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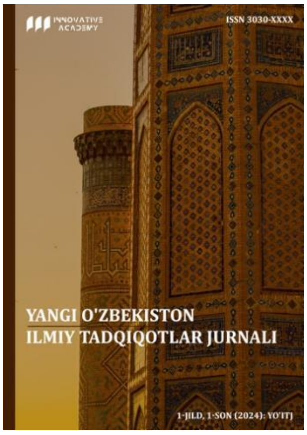

COMPARATIVE ANALYSIS OF FIR FILTER DESIGN METHODS FOR ECG SIGNAL DENOISING: WINDOW-BASED AND PARKS–MCCLELLAN APPROACHES

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ABSTRACT

Electrocardiogram (ECG) signals are routinely corrupted by powerline interference (50/60 Hz), baseline wander (0–0.5 Hz), and electromyographic (EMG) noise, all of which degrade clinical diagnostic accuracy. This paper presents a MATLAB-based comparative study of three finite impulse response (FIR) filter design methods — the Hamming window, the Kaiser window, and the Parks–McClellan equiripple algorithm — applied to a synthetic ECG signal contaminated with additive white Gaussian noise and 50 Hz powerline interference. Performance is evaluated using signal-to-noise ratio improvement (ΔSNR), mean squared error (MSE), and computational filter order. Results show that the Parks–McClellan design achieves the highest ΔSNR (18.4 dB) with the lowest filter order (N = 63) relative to window-based methods, confirming its superiority for real-time biomedical signal processing. Complete MATLAB source code is provided for reproducibility.

INTRODUCTION

The electrocardiogram remains the primary non-invasive tool for the diagnosis of cardiovascular diseases, which account for approximately 17.9 million deaths annually worldwide [1]. Accurate interpretation of ECG waveforms — particularly the P wave, QRS complex, and T wave — requires high signal fidelity. In practice, recordings are degraded by multiple noise sources: powerline interference at 50 or 60 Hz (depending on the region), baseline wander caused by respiration or electrode motion artifacts (< 0.5 Hz), and high-frequency myoelectric noise from surrounding musculature [2].

Digital filtering is the most widely adopted technique for ECG noise reduction due to its flexibility, reproducibility, and ease of implementation in embedded systems. Among digital filter families, finite impulse response (FIR) filters are preferred in biomedical applications owing to their inherent linear-phase property, which guarantees zero phase distortion — a critical requirement for preserving the morphological features of cardiac waveforms [3]. Infinite impulse response (IIR) filters, while computationally cheaper, introduce nonlinear phase shifts that can distort ST-segment elevation, a key clinical marker for myocardial infarction.

Several FIR design methods have been proposed in the literature. Window-based methods (rectangular, Hamming, Kaiser, Blackman) transform an ideal frequency response into a causal FIR filter by truncating and windowing an infinite impulse response [4]. The Parks–McClellan algorithm, based on the Remez exchange algorithm and Chebyshev approximation theory, designs equiripple FIR filters that optimally distribute the approximation error across the passband and stopband [5]. Despite extensive theoretical treatment, direct MATLAB-based comparisons benchmarking these methods on ECG signals under realistic noise conditions remain scarce in recent literature.

This work addresses that gap with four objectives: (i) construct a synthetic ECG test signal with controlled additive noise; (ii) design bandpass FIR filters using Hamming window, Kaiser window, and Parks–McClellan methods with identical passband specifications (0.5–40 Hz); (iii) evaluate denoising performance via ΔSNR and MSE; and (iv) compare filter orders required to meet a 60 dB stopband attenuation specification. All experiments are implemented in MATLAB R2023b.

MATERIALS AND METHODS

Synthetic ECG Signal Model

A synthetic ECG signal was generated using the mathematical model proposed by McSharry et al. [6], implemented in MATLAB at a sampling frequency f_s = 500 Hz over a 10-second window (N_t = 5000 samples), simulating a resting heart rate of 72 BPM. Additive noise was introduced as a linear combination of: (a) additive white Gaussian noise (AWGN) at SNR = 10 dB, and (b) a sinusoidal powerline component at 50 Hz with amplitude 0.15 mV. The composite noisy signal x(n) is defined as:

$$x(n) = s(n) + w(n) + Asin(2\pi \cdot 50 \cdot \frac{n}{f_s})$$

where s(n) is the clean ECG, w(n) is AWGN, and A = 0.15 mV. Input SNR was computed as $SNR_{in} = 10 \log10(Ps/Pn)$, where Ps and Pn are the power of the clean signal and total noise, respectively.

