Removing Power Line Interference from ECG Signal Using Adaptive Filter and Notch Filter and wavelet denoising

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Abstract: In this paper, the most suitable filtering methods for the suppression of 50 Hz power line contamination of ECG signals are pursued. The NLMS and RLS adaptive filters, notch filter, and median filter have been tested in both time and frequency domains. The considered important parameters are SNRs, RMS difference, and MSE for real ECG recordings taken from the MIT-BIH arrhythmia database. It is shown that the adaptive NLMS filtering technique outperforms the RLS, notch, and median filters in terms of giving better SNR. This proves that the NLMS filter can be the best among the filters for ECG signal denoising.

***Index Terms*—Keywords-ECG signal; power line interferrence; adaptive NLMS filter; PSD; spectrogram.**

I. Introduction

The ECG signal plays a crucial role in diagnosing and evaluating various cardiac conditions. However, when recorded, the ECG signal can be contaminated by several types of noise, such as power line interference, baseline wander, electrode contact noise, motion artifacts, muscle contractions, instrumentation noise, and electrosurgical interference, among others [1]. The most significant source of interference is the 50 Hz power line interference, as it lies within the ECG signal's frequency range (0.05-100 Hz), particularly affecting the ST segment. This interference can hinder the accurate diagnosis of arrhythmias, making it essential to remove the 50 Hz power line interference from the ECG signal to obtain reliable results. Various digital filters, such as FIR and IIR filters, have been employed to address this issue [2]-[4]. However, due to the non-stationary nature of the ECG signal, applying filters with fixed coefficients to remove the 50 Hz power line interference can be challenging. Recently, adaptive filtering has emerged as a highly effective and widely used technique for processing ECG signals [5]-[7]. Adaptive filters, particularly those using the Least Mean Square (LMS) algorithm, have demonstrated good performance in analyzing non-stationary biomedical signals. In our previous research [8], it was shown that the adaptive Normalized Least Mean Square (NLMS) filter outperforms other LMS-based adaptive filters in removing 50 Hz power line interference. This study investigates and compares traditional notch filters [9], adaptive Recursive Least Squares (RLS) filters [5], and adaptive NLMS filters to mitigate the impact of 50 Hz power line interference in ECG signals. Simulation results confirm that the adaptive NLMS filter is highly effective in eliminating 50 Hz power line interference.

Additionally, the median filter is a non-linear digital filtering technique commonly used to remove noise from signals, images, and videos. This type of noise reduction is often a crucial preprocessing step to improve subsequent processing results, such as edge detection in images. Median filtering is widely utilized in digital image processing because it can preserve edges while effectively removing certain types of noise [12]. It also finds applications in signal processing.

II. MATERIALS AND METHODS

The original ECG signals, recorded from the benchmark MIT-BIH arrhythmia database [10], are taken from records #100, 104, 105, and 106. To simulate 50 Hz power line interference, MATLAB® is used to generate this noise. The noisy ECG signal is created by combining the original ECG signal with the generated power line interference. To eliminate the 50 Hz power line noise, the noisy ECG signal is processed through two adaptive filtering algorithms, namely NLMS and RLS, as well as a traditional notch filter. The basic block diagrams illustrating the overall processes for adaptive and notch filtering are shown in "Fig.1".

The noisy, as well as, filtered ECG signals are analyzed both in time and frequency domains. Different parameters used to measure the performance of adaptive filters and notch filter are power spectral density (PSD), spectrogram, signal-to-noise ratio (SNR), percentage root mean square difference (%PRD) and mean square error (MSE). Signal Processing Toolbox built in MATLAB® has been used to simulate the program.

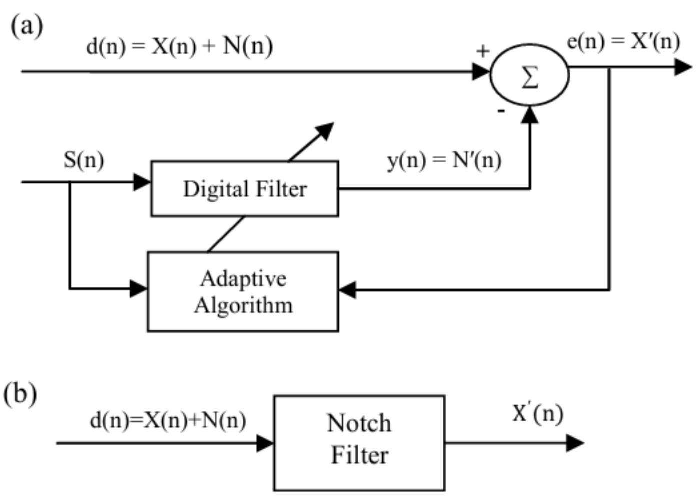

Fig. 1. Principles of (a) adaptive and (b) notch filters.

