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Denoising Electrocardiogram Signals using Multiband Filter and its Implementation on FPGA

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Abstract: The electrocardiogram (ECG) signal carries vital information related to cardiac activities. While measuring ECG using electrodes, the signal is contaminated with powerline interference (PLI) from harmonics, baseline wandering (BW), motion artefacts (MA) and high frequency (HF) noise. The extraction of the ECG signal, without the loss of useful information from the noisy environment, is required. Therefore, the selection and implementation of an efficient filter design is proposed. The Finite Impulse Response (FIR)-based multiband needs separate digital filters, such as Lowpass, Highpass, and Bandstop Filter in cascade. The coefficients of the FIR multiband filter are optimised using a least squares optimisation method and realised in a direct form symmetrical structure. The capability of the proposed filter is evaluated on a Physionet ECG ID database, having records of inherent noisy ECG signals. The performance is also verified by measuring the power spectrum of the noisy and filtered ECG waveform. Also, the feasibility of the proposed multiband filter is investigated on Xilinx ISE and the design is implemented on a field programmable gate array (FPGA) platform. A low order simple multiband filter structure is designed and implemented on the reconfigurable FPGA device.

Keywords: Baseline wandering (BW), Electrocardiogram (ECG), Field programmable gate array (FPGA), Multiband filter, Motion artefact (MA), Power line interference (PLI).

1 Introduction

The electrocardiogram (ECG) signal contains information about various cardiac activities, which are helpful in identifying abnormalities [1]. The denoising of ECG signals is required to remove unwanted interference and get information without the loss of useful data. A high quality ECG signal is needed for a better diagnosis of diseases and treatments. While capturing the real time ECG signal, different types of noise are captured, such as powerline interference (PLI) with harmonics, baseline wandering (BW), motion artefacts (MA) and high frequency (HF) noise [2].

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Different adaptive algorithms are used for the denoising of ECG signals. The adaptive algorithm based filters for eliminating PLI noise were proposed in [3 – 6]. Different adaptive filter algorithms were discussed in [7], for eliminating MA, BW, PLI and Muscle artefact noises from the ECG signal. In [8], the application of noise cancellation and arrhythmia detection is given, using adaptive filters for ECG analysis. In [9], an adaptive line enhancer is designed for the ECG signal, to remove EMG noise. In [10], adaptive and non-adaptive filters were discussed, with a comparative analysis for removing PLI noise from the ECG signal. However, the application of an adaptive filter for ECG noise cancellation requires a known model of noises.

Many algorithms are proposed for the signal processing and classification of ECG signals using discrete wavelet techniques (DWT) [11 – 14]. The non-local wavelet transform based filter algorithm was proposed in [15], for the denoising of ECG signals. An extended Kalman filter structure was proposed for the denoising and compression of the ECG signal in [16]. In [17], a nonlinear Bayesian filtering algorithm was given for the denoising of ECG signals. Different neural network based algorithms were proposed for arrhythmia classification and denoising of ECG signals in [18, 19]. Basically, DWT and neural network based algorithms are used for the pre-processing of ECG signals for arrhythmia classification.

However, many of the algorithm designs concentrate on the removal of one type of noise at a time. In this paper, a multiband filter is designed to remove all the dominant noises from the ECG database simultaneously, with its implementation on FPGA. The high speed, low cost and reconfigurable features of the FPGA have proved to be a better platform for the implementation of digital filter designs for ECG signal processing [5, 20 – 25]. In [26], an attempt was made to design a multiband filter for simulated ECG signals and noises of the order of 1500. In [27], a simulation based multiband filter was designed, whereas the proposed multiband filter design structure has provided better attenuation of noises with a lower filter order. Moreover, the proposed filter design is validated on distinct samples of ECG and the main contributions are:

– It avoids the need for the cascade design of Lowpass, Highpass, and Bandstop Filter.
– It simultaneously removes powerline interference (PLI) with its harmonics, baseline wandering (BW), motion artefact (MA) and high frequency (HF) noises from ECG signals.
– A lower order and simple multiband structure is proposed.
– Power spectrum analysis is used to verify the effectiveness of the proposed multiband filter design for the processing of ECG signals.
– The feasibility of the proposed design is verified by implementing the FPGA.