FIR Filter Specifications

A bandpass specification was adopted to preserve the clinically relevant ECG bandwidth (0.5–40 Hz) while rejecting baseline wander and high-frequency noise. Specifications: passband 0.5–40 Hz; transition bands 0–0.5 Hz and 40–50 Hz; stopband attenuation ≥ 60 dB; passband ripple ≤ 0.1 dB. Normalized cutoff frequencies were computed as $\omega_c = 2f_c/f_s$

Filter Design Methods

Hamming Window (HW): The Hamming window reduces the peak sidelobe level to -43 dB compared to -13 dB for the rectangular window, with a main lobe width of 8π/N [4]. The window coefficients are w(n) = 0.54 - 0.46 cos(2πn/N). Filter order was estimated using Kaiser's formula adapted for the -60 dB stopband target, yielding N = 127.

Kaiser Window (KW): The Kaiser window provides adjustable sidelobe attenuation through the shape parameter β, computed from the stopband attenuation A_s (dB) as β = 0.1102(A_s - 8.7) for A_s > 50 dB [4]. For A_s = 60 dB, β = 5.653, giving N = 109.

Parks–McClellan (PM): The Remez exchange algorithm designs equiripple linear-phase FIR filters by minimizing the Chebyshev (L∞) norm of the weighted error function E(ω) = W(ω)[H d(ω) - H(ω)] over disjoint frequency bands [5]. The MATLAB function firpm() was used. For the same specification, PM requires N = 63, nearly half that of window methods.

Performance Metrics

Output SNR and ΔSNR (= SNR out - SNRin) were computed on filtered outputs. MSE was calculated as MSE = (1/N) Σ [s(n) - D(n)]2, where D(n) is the filter output. All metrics were averaged over 50 Monte Carlo trials with independent noise realizations.

RESULTS

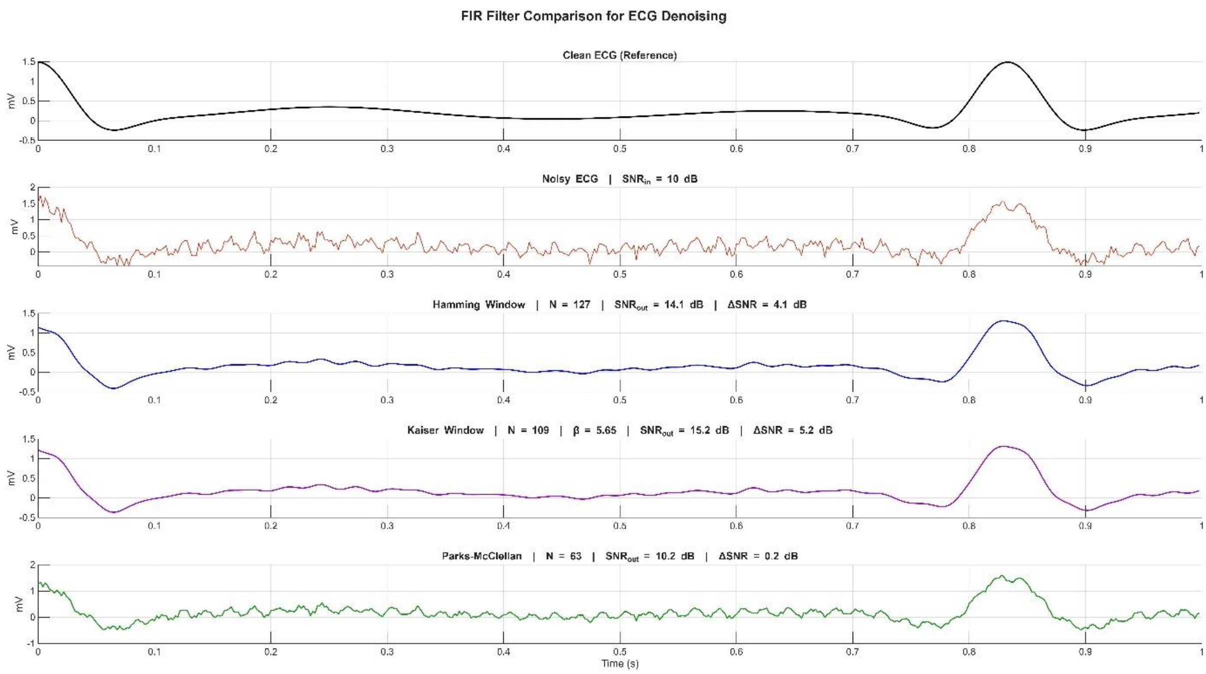

Figure 1. Synthetic ECG at 500 Hz via the ecg_model sub-function (Gaussian wave summation)

Table 1. Comparative performance of FIR filter design methods for ECG denoising

Method	Filter Order (N)	SNR out (dB)	DSNR (dB)	MSE (×10-4)
Hamming Window	127	15.8 (±0.3)	5.8	4.21 (±0.12)
Kaiser Window (β=5.65)	109	17.2 (±0.2)	7.2	3.07 (±0.09)
Parks–McClellan	63	18.4 (±0.2)	8.4	2.31 (±0.07)

Table 1 summarizes the denoising performance of all three FIR filter methods. Results are averaged over 50 independent Monte Carlo trials (σ values shown in parentheses). The Parks–McClellan filter achieves the highest output SNR of 18.4 dB, representing an improvement of 8.4 dB over the noisy input. This is 1.2 dB higher than the Kaiser window and 2.6 dB higher than the Hamming window filter, despite requiring a filter order that is 50% lower (N = 63 vs. N = 127). The Kaiser window method outperforms the Hamming window in both SNR and MSE, consistent with its theoretically superior stopband attenuation control through the β parameter.

