [22].

Different Adaptive algorithms are classified as Normalized Least Mean Square (NLMS), Least Mean Square (LMS), and Recursive Least Square (RLS) algorithm

a. **LMS algorithm-**The LMS algorithm adjusts the coefficients of FIR filters iteratively. The weight of the adaptive filter calculated at the k^{th} iteration is determined by

$$w_{k+1}(i)=w_k(i) + 2\mu\, e_k\, x_{k\text{-}I} \quad (8)$$

The filter output of LMS algorithm is given as

$$\tilde{n}_k = \sum_{i=0}^{N-1} w_k(i)x_{k-i} \quad (9)$$

Least mean square algorithm is defined as:

Initialize μ

For each k

{

$e_K = y_k - \tilde{n}_k$;

$w_{k+1} = w_k + 2\mu\, e_K\, x_{k\text{-}i}$;

}

where w_k is the weight of the digital filter, x_k is the input of digital filter.

NLMS algorithm–In NLMS algorithm step size parameter is not constant and is independent of the input signal power and number of tap weights. The weight of adaptive filter using NLMS algorithm is given by

$$w_{k+1}(i) = w_k(i) + \mu_k\, e_k\, x_{k\text{-}i} \quad (10)$$

NLMS algorithm is defined as:

Initialize $\epsilon \approx 0$ and $0<\tilde{u} \leq 1$

For each k

{

$e_k = y_k - \tilde{n}_k$

$$w_{k+1} = w_k + \frac{\tilde{u}}{x_k^{/} x_k + \epsilon} e_k x_k$$

}

Where $y_k = s_k + n_k$

where $\mu = \frac{\tilde{u}}{x_k^{/} x_k + \epsilon}$ and ϵ is smallest positive number

RLS algorithm-RLS algorithm has faster convergence rate as compared to LMS algorithm but it has high computational complexity and stability problems. RLS algorithm defined the filter output as

$$\tilde{n}_k = \sum_{i=0}^{n-1} \hat{w}(i)x_{k-i} \quad (11)$$

where k= 1,2,3……….m

Notch filter-A notch filter is a narrow stop band having high Quality factor [14].This filter eliminates the power line interference from an ECG signal by band stop with cut-off frequency of 49.5 Hz-50.5 Hz.

III. METHODOLOGY

The data set of the input signal is taken from Physio Bank ATM database of MIT-BIH Arrhythmia. The signals are sampled at 360 Hz with 1454 samples having frequency range 0.5 Hz -100 Hz. Different filters have been designed to denoise ECG signal. Flow graph for removal of noise from ECG signal is shown in Fig. 1.