This paper is organised as: Section 2 discusses the multiband filter design structure, Section 3 describes the experimental results with the ECG database, simulation results, multiband filter, and hardware implementation and Section 4 presents the discussion. Finally, Section 5 concludes the work.

2 Multiband Filter Design

The ability of a multiband filter to reject more than one frequency band from the frequency spectrum of the signal makes it more suitable to simultaneously eliminate multiple noises from the ECG signal. In this research, a noisy ECG signal is considered with PLI, BW and MA noises in the low frequency range and other HF noises. Here, the noisy ECG signal $ECG_n(n)$ is represented as:

$$ECG_n(n) = ECG_f(n) + N_{ECG}(n), \tag{1}$$

where $ECG_f(n)$ represents the filtered ECG signal and $N_{ECG}(n)$ represents noises in the ECG. Here, $ECG(n)$ is defined as:

$$N_{ECG}(n) = N_{BW}(n) + N_{MA}(n) + N_{PLI}(n) + N_{HF}(n), \tag{2}$$

where $N_{BW}(n)$, $N_{MA}(n)$ and $N_{HF}(n)$ are BW, MA and HF noises, respectively. $N_{PLI}(n)$ is considered to be 50 Hz PLI noise with harmonics and is defined as:

$$N_{PLI}(n) = \sum_{p=1}^{H} A_p(n) \sin\left(2\pi p \frac{f_0}{f_s} n + \varphi_p\right), \tag{3}$$

where A_p and φ_p are the amplitude and phase of the p^{th} harmonic component, H represents the total number of harmonics, f_0 is the 50 Hz fundamental frequency, and f_s denotes the sampling frequency. The multiband filter provides the flexibility to remove $N_{ECG}(n)$ having a different frequency band in a single design. The FIR-based multiband filter is preferred due to its linear phase relationship and better stability [28]. The FIR-filtered ECG output $ECG_f(n)$ is obtained from the convolution of impulse response $h_f(k)$ of the proposed filter with the noisy ECG input $ECG_n(n)$ and is given as:

$$ECG_f(n) = \sum_{k=0}^{N-1} h_f(k) ECG_n(n-k), \tag{4}$$

where k represents the number of impulse response samples for the filter, represents the number of input ECG samples and $N-1$ gives the order of the FIR filter.

The frequency response of $h_f(k)$ is defined as:

$$H_f(\omega) = \sum_{k=0}^{N-1} h_f(k)\, e^{-j\omega k}. \tag{5}$$

The desired multiband filter frequency response is defined as $H_{df}(\omega)$. In this research, a least squared algorithm is used to minimise the error function, defined as:

$$E = \sum_{l=0}^{M-1} \left| H_f(\omega_l) - H_{df}(\omega_l) \right|^2, \tag{6}$$

where $H_{df}(\omega_l)$ are M samples of desired response and $\omega_l = 2\pi l / M$. The selection of the M sample should satisfy the condition $M \gg N$. Now, (5) is redefined on the frequency grid ω_l as:

$$H_f(\omega_l) = \sum_{k=0}^{N-1} h_f(k)\; e^{-j\omega_l k}, \quad l = 0,1,2,\ldots,M. \tag{7}$$

Here, the linear phase FIR filter, with an even symmetry type-I, is used to design the multiband filter structure. Therefore, the frequency response in (7) is represented as a sum of the cosines, i.e.

$$H_f(\omega_l) = h(0) + 2 \sum_{k=0}^{(N-1)/2} h(k) \cos(\omega_l k). \tag{8}$$

Here, by the optimisation of the function given in (6), the coefficients for the designed filter are obtained.

In this work, the multiband filter is designed for the given magnitude versus frequency response shown in Fig. 1.