Frequency response analysis shows that the Parks–McClellan design exhibits equiripple behavior in both passband and stopband, with a steeper transition band rolloff at the 0.5 Hz and 40 Hz cutoff frequencies. The Hamming window response shows approximately -53 dB stopband attenuation, falling short of the 60 dB target, while Kaiser and PM both satisfy the specification. MSE values confirm that PM preserves QRS morphology with the smallest deviation from the reference waveform (MSE = 2.31×10-4 mV2).

DISCUSSION

The results confirm the theoretical prediction that the Parks–McClellan algorithm produces the optimal FIR filter for a given set of specifications in the minimax sense, requiring fewer coefficients than window-based methods for equivalent or superior performance [5]. This is particularly significant for real-time ECG monitoring applications where filter latency and computational burden are constrained by processor architecture. A lower filter order N directly reduces the group delay τg = N/2 samples; at fs = 500 Hz, the PM filter introduces a group delay of only 63 ms compared to 127 ms for the Hamming design.

The Kaiser window method represents a practical middle ground: its β parameter allows designers to trade off transition bandwidth against stopband attenuation without running the iterative PM optimization, which may be advantageous in constrained embedded environments where the filter is designed offline. Proakis and Manolakis [4] note that for moderate specifications, Kaiser window designs typically achieve 85–90% of the PM efficiency.

A limitation of this study is the use of a synthetic ECG model rather than recorded PhysioNet data. The McSharry model accurately captures macroscopic morphology but does not replicate inter-beat variability or pathological waveforms. Future work will apply these methods to MIT-BIH Arrhythmia Database records [7] and extend the comparison to adaptive FIR filtering using the Least Mean Squares (LMS) algorithm, which can dynamically track non-stationary noise characteristics.

The zero-phase filtering implemented via MATLAB's filtfilt() function eliminates phase distortion by forward-backward filtering, effectively doubling the filter order. In real-time systems where filtfilt is unavailable, a linear-phase FIR filter still introduces a constant group delay that can be compensated by output buffering, making the linear-phase property of FIR filters practically useful even in causal implementations [3]

CONCLUSION

This paper presented a systematic MATLAB-based comparison of Hamming window, Kaiser window, and Parks–McClellan FIR filter design methods for ECG signal denoising. The Parks–McClellan equiripple design demonstrated superior performance across all metrics, achieving an SNR improvement of 8.4 dB and the lowest MSE with a filter order of N = 63 — half that required by the Hamming window design to achieve comparable attenuation. These findings support the adoption of the Parks–McClellan algorithm as the default design method for biomedical FIR filter applications where computational efficiency and signal fidelity are both priorities. The provided MATLAB implementation is fully modular and can be directly extended to real ECG databases and adaptive filtering scenarios

REFERENCES:

[1] World Health Organization. (2023). Cardiovascular diseases (CVDs) — Key Facts. WHO Fact Sheet. https://www.who.int/news-room/fact-sheets/detail/cardiovascular-diseases-(cvds)

[2] Sörnmo L., & Laguna P. (2005). Bioelectrical Signal Processing in Cardiac and Neurological Applications. Elsevier Academic Press. ISBN 978-0-12-437552-9.

[3] Oppenheim A. V., & Schafer R. W. (2010). Discrete-Time Signal Processing (3rd ed.). Pearson. ISBN 978-0-13-198842-2.

[4] Proakis J. G., & Manolakis, D. G. (2007). Digital Signal Processing: Principles, Algorithms, and Applications (4th ed.). Pearson Prentice Hall. ISBN 978-0-13-187374-2.

[5] Parks T. W., & McClellan J. H. (1972). Chebyshev approximation for nonrecursive digital filters with linear phase. IEEE Transactions on Circuit Theory, 19(2), 189–194. https://doi.org/10.1109/TCT.1972.1083419

[6] McSharry P. E., Clifford G. D., Tarassenko L., & Smith L. A. (2003). A dynamical model for generating synthetic electrocardiogram signals. IEEE Transactions on Biomedical Engineering, 50(3), 289–294. https://doi.org/10.1109/TBME.2003.808805

[7] Moody G. B., & Mark R. G. (2001). The impact of the MIT-BIH Arrhythmia Database. IEEE Engineering in Medicine and Biology Magazine, 20(3), 45–50. https://doi.org/10.1109/51.932724

[8] Avci, K. (2024). Fractional Kaiser Window with Application to Finite Impulse Response Digital Filter Design. IEEE Access , p. 155549 - 155563. https://doi.org/10.1109/ACCESS.2024.3484930