Journal of Rare Cardiovascular Diseases
ISSN: 2299-3711 (Print) | e-ISSN: 2300-5505 (Online)
www.jrcd.eu
RESEARCH ARTICLE

FPGA Implementation of FIR Filter for ECG Signal Denoising using Blackman Window

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Article History
Received: 02/10/2025
Revised: 31/10/2025
Accepted: 08/11/2025
Published: 16/11/2025

Abstract: Electrocardiogram (ECG) signals are often contam- inated by noise sources such as powerline interference, baseline wander, and muscle artifacts that can obscure important cardiac information and impair diagnosis. In this article, we propose an efficient hardware-based FIR filter with a Blackman window for removing noise from ECG signals. The proposed filter utilizes Dadda multipliers, Carry Save Adders (CSA), and D Flip-Flops to enhance computational efficiency and lower energy consumption. We constructed a 21-tap direct form FIR filter and cascaded it with a three-stage notch filter capable of removing powerline interference while preserving the important diagnostic features of ECG data such as P, QRS, and T waves. The FIR filter was designed in Verilog HDL and synthesised on the Xilinx Kintex- 7 FPGA. The implementation demonstrates excellent timing performance with poor violations and adequate thermal margins. This is highly applicable to portable biomedical monitoring systems.Index Terms—ECG denoising, FIR filter, Blackman window, Dadda multiplier, FPGA implementation, biomedical signal pro- cessing.

Keywords: ECG denoising, FIR filter, Blackman window, FPGA implementation, Dadda multiplier

INTRODUCTION

ECG signals are a crucial source of diagnostic information about cardiac health by monitoring electrical activities of the heart. ECG signal data, however, is commonly corrupted by a multitude of noise sources, such as power-line interference (50 Hz/60 Hz), baseline wander (0.05 Hz to 2 Hz), electromyo- graphic (EMG) artifacts, and electrode motion artifacts [1]. All of these interferences have the potential to obscure valuable diagnostic information and consequently misguide clinical interpretations of cardiac status.

ECG signals are indicated to have amplitudes in the range of 10 µV to 5 µV and frequency information from 0.05 Hz to 100 Hz [2]. The P wave denotes atrial depolarization, the QRS complex denotes ventricular depolarization, and the T wave denotes ventricular repolarization. The integrity of the morphology of the three waves must be preserved, and interferences must be removed, for a right clinical diagnosis is to take place. ECG signals are important for assessing the electrical ac- tivity of the heart and are a cornerstone in the diagnosis of various cardiac pathologies. Additionally, ECG signals provide accurate real-time information about the heart rate, rhythm, and waveform abnormalities by which the clinician can promptly ascertain other issues, such as arrhythmias, ischemia, and myocardial infarction. Due to the non-invasive and easily acquired nature of ECG signals, ECG signals are often adopted for routine monitoring of cardiac health in research and clinical environments.
Moreover, the evaluation of ECG data provides the ground- work for an automated method for the detection of cardiac disorders, enhancing patients' care, and decreasing the time to diagnosis. For these reasons, ECG signal processing is a key foundation of modern biomedical engineering and health care technologies.

ECG signals are often contaminated by all types of noise, which act to compromise the true cardiac waveform and affect diagnostic accuracy. Examples of sources include power line interference (normally at 50 or 60 Hz) from electrical equipment located proximally, baseline wander (the ECG moves up and down) from patient movement or breathing, and muscle artifacts (from voluntary or involuntary movement). Along with electrode contact noise, and motion artifact that occurs when skin-electrode contact is poor, and/or the patient's position is altered during the recording. There are electro- magnetic interference coming from medical instruments, or mobile electronic devices that can affect the quality of our signal. Thus, development of filtering and signal processing methods is critical in detecting true data for utilization in clinical interpretation.

Digital filtering techniques, particularly Finite Impulse Re-
sponse (FIR) filters, have proven to be effective alterna- tives for denoising ECG signals due to their stability, linear phase response, and well-established theoretical foundation. FIR filters offer several key advantages, including guaranteed stability regardless of the coefficient magnitudes, a linear phase response that preserves the morphology of the signal, a finite impulse response that prevents oscillations, and a straightforward hardware implementation.