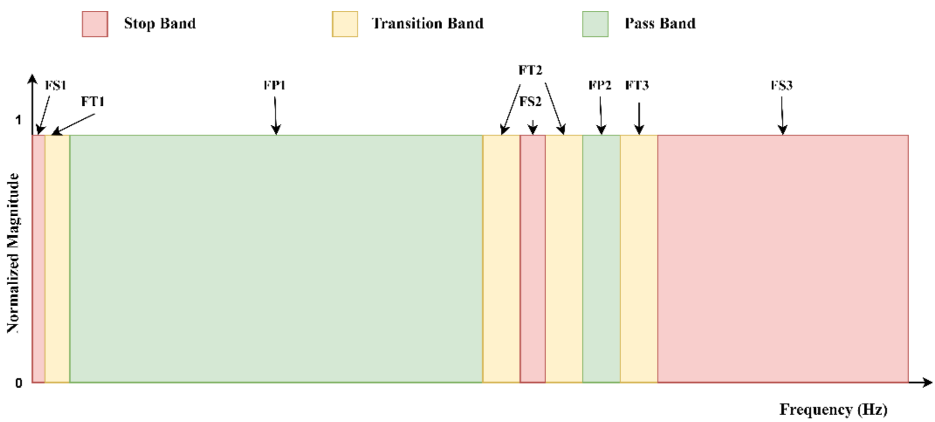

Fig. 1 – *Multiband amplitude response with stopband and passband.*

In Fig. 1, different bands are designed based on the frequency of noises present in the ECG signal and details of the bands are as follows:

Filter stop bands:

FS1: (0.0-0.5 Hz) BW and MA noises stop band;

FS2: (49-51 Hz) Power supply Interference signal stop band;

FS3: (62-250 Hz) HF noise and power supply harmonics stop band out of the ECG signal band.

Filter Transition bands:

FT1: 0.5-1.5 Hz;

FT2: 45-49, 51-55 Hz;

FT3: 59-62 Hz.

Filter Pass bands:

FP1:1.5-45.0 Hz;

FP2:55-59 Hz.

In **Table 1**, the details of the multiband filter design, with different corner frequencies and attenuation levels, are given. The noisy ECG input signal has a sampling frequency of 500 Hz and duration of 10 s. For the processing of a given input ECG signal, the specifications of the proposed multiband digital filter design are given in **Table 2**.

Table 1

Multiband filter corner frequency and attenuation level.

SUB-SECTION OF MULTIBAND FILTER	CORNER FREQUENCY [Hz]	ATTENUATION LEVEL [dB]
High pass filter	0.5	-55.0
Low pass filter	62.0	-50.0
Stop band filter	49.0–51.0	-45.0

Table 2

Specifications of multiband filter.

PARAMETERS	VALUE
Filter sampling frequency (f_s)	500 Hz
Number of input samples (n)	5000
FIR filter order ($N - 1$)	350
Input Signal (ECG_n) bit length	12 bits
Filter Coefficients bit length	12 bits
Optimising algorithm	Least square
FIR filter structure	Direct form symmetric

3 Experimental Results

In this study, a Matlab R2019b platform was used to process the noisy ECG input signal with a design and synthesis multiband filter. The multiband filter design was validated in ModelSim software and implemented on FPGA using Xilinx 14.7, as mentioned in the schematic represented in Fig. 2.

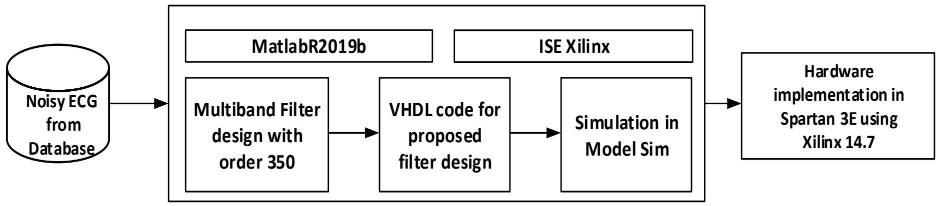

Fig. 2 – *Schematic view for multiband filter implementation.*

3.1 ECG database

In this work, the noisy ECG signals are taken from the Physionet website [29] ECG ID database. Tatiana Lugovaya provides this database for the use of researchers and scientists [30]. A total of 310 ECG recordings are included, which were obtained from 44 men and 46 women of different age groups, from 13 to 75 years. For each person, a different number of records was collected over a period of time, varying from one day to six months. The signal is digitized with a sampling time of 0.02 s. The ECG signal available in the database was quantized using an ADC of 12 bits with an amplitude resolution of 200 adu/mV in the range of ±10 mV. The noisy ECG signals contained high frequency noise, as well as low frequency noise components. In each record, the noisy ECG signal was referred to as signal 0 and the filtered ECG signal was referred to as signal 1.