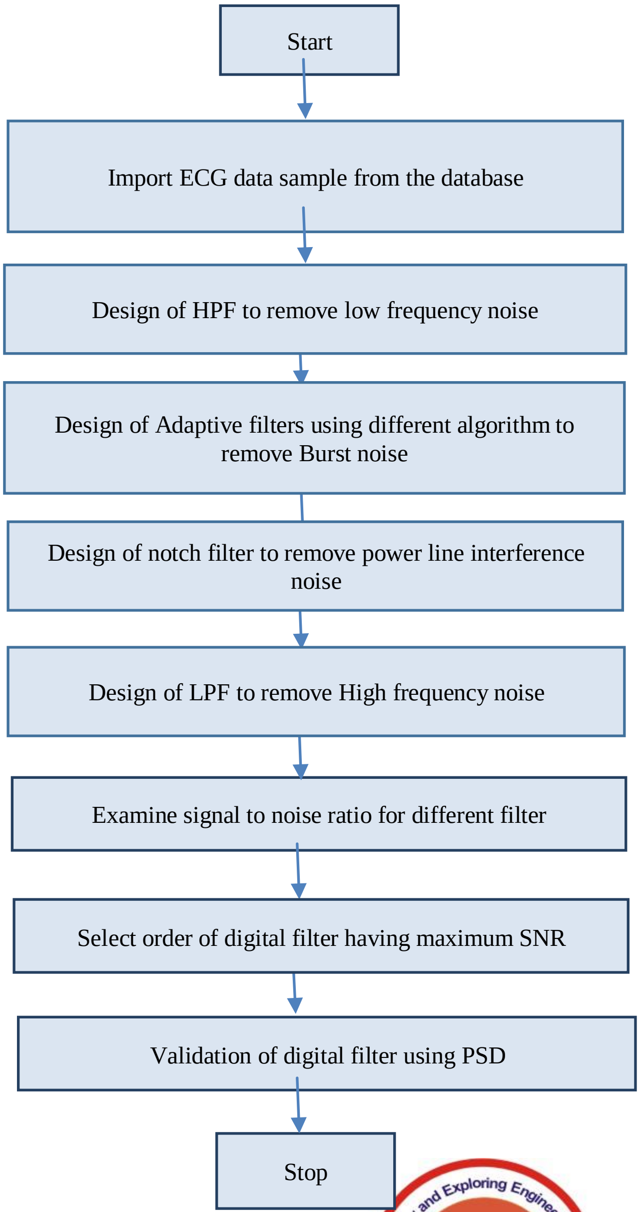

Fig. 1 Flow graph for proposed methodology

The following steps are followed for denoising ECG signal.

Step 1: MIT-BIH Arrhythmia database of ECG signal 100m.txt was loaded.

Step 2: To remove Base Line Wander noise with cut-off frequency (f_c) of 0.5 Hz, input ECG signal was fed to digital FIR HPF using windowing technique like Rectangular, Kaiser, Hamming, Hanning and Blackman. The cut off frequency, normalized frequency (f_n) for FIR High pass filter has been calculated using Eq. (12) and Eq. (13).

$$\omega_n = f_n * f_s \quad (12)$$

$$2\pi(0.5) = f_n * 360 \quad (13)$$

Normalized frequency for digital FIR High pass filter is 0.002π.

A simple high pass filter is used to filter the low frequency noise without discarding ECG components. Following specifications has been considered to design High pass FIR filter.

FIR Filter with Window Method	SNR before filtering (db)	SNR after filtering (db)	PSD before filtering (db/Hz)	PSD after filtering (db/Hz)
Hamming window	-5.5313	6.0130	-54.8834	-54.7319
Hanning window	-5.5313	6.0212	-54.8834	-54.7309
Kaiser window	-5.5313	5.9340	-54.8834	-54.7409
Rectangular window	-5.5313	5.9156	-54.8834	-54.7437
Blackman window	-5.5313	6.0315	-54.8834	-54.7295

(i) Cut-off frequency = 0.5Hz
(ii) Sampling frequency = 360 Hz
(iii) Window length = $N + 1$
(iv) Order of Filter (N) = 10

Step 3: Burst noise has been removed by designing Adaptive filter using LMS and NLMS algorithm by considering following specifications.

(i) Sampling frequency = 360 Hz
(ii) Adaptive Filter length = 11
(iii) Order of Adaptive Filter (N) = 10
(iv) Step size = 0.533.
(v) Normalized frequency $=0.55\pi$.
(vi) Offset (for NLMS algorithm) = 10

Step4: Power line interference has been removed by designing a band stop filter with cut-off frequency 49.5Hz-50.5Hz .

Step5: To remove the Electromyography noise, Low pass IIR filter is designed using various approximation methods like Butterworth, Chebyshev I and Elliptic with f_c 100 Hz. Normalized frequency for IIR LPF has been calculated using Eq. (14).

$$2\pi(100) = f_n * 360 \quad (14)$$

Normalized frequency for digital IIR LPF is 0.55π.

The different low pass IIR filters has already been implemented in [24] which shows elliptic filter gave better performance.

Step6: Evaluation of SNR parameter- The filter with maximum SNR was selected as an optimal order filter.

Step7: The performances of the optimal order digital filters are validated visually, based on PSD and FFT. PSD describes the signal power distribution over the frequency and is expressed in dB/Hz. PSD is determined by Eq. (15) :

$$\text{PSD} = lim_{N\to\infty} E\{1/N |\textstyle\sum_{t=1}^{N} y(t)e^{-j\omega t}|^2\} \quad (15)$$

PSD has been estimated by Burg's method which is an autoregressive PSD estimate p_{xx} ,of a discrete time signal x.