The mathematical representation of an FIR filter is given by:

$$y[n]=\sum_{k=0}^{n-1} h[k] \,.x[n-k] \qquad (1)$$

where y[n] is the filtered output, x[n] is the input signal, h[k] are the filter coefficients, and N is the filter order.

In the proposed FIR filter, a direct form low pass FIR filter with the least amount of latency and power consumption is developed with a focus on real-time processing requirements of a digital signal. Filter coefficients are generated by utilizing the Blackman Window function in the MATLAB Filter Design

Bahoura and Hassani mapped the use of Blackman-Harris windows for suppressing powerline interference using narrow- band notch filters where high attenuation was attained with minimal distortion of the QRS [8].

and Analysis (FDA) tool. Due to flexibility in filter design to design a filter with the desired frequency response, passband ripple, and stopband attenuation, Blackman window-based

$w[n] = 0.42 - 0.5 \cos$

$2\pi n \;\; N - 1$

$+ 0.08 \cos$

$4\pi n \;\; N - 1$

(2)

filter design has been used for ECG denoising purposes in this work. The design furthermore uses advanced arithmetic units such as Dadda multipliers for multiplying and Carry Save Adders for accumulating, optimized to improve design efficiency.

LITERATURE REVIEW

A number researchers have used FIR filter-based methods to denoise the ECG, focusing on window functions and hardware level optimization approaches.

Hamilton et al. showed that band-pass FIR filters are effective at removing noise components associated with a frequency range of 0.5 Hz - 100 Hz, and pointed to the importance of considering linear phase response to preserve the morphology of the waveforms [4]. Acharya et al. described an improved methodology through modular and multistage FIR designs with improved Signal-to-Noise Ratio (SNR) and artifact suppression in ambulatory ECG recordings [5].

Additionally, researchers have examined using baseline wander and powerline interference as targets for improvement when pre-processing ECG data. High-pass FIR filters with a cut-off frequency of approximately 0.5 Hz are often utilized to reduce baseline wander with the exception of overly degrading expected low-frequency cardiac information.

Adaptive filtering and polynomial fitting techniques have been examined as options for drift correction. When address- ing powerline interference, notch filters or adaptive noise cancellers are often used to remove the 50/60 Hz components of the signal. The application of notch filters must be evaluated closely, so as to avoid any distortion in the QRS complex, which is often comprised of overlapping or interfering fre- quencies.

With this consideration in mind, it was shown that the use of a low-pass/band-limiting FIR Filter with a notch filter may successfully eliminate baseline drift and powerline interfer- ence, while maintaining validity in diagnostic signals. This led to the selection of the Blackman-window FIR filter with a three-tap notch filter in this work.

The choice of window functions has been explicitly stud- ied for ECG applications. Gupta et al. examined several windows, such as the Hamming, Hanning, Blackman, and Kaiser windows, and concluded that the Blackman window exhibited the greatest noise suppression as a result of better high-frequency attenuation and lower spectral leakage [6]. Issues related to the hardware efficiency led some work on efficient hardware implementations of PCR. Kaur and Saini proposed efficient multiplier architectures in low-power FIR filters that featured reduced critical path delay and power [7].

where n = 0, 1, . . . , N − 1 and N is the window length.

METHODOLOGY

A. Filter Design Specifications

The proposed ECG denoising system is designed using a 21-tap transposed direct form FIR filter cascaded with a three- tap notch filter to effectively remove noise and interference from ECG signals. The main FIR filter is a low-pass filter designed using the Blackman window method, with a cutoff frequency of 40 Hz to retain the essential ECG components while suppressing high-frequency noise. The system operates at a sampling frequency of 1000 Hz, ensuring accurate signal representation. To mitigate power line interference at 50 Hz, a three-tap notch filter is cascaded with the main FIR filter, resulting in a clean and reliable ECG signal suitable for medical analysis and diagnostic applications.

B. Arithmetic Unit Selection

The hardware implementation will utilize optimized arith- metic components selected based on performance comparison study.