The ECG signals captured by the electrodes are contaminated with various types of interference signal: EMG noise captured by electrodes along with ECG, BW noise due to the movement of the electrode, MA noise due to respiration as well as patient movements, and PLI noise due to the power supply around 50Hz along with its harmonics. For the experimental investigation, ten cases with different noise levels were considered from the database. In Fig. 3, the waveform of a noisy ECG signal, with respect to time, is given for four of the cases. As shown in Fig. 3a and Fig. 3b, case-2 has more high frequency noises while, case-7 has more low frequency noises. Fig. 3c and Fig. 3d show that the ECG signal contains less noise compared to the aforementioned cases.

The frequency spectrums of noisy ECG signals for four cases are given in Fig. 4. The amplitude of power is in dBm, with respect to frequency. The detail of the ten cases, along with noise amplitude measurements from the Power spectrum, is given in **Table 3**.

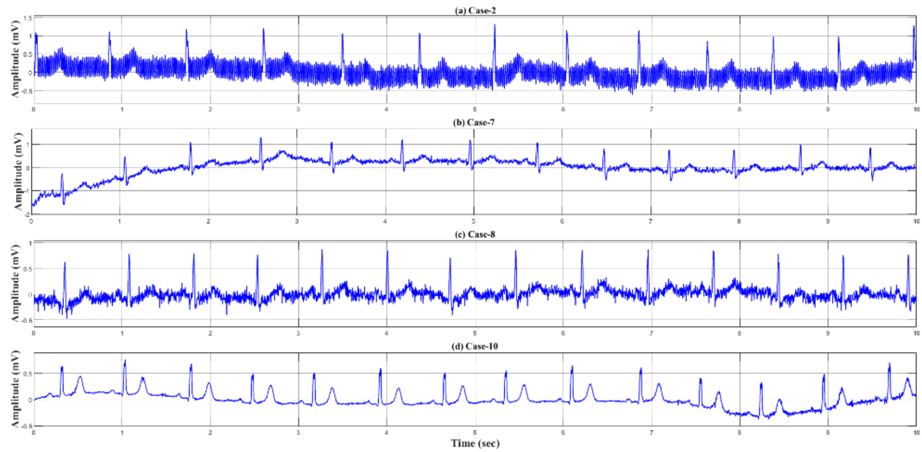

Fig. 3 – *Noisy ECG signals for:* (a) Case-2;
(b) Case-7; (c) Case-8; (d) Case-10.

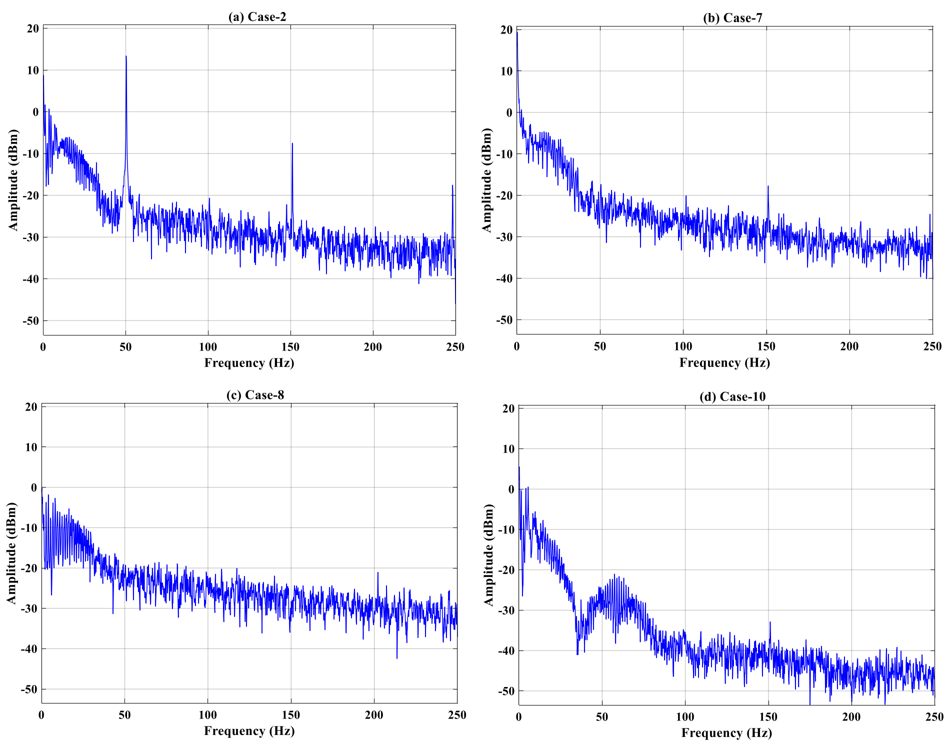

Fig. 4 – *Noisy ECG frequency spectrum for:*
(a) Case-2; (b) Case-7; (c) Case-8; (d) Case-10.