III. RESULTS AND DISCUSSION

We utilized 13-bit real data from four patients in the MIT-BIH Arrhythmia Database [10], selecting patient record #105 as a reference for analysis. The process can be similarly applied to the other patients. In our study, we simulated the 50 Hz power line interference (noise signal), noisy ECG signal, and the resulting filtered signals using a notch filter, adaptive RLS filter, and adaptive NLMS filter in the time domain. The 50 Hz power line interference was generated to align with the patient's ECG signal. By combining the interference with the ECG signal, we obtained a noisy ECG signal. In the following, we present and discuss the results obtained from MATLAB for each filter.

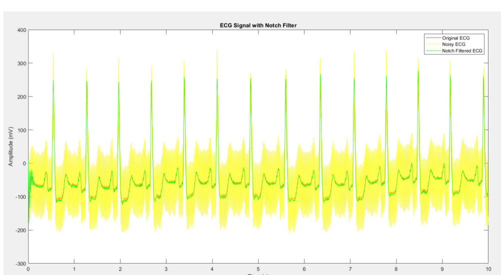

Fig. 2. Notch Filter

1- Notch Filter (fig 2)

- In figure 2, we observe three signals: the original ECG signal (red), the noisy ECG signal (yellow), and the filtered ECG signal after applying the notch filter (green).
- The notch filter successfully reduces the 50 Hz power line interference, as evidenced by the green line aligning closely with the original red signal. However, some minor distortions may still be present, especially in regions with more prominent noise. This indicates that while the notch filter is effective, it is less adaptive to variations in noise levels compared to other advanced techniques.

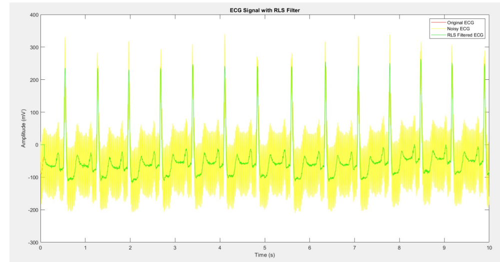

Fig. 3. RLS Filter

2- RLS Filter (fig 3)

- The third figure compares the original ECG (red), noisy ECG (yellow), and the ECG signal after processing with the adaptive RLS filter (green).
- Here, the RLS filter demonstrates its capability to dynamically adapt to noise and remove interference effectively. The filtered ECG signal (green) is much cleaner and closely resembles the original ECG signal, showing a smoother output compared to the notch filter. This highlights the advantage of the RLS filter in handling real-time variations in noise and interference.

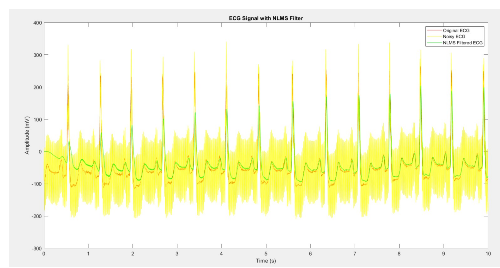

Fig. 4. NLMS Filter

3- NLMS Filter (fig 4)

- In the final figure, the NLMS filter's performance is depicted alongside the original ECG (red) and noisy ECG (yellow). The green signal, which represents the NLMS filtered output, shows excellent noise suppression while preserving the original signal's morphology.
- The NLMS filter offers results comparable to the RLS filter, demonstrating a high level of adaptability and effectiveness in eliminating power line interference. Its performance showcases robustness, making it suitable for precise ECG signal filtering applications.

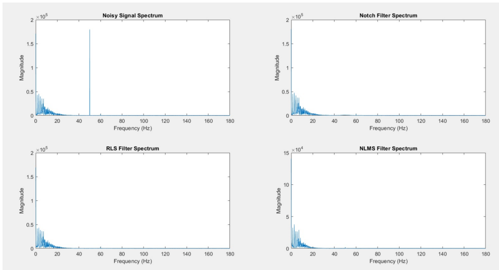

Fig. 5. Amplitude Spectrum for each Filter

The analysis of the Power Spectral Density (PSD) of the ECG signal with different filtering techniques highlights the effectiveness of each method in reducing noise, particularly the 50 Hz power line interference.