1) Dadda Multiplier: The Dadda multiplier represents an efficient hardware based binary multiplication method, which is commonly used in digital signal processing implementa- tions, such as FPGAs, because of the best area and speed trade- off. It

reduces the partial product matrix in an efficient manner based on a minimum number of full and half adders in a series of reduction (Dadda reduction) steps. In this method, as compared to Wallace multiplier, Dadda delays some reductions to some future step to keep the number of adders minimum. Therefore, this approach decreases the overall critical path delay and hardware complexity. It results in efficient and high-speed multiplication circuits, which are well-suited for high throughput computing and enables efficient execution of FIR filters and other multiply-intensive algorithms in resource- constrained hardware.

2) Carry Save Adder: Carry Save Adder (CSA) is a basic arithmetic module designed to add three or more binary numbers simultaneously without propagating carries through the operation, thus speeding up multi-operand addition. Carry Save Adders produce two outputs, one as a partial sum and the other as a carry vector, both of which can be added in a future step.The carry-save notation avoids the time cost of carry propagation inherent to regular adders and thus is ideal for an efficient summation of the partial products in multipliers and accumulations of multiple filter tap outputs in FIR designs. By integrating CSA trees into the arithmetic pipeline, systems achieve substantial gains in clock frequency and power effi- ciency—important for real-time biomedical signal processing on FPGA platforms.

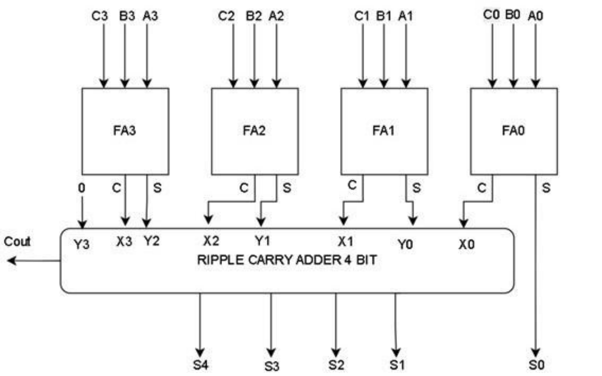

Fig. 1: Block diagram of Carry save adder

C. Filter Coefficient Generation

The Blackman window function, believed to offer the most sidelobe rejection of any commonly used window function and nearly eliminating spectral leakage, is well-suited for empirical denoising of ECG signals where low frequency morphological features must be preserved while high-frequency noise com- ponents are attenuated. While the Blackman window will has wider main lobe than the Hanning or Hamming window, the loss of frequency resolution is acceptable for this biomedical signal analysis application.

This compromise between main lobe width and sidelobe reduction means that the Blackman window offers great sup- pression of out-of-band noise components, which we rely on to minimize ECG artifacts such as muscle noise, whilst preserving the low-frequency information associated with P, QRS and T waves. While the narrower main lobe of other windows, including Hamming, results for a slightly better frequency resolution, this comes at an increased risk of side- lobe leakage that could allow more high-frequency artifacts to pass through the filter. Recent comparative studies found the Blackman window to be superior for biomedical filtering because of its ability to eliminate further baseline noise and reduce false wave detection, despite needing a marginally longer filter length to achieve the same transition width. Thus, the Blackman-windowed FIR design is a reasonable compromise between time-domain accuracy, and frequency- domain selectivity in challenging noise environments when it comes to ECG.

To create the filter coefficients, MATLAB’s Filter Design and Analysis (FDA) tool was used to develop the coefficients with the Blackman window applied. The Blackman window is a widely used FIR window providing strong stopband attenuation and reduced spectral leakage in filter design. It employs fixed cosine coefficients, yielding a smooth taper, a first sidelobe near 58 dB, and wider transition bands; sym- metric FIRs achieve near-linear phase, preserving waveform morphology in practical applications.