Table 3
Noise amplitudes in raw ECG using power spectrum analysis.

CASE	DATABASE RECORDING	AGE	GENDER	BW		MA		PLI		HF >60Hz
				Amplitude [dBm]	Frequency [Hz]	Amplitude [dBm]	Frequency [Hz]	Amplitude [dBm]	Frequency [Hz]	Amplitude [dBm]
1	Person 1.1	25	Male	1.99	0.48	2.90	1.13	–10.71	50.29	–45
2	Person 3.3	23	Female	8.73	0.16	1.67	1.13	13.36	50.29	–30
3	Person 13.1	51	Male	10.47	0.16	2.00	0.97	6.24	50.29	–40
4	Person 24.2	46	Female	10.40	0.16	1.99	1.30	10.12	50.29	–30
5	Person 25.3	48	Male	11.50	0.16	1.29	1.13	7.84	50.29	–35
6	Person 26.4	31	Female	7.27	0.16	–2.18	1.13	–4.07	50.45	–45
7	Person 33.1	59	Male	19.31	0.16	3.27	1.30	–17.36	50.45	–30
8	Person 45.1	75	Male	-0.11	0.16	–6.74	1.30	–19.28	50.45	–30
9	Person 50.2	19	Male	10.56	0.16	–1.13	1.62	–1.85	50.29	–30
10	Person 60.1	16	Female	5.52	0.16	–0.34	1.30	–24.92	50.45	–45

3.2 Simulation result of multiband filter

The multiband filter was designed to remove the noises mentioned in (2) from the ECG signal represented by (1). Simulation of a multiband filter was carried out in a MATLABR2019b environment. The multiband FIR filter coefficients were calculated with the given specification in **Tables 1** and **2,** using a Filter Designer tool. The filtered ECG response was obtained by the convolution of the impulse response of the designed Multiband filter with the noisy ECG input signal. The filtered ECG response in the time domain for four cases is given in Fig. 5. The frequency spectrum of the filtered ECG signal is given in Fig. 6, for all four cases.

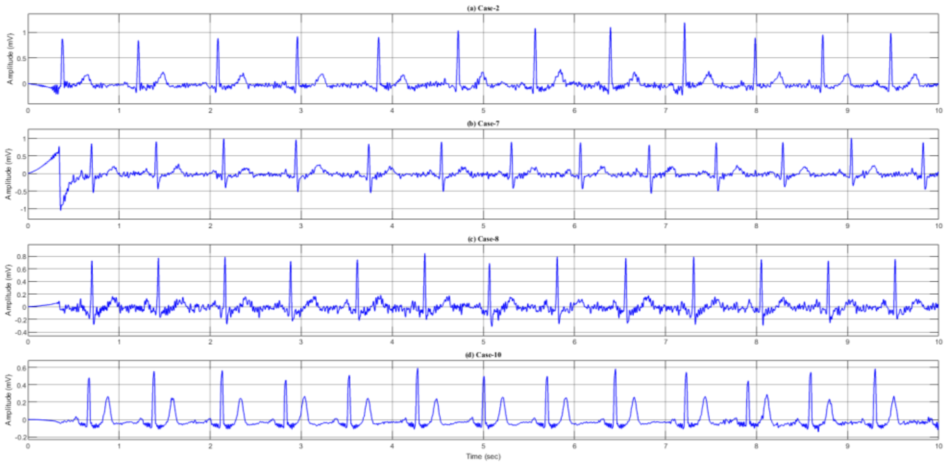

Fig. 5 – *Filtered ECG signal using multiband:*
(a) Case-2; (b) Case-7; (c) Case-8; (d) Case-10.