- **Noisy Signal Spectrum:** The spectrum of the original signal shows a prominent spike at 50 Hz, indicating significant power line interference.
- **Notch Filter Spectrum:** The notch filter effectively removes the 50 Hz noise, leaving the rest of the signal mostly unaffected.
- **RLS Filter Spectrum:** The RLS adaptive filter successfully eliminates the 50 Hz noise while preserving the low-frequency components of the signal.
- **NLMS Filter Spectrum:** The NLMS adaptive filter also reduces the 50 Hz noise effectively, although slight traces of noise might still be visible.

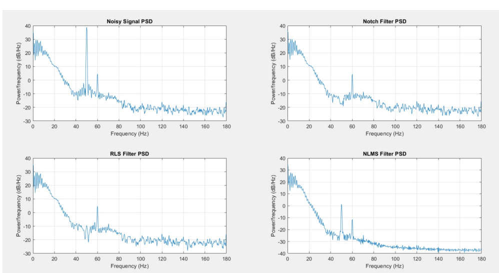

Fig. 6. Power Spectral Density (PSD)

This analysis demonstrates how different filtering techniques impact the Power Spectral Density (PSD) of a noisy ECG signal, focusing on the removal of 50 Hz power line interference. ECG signals are essential for monitoring heart health, but they are often contaminated by noise, such as 50 Hz power line interference. This interference can obscure important heart activity, making it necessary to apply effective filters. We compare four filtering methods: the original noisy signal, notch filter, RLS adaptive filter, and NLMS adaptive filter.

- **Noisy Signal PSD** : This plot shows the original ECG signal with 50 Hz power line interference. The noise causes a noticeable peak at 50 Hz.

- **Notch Filter PSD** : After applying the notch filter, the 50 Hz interference is greatly reduced, with minimal impact on the rest of the signal.

- **RLS Filter PSD** : The Recursive Least Squares (RLS) adaptive filter removes the 50 Hz noise effectively, preserving the lower-frequency components that are vital for ECG analysis.

- **NLMS Filter PSD** : The Normalized Least Mean Squares (NLMS) adaptive filter reduces the 50 Hz noise, but some residual interference remains compared to the RLS and notch filters.

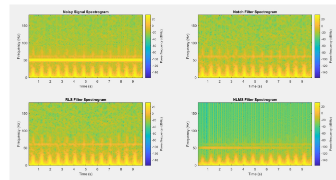

Fig. 7. Spectrogram for each filter

In this analysis, we examine how different filters affect the spectrograms of ECG signals contaminated with noise. By observing the spectrograms of the noisy ECG signal, as well as those processed with a notch filter, RLS filter, and NLMS filter, we can assess how each method mitigates noise and preserves the integrity of the ECG signal. This comparison helps us understand the strengths and limitations of each filtering technique in improving signal clarity for accurate analysis.

- **Noisy Signal:** The original signal with visible 50 Hz noise and other frequency components.
- **Notch Filter:** Effectively removes the 50 Hz noise while keeping the rest of the signal intact, making it ideal for specific frequency removal like power line interference.
- **RLS Filter:** Reduces noise across the spectrum but leaves some residual noise, offering good adaptive noise cancellation without significant signal loss.
- **NLMS Filter:**Suppresses noise well, including 50 Hz, but might over-filter the signal, potentially removing important components.

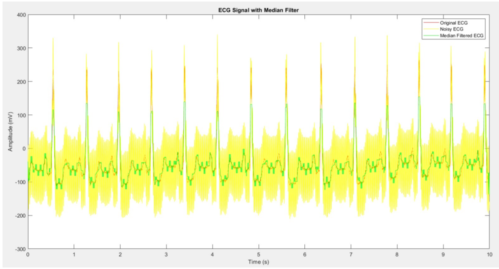

Fig. 8. Median Filter

Figure 8 demonstrates the result of applying a median filter to a noisy ECG signal after testing several alternative filtering techniques. Various filters, such as the notch filter, Recursive Least Squares (RLS), and Normalized Least Mean Squares (NLMS), were initially evaluated to reduce noise in the ECG signal. While these methods showed varying degrees of effectiveness, we sought a solution that would preserve the sharp transitions of the QRS complex. The median filter was chosen for this purpose, and the figure presents the original ECG (red line), the noisy ECG (yellow region), and the output after applying the median filter (green line). This method successfully reduces noise while maintaining the important features of the ECG waveform, making it an ideal choice for this application.

The performance parameters (SNR, %PRD, and MSE) for the noisy, notch-filtered, adaptive RLS-filtered, and adaptive NLMS-filtered ECG signals were calculated and are shown in Table I. Higher SNR values and lower %PRD and MSE values are considered indicators of better performance. From the table, we observe that the noisy ECG signal has a very low SNR, while all the filtered signals show higher SNR values. Additionally, the noisy signal has high %PRD and MSE, but the filtered signals display significantly lower values. Among the filtered signals