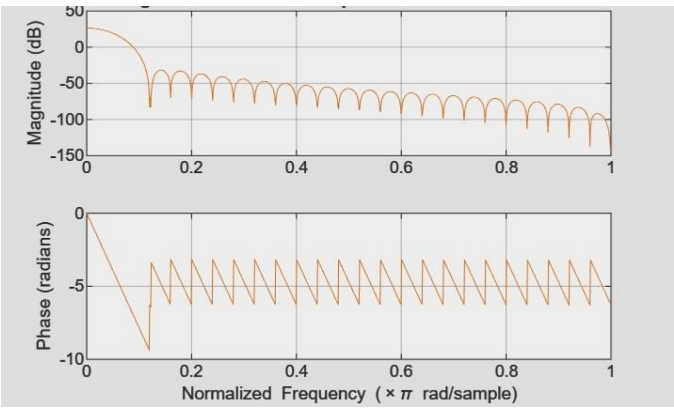

Fig. 2: Magnitude and phase Response of Blackman Window

The Blackman-window FIR filter is a 21-tap filter that is pri- marily designed to counteract baseline wander by attenuating very low-frequency components without distortion of cardiac waveforms.

The 40 Hz cutoff allows diagnostic frequency bands like the QRS complex (up to 30 Hz) to remain intact. The 3-tap notch filter was employed to address the narrowband 50 Hz powerline interference with sharp attenuation and no distortion. These two stages were cascaded to remove baseline drift and mains interference enhancing the quality of the signal for clinical evaluation.

D. Hardware Architecture

The implementation follows a direct form FIR structure as shown in Figure 3.

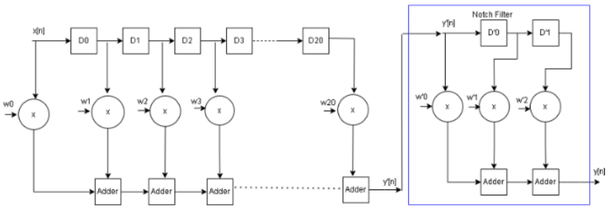

Fig. 3: Direct Form FIR Filter Architecture with Cascaded Notch Filter

The architecture of the ECG denoising system consists of 21 delay elements implemented using D flip-flops for storing input samples, and 21 Dadda multipliers used for performing coefficient multiplication in the FIR filtering process. The partial products generated by the multipliers are accumulated through a cascade of carry save adders, ensuring efficient and high-speed computation. Additionally, a three-tap notch filter is cascaded with the main filter to effectively eliminate powerline interference, thereby enhancing the overall signal quality and ensuring accurate ECG waveform reconstruction.

The transfer function of the complete system can be expressed as:

TABLE I: FPGA Implementation Results

H(z) = HF IR(z) · Hnotch(z) (3)
where HF IR(z) represents the main lowpass filter and Hnotch(z) represents the notch filter for removal of powerline interference.

RESULTS AND ANALYSIS

A. Signal Processing Performance

The denoising effectiveness was tested using ECG signals that were knowingly corrupted with both baseline wander and powerline interference. The filter effectively removed slow-varying baseline drift while rejecting the narrowband 50 Hz interference to allow clear visibility of P waves, and QRS complex, and T waves. Thus in its dual-stage filtering structure, the filter was able to handle both low-frequency and narrowband sources of noise, which are prevalent in both ambulatory and clinical ECG records.

The FIR filter was tested with synthetic generated ECG signals, with added noise components. Performance metrics were derived as:
Signal-to-Noise Ratio (SNR):

Timing Performance

$$\mathrm{SNR}_{dB} = 10\log_{10}\frac{P_{signal}}{P_{noise}} \quad (4)$$

Mean Squared Error (MSE):

$$\mathrm{MSE} = \frac{1}{N}\sum_{i=1}^{N}(S_{original}[i] - S_{filtered}[i])^2$$

The filtering results demonstrate strong performance, achieving an output signal-to-noise ratio (SNR) of 22.47 dB, indicating a significant improvement in signal quality. The mean squared error (MSE) was found to be 6.2944, confirming the accuracy and stability of the filtering process. In addition, the design effectively suppressed noise in all target frequency bands, ensuring that the essential characteristics of the ECG signal were preserved while minimizing unwanted distortions.

B. FPGA Implementation Results

The design was synthesized on Xilinx Kintex-7 FPGA (xc7k70tfbv676-1) with the resource utilization and performance metrics shown in Table I.