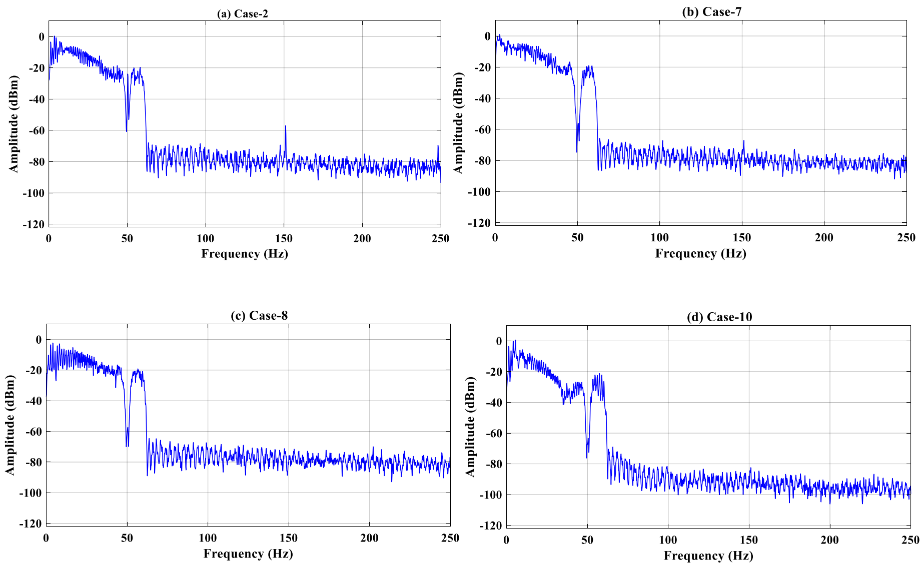

Fig. 6 – *Filtered ECG frequency spectrum for:*
(a) Case-2; (b) Case-7; (c) Case-8; (d) Case-10.

3.3 Hardware implementation

The proposed multiband filter was synthesised with Xilinx 14.7, targeting a FPGA Spartan 3E series device using VHSIC-HDL (Very High Speed Integrated Circuit Hardware Description Language). In this design, the direct form symmetric structure was used to implement the proposed multiband FIR filter design on FPGA. The filter coefficients and input sample data were quantised by 12 bits to improve resource usage and execution time. In this work, partial serial architecture was used to synthesise the proposed design on hardware with a 10 ns clock period. The proposed filter hardware design was tested for noisy ECG signals in the ModelSim simulator and the results for case-2 are shown in Fig. 7. From a visual inspection of Fig. 7, the noises present in ECG are filtered by FPGA with a linear time delay. The resource utilisation summary of the proposed architecture for the FPGA is provided in **Table 4**. The multiband filter utilises slice Flip Flops of 5292 out of 9312, 4 input LUTs of 4039 out of 9312 and 19 multipliers out of 20. The maximum frequency obtained was 61.596 MHz for multiband filter synthesis.

Table 4
Resource Utilisation Summary of FPGA.

LOGIC UTILISATION	USED	AVAILABLE	PERCENTAGE UTILISATION
Number of Slices:	3973	4656	85%
Number of Slice Flip Flops:	5292	9312	56%
Number of 4 input LUTs:	4039	9312	43%
Number of bonded IOBs:	41	232	17%
Number of MULT18X18SIOs:	19	20	95%
Number of GCLKs:	1	24	4%

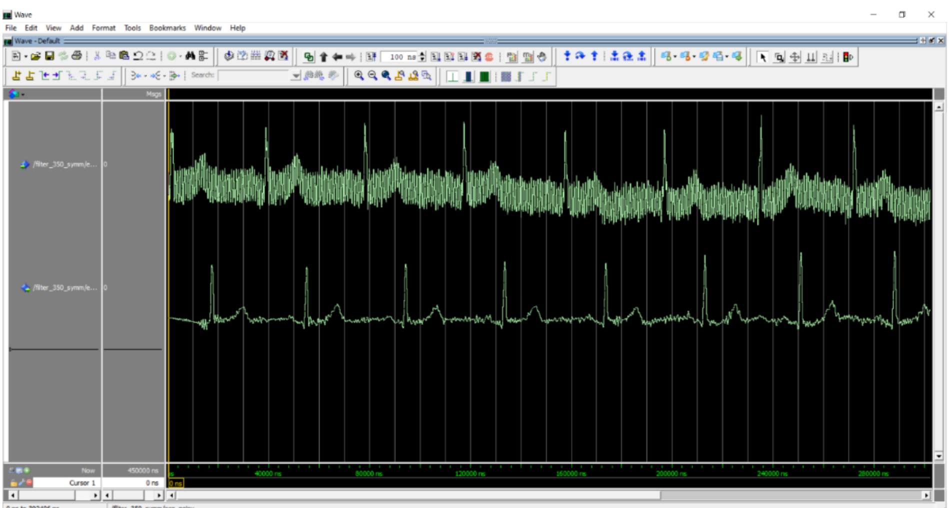

Fig. 7 – *ModelSim simulator waveform of noisy input and output filtered ECG for* Case-2.