IV. RESULTS AND DISCUSSION

In this section, output of ECG signal has been generated by filtering the noise using different types of filter discussed in section III. The comparison of different filters has been done by calculating the values of SNR and PSD before and after filtering of ECG signal.

Removing low frequency noise by FIR High Pass filter using window technique: To remove low frequency baseline wander noise, FIR filter has been designed using various window techniques. We have calculated the different parameters in section III i.e. Order of filter as 10 and window length as $N + 1$.

Table I. shows the SNR and PSD of different FIR high pass filters having filter order (N =10) with all the specifications mentioned in step 2 of Section III. BW shows the best result as it has high SNR and low PSD.

Table I : SNR And PSD Of Window Based Fir Filters

Removal of PLI using Notch filter: An IIR notch filter has been designed to remove PLI noise of 50 Hz with frequency band of 49.5 Hz - 50.5 Hz. SNR and PSD after applying notch filter has been calculated and shown in Table II.

Table II: SNR and PSD of Notch Filter

SNR before filtering (db)	SNR after filtering (db)	PSD before filtering (db/Hz)	PSD after filtering (db/Hz)
-5.5313	33.4260	-54.8834	-54.8505

Removing Burst noise by designing Adaptive filter using different algorithms: The frequency of Burst noise is not defined. Thus adaptive filter using LMS or NLMS algorithm has been designed that give the output waveform as desired signal, output signal and error signal. Performance metrics in terms of SNR and PSD before filtering and after filtering has been observed and shown in Table III and Table IV respectively. Time domain output waveform of ECG signal filtered by adaptive filter using LMS algorithm is shown in Fig 2(a) and corresponding Frequency spectrum of an ECG filtered signal is shown in Fig 2(b) while for NLMS is shown in Fig 3.

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Table III :SNR and PSD of Adaptive filter using LMS algorithm with N =10

SNR before filtering (db)	SNR after filtering (db)	PSD before filtering (db/Hz)	PSD after filtering (db/Hz)
-5.5313	6.2771	-54.8834	-71.6306

Table IV: SNR and PSD of Adaptive filter using NLMS algorithm with N=10

SNR before Filtering (db)	SNR after filtering (db)	PSD before filtering (db/Hz)	PSD after filtering (db/Hz)
-5.5313	7.1699	-54.883	-86.2620