C. Performance Analysis

Several aspects demonstrate that the implementation is highly efficient. The design exhibits strong resource efficiency, utilizing only a small portion of the available FPGA resources, which leaves ample room for incorporating additional hard- ware capabilities or keeping them reserved for future system requirements. In terms of timing performance, the design achieves a high level of timing closure, as indicated by a marginally acceptable negative slack, and it can even support higher clock frequencies if required. The power efficiency of the system is notable, with an overall consumption of just 0.231 W, making it well-suited for portable or battery-powered

TABLE I: FPGA Implementation Results

Worst Negative Slack	2.248 ns	–
Worst Hold Slack	0.064 ns	–
Timing	Endpoints 1623/1623 100%	Met

Power Analysis

Total	On-Chip	0.231 W	–

Power		
Dynamic Power	0.150 W	65%
Static Power	0.081 W	35%
Junction Temperature	25.4 °C	–
Thermal Margin	59.6 °C	–

Resource/Metric	Utilization	Percentage
LUTs	2737/41000	6.68%
Flip-Flops	1607/82000	1.96%
I/O Pins	82/300	27.33%
LUTRAM	–	0.02%

devices. Furthermore, the thermal performance is impressive, with a junction temperature of 25.4°C and a thermal margin of 59.6°C, ensuring reliable operation across a wide range of environmental conditions.

D. Visualization of Filtered Output

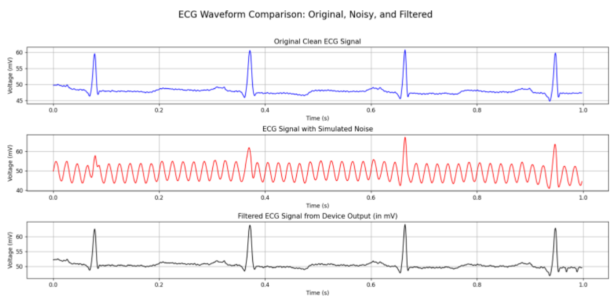

Fig. 4: Comparison of ECG signals: (a) Original clean input,

Noisy input with baseline wander and powerline interfer- ence, (c) Denoised output from FPGA implementation.

DISCUSSION

In summary, we have successfully completed a FIR filter design implementation which solves the problem of ECG signal denoising at the same time showing adequate perfor- mance in hardware. Pointed out below are the most important contributions:

Algorithm Effectiveness

The design based on the Blackman Window is able to keep ECG morphologies with an acceptable amount of noise artifacts. The 22.47 dB SNR shows an improved denoising quality from noisy input signals.

B. Hardware Optimization

Dadda multipliers and carry save adders exhibit an optimal trade-off between performance, area, and power requirement. The choice of a modular design facilitates all combinations of filter order and applications to be tackled.

The design's low resource utilization and minimal power consumption make it highly suitable for practical biomedical applications. It can be effectively integrated into portable ECG monitoring devices and wearable health sensors, where energy efficiency and compactness are essential. Furthermore, its capability for real-time signal processing makes it ideal for continuous cardiac monitoring systems. The design also holds strong potential for telemedicine applications, enabling remote and reliable patient monitoring with reduced hardware and power requirements.

CONCLUSION

This work presents a complete FPGA implementation of an FIR filter for ECG signal denoising using the Black- man windowing function. The design effectively balances algorithmic performance with hardware efficiency, achieving substantial noise suppression with minimal resource usage and low power consumption. Its robust timing performance and modular structure make it well-suited for portable, real- time biomedical applications and scalable for future signal processing enhancements.

FUTURE SCOPE

Future work can focus on incorporating adaptive filtering techniques to effectively handle time-varying noise charac- teristics in ECG signals. Another promising direction is the integration of machine learning algorithms to enable auto- mated diagnosis and enhance the accuracy of cardiac condi- tion detection. Further optimization for ultra-low-power ASIC implementations would make the system more suitable for compact and energy-efficient biomedical devices. Additionally, extending the design to support multi-lead ECG processing can improve diagnostic reliability and broaden its clinical applicability. Overall, the presented design establishes the feasibility of FPGA-based ECG signal processing for real- world biomedical applications, laying a strong foundation for the development of advanced cardiac monitoring systems.

The presented design demonstrates the viability of FPGA- based ECG signal processing for practical biomedical applica- tions, providing a foundation for advanced cardiac monitoring systems.

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