4 Discussion

The performance of the designed multiband filter is validated for10 different cases with different levels of noise. The noise amplitude of the filtered ECG signal, along with the attenuation level using the proposed multiband filter design, is given in **Table 5**. For this investigation, the noisy input signals are selected with BW noise amplitudes varying from -0.1 dBm to 19.0 dBm and PLI noise amplitude varies from -25 dBm to 13 dBm. The average attenuation level of BW, MA and PLI noise were obtained as 34 dBm, 5 dBm and 38 dBm, respectively. The HF noises above 60 Hz were filtered with attenuation levels of 50 dBm. As in **Table 5**, the performance of the multiband filter to attenuate a wide range of noise amplitudes is found to be consistent. In **Table 6,** a performance comparison is given for the developed ECG filter algorithm and those implemented by other researchers for different types of noise. In this work, the inherently corrupted noisy ECG recorded database is used, as compared to the simulated database used by researchers in [5, 6, 21, 26]. The proposed filter is able to remove additional BW and MA noise, while in [5, 6], only PLI and HF noises are considered. The proposed multiband filter structure is designed with a 350 order multiband filter design, compared to the 1500 order multiband filter design in [26].

Table 5
Noise amplitude in filtered ECG and attenuation level.

CASE	NOISE AMPLITUDE IN FILTERED ECG [dBm]				ATTENUATION LEVEL [dBm]			
	BW	MA	PLI	HF noises (> 60 Hz)	BW	MA	PLI	HF noises (> 60 Hz)
1	–16.14	–3.28	–47.95	–95	18.13	6.18	37.23	50
2	–28.02	–3.44	–23.93	–80	36.75	5.12	37.29	50
3	–26.97	–5.69	–31.11	–90	37.44	7.69	37.36	50
4	–27.01	–1.68	–27.04	–80	37.41	3.67	37.16	50
5	–23.30	–3.66	–29.36	–85	34.80	4.96	37.21	50
6	–29.35	–7.24	–41.71	–95	36.62	5.06	37.64	50
7	–17.64	–0.32	–56.10	–80	36.96	3.60	38.74	50
8	–36.00	–10.23	–57.37	–80	35.88	3.49	38.08	50
9	–17.92	–2.88	–39.28	–80	28.49	1.74	37.42	50
10	–31.10	–3.58	–63.28	–90	36.62	3.24	38.36	50

Table 6
Performance Comparison.

PARAMETER	PROPOSED FILTER	Ref. [6]	Ref. [26]	Ref. [21]	Ref. [5]
ECG database	ECG ID Database	MIT-BIH polysomnographic database (http://www.physionet.org/cgi-bin/atm/ATM)	Direct Digital Frequency Synthesisers (DDFS)	Real time ECG from lead I	Function generator HP 33120A
Noisy Database	Inherent corrupted noisy database from [29]	Simulated PLI	Direct Digital Frequency Synthesisers (DDFS)	External added PLI and white Gaussian noise	Function generator HP 33120A
BW and MA removal	BW and MA removed	Not considered	BW and MA removed	BW removed	Not considered
Sampling Frequency	500 Hz	250 Hz	1000 Hz	Varies from (0-12800) Hz	1000 Hz
Hardware Implementation	3s500efg320-5	Not considered	CycloneIIEP2C70F896C6F PGA, Altera	XC3S2000FG456-4	XC4010E-1-PC84

5 Conclusion

In this work, a multiband filter design is proposed for the records of the ECG database, which has inherent noise. The proposed multiband filter simultaneously removes PLI, BW, MA and HF noises. The results given in **Table 5** validate the performance efficiency of the proposed multiband filter. The filter design has been implemented on the FPGA3s500efg320-5 device with partial serial architecture and direct form symmetric structure. The proposed multiband filter design has a low order, simple structure, the capability to deal with a wide range of noise levels, good attenuation levels for the removal of noise and the implementation of FPGA.

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