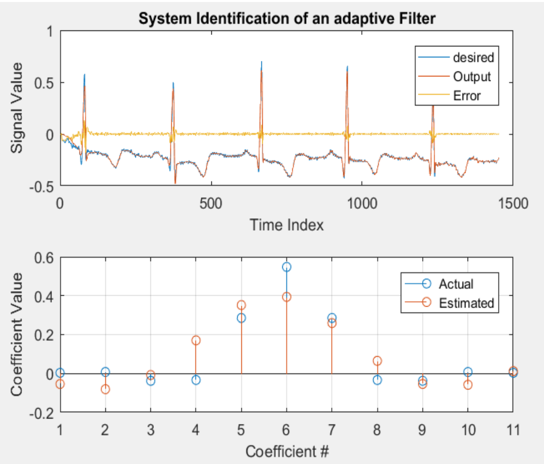

Fig. 2(a) Time domain analysis using LMS algorithm

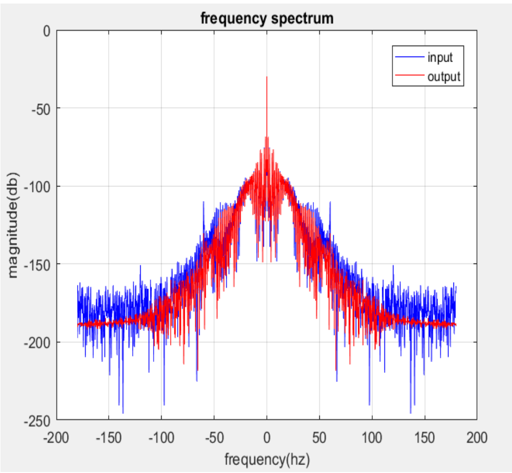

Fig. 2(b) Frequency spectrum using LMS algorithm

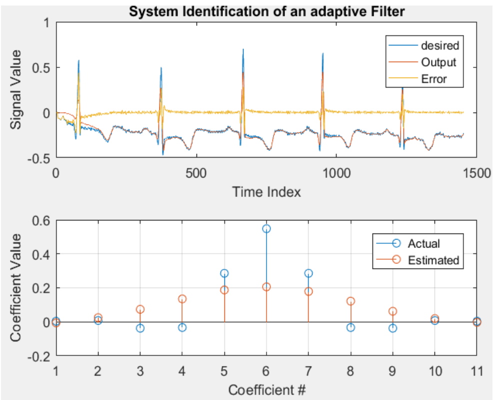

Fig. 3(a) Time domain analysis using NLMS algorithm

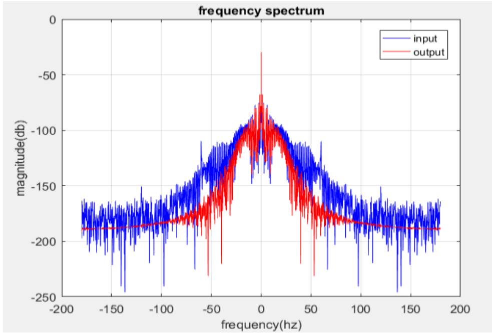

Fig. 3(b) Frequency spectrum using NLMS algorithm

Cascaded filter design to denoise ECG signal : Different types of ECG interference may be removed by band pass filter but filtering of ECG signal by band pass filter have limitations with low SNR [6]. To overcome this limitation, cascaded filters design is proposed. The parameters before filtering and after filtering have been evaluated and shown in Table V. The output waveform of cascaded Filter in terms of Time domain is shown in Fig. 5(a) and its frequency spectrum is represented in Fig. 5(b).

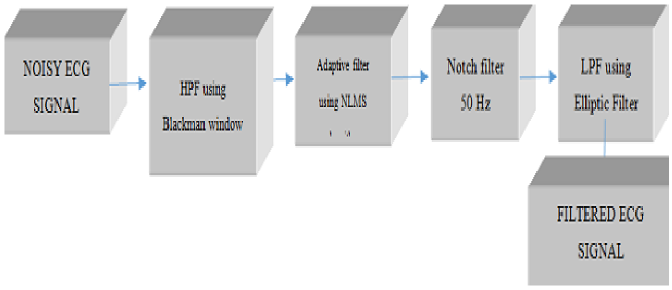

Fig. 4 Cascade filter using Adaptive NLMS algorithm

Table V : SNR and PSD using Cascading Adaptive NLMS Filter

SNR before Filtering (db)	SNR after filtering (db)	PSD before filtering (db/Hz)	PSD after filtering (db/Hz)
-5.5313	2.2226	-54.883	-90.102

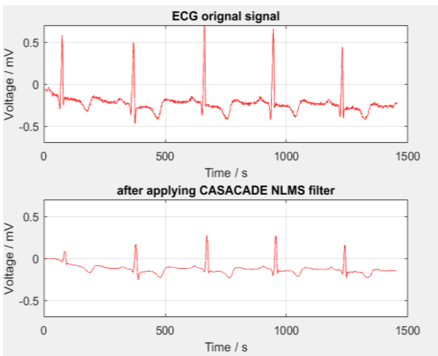

Fig. 5 (a) Time domain analysis by Cascaded Filter design

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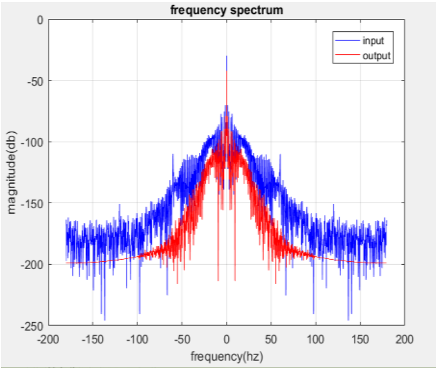

Fig. 5(*b*) Frequency spectrum of an ECG signal filtered by Cascaded Filter design.

COMPARSION TABLE WITH EXISTING WORK

Comparison of proposed work with previous reference papers have been done on the basis of SNR improvement and minimal PSD after filtering. For comparative analysis of proposed work, orders of different filters are choosen

Table VI shows the comparison of proposed High pass FIR filter using windowing techniques with previous reference papers and Table VII shows the comparison of Proposed Blackman High pass FIR filter with previous Reference papers with different filter orders.

Table VI Comparison of Proposed High pass FIR filter with previous reference papers taking order 56

	Rectangular FIR Filter		**Kaiser FIR Filter**		**Hanning FIR filter**		**Hamming FIR Filter**		**Blackman FIR Filter**	
	SNR improvement (dB)	PSD Minimization (dB/Hz)	SNR improvement (dB)	PSD Minimization (dB/Hz)	SNR improvement (dB)	PSD Minimization (dB/Hz)	SNR improvement (dB)	PSD Minimization (dB/Hz)	SNR improvement (dB)	PSD Minimization (dB/Hz)
(Kumar et al.,2015) [23]	0.95		0.92		0.36		0.4		0.28	
Proposed Model	8.49	0.11	8.58	0.10	9.04	0.10	9.00	0.10	9.116	0.10

Table VII Comparison of Proposed Blackman High pass FIR filter with previous Reference papers with different filter order

Order of filter	**Author name**	**SNR improvement (dB) (Previous work)**	**SNR improvement (dB) (Proposed work)**	**PSD Minimization (dB/Hz) (Previous work)**	**PSD Minimization (dB/Hz) (Proposed work)**
56	(Kumar et al., 2015)[23]	0.28	9.116	-	0.10
100	(Bhaskar et al., 2015)[24]	-27.1	8.756	-	-0.04
300	(Kumar et al., 2014)[25]	1.944	6.072	-	-0.43

From above Table VI and VII, it has been observed that proposed filters using different windowing techniques have greater SNR improvement than previous reference papers.

Table VIII Comparison of Proposed Adaptive filter with existing work

Type of Filter	**Author name**	**SNR improvement (dB)**	**SNR improvement (dB) (Proposed work)**	**PSD Minimization (dB/Hz)**	**PSD Minimization (dB/Hz) (Proposed work)**
Adaptive LMS	(Mohammad et al.,2009) [26]	4.9304	11.8084	-	-16.74
Adaptive LMS	(Sharma et al.,2015) [27]	11.0749	11.8084	-	-16.74
Adaptive LMS	(Sehamby et al., 2016) [28]	11.0749	11.8084	-	-16.74
AdaptiveLMS	(Shetty et al., 2015) [29]	0.345	11.46	-2.79	-16.74
Adaptive NLMS	(Wagh et al., 2014) [30]	7.7729	12.7012	-	-31.37
Adaptive NLMS	(Patil et al.,2015) [31]	6.11	12.7012	-	-31.37

Table VIII shows the comparison of proposed adaptive filter using LMS and NLMS which has been done with previous reference papers. Comparison shows that proposed work have better results in terms of SNR improvement with reduction in PSD. Table IX, shows the proposed cascaded design which have significant improvement in SNR from previous cascaded Window based digital filter configuration.

Table IX Comparison of proposed cascaded filter design with existing work

Author name	Database	SNR improvement after filtering(dB)	PSD Minimization (dB/Hz)
(Patro et al., 2015) [32]	MIT-BIH NSR DATA	4.14	-
Proposed	MIT-BIH Arrhythmia	7.75	-35.21

V. CONCLUSION

This paper outlines the various approximation methods, windowing techniques and different algorithms for designing of IIR, FIR and Adaptive digital filter to remove the noise from ECG signal. The performance metrics of these filters in terms of Signal to noise ratio and Power Spectral density has been obtained. On comparing these parameters Elliptic IIR filter, Blackman window of FIR filter and Adaptive filter using NLMS algorithm showed better results. By combining these high performances FIR and IIR filters along with notch and adaptive NLMS filter in series, we have designed a cascaded filter design to remove different noises from ECG signal. Results with cascaded filter design get the high SNR improvement as 7.75dB and low PSD minimization (35.21dB/Hz) that showed the improvement in quality of denoised ECG signal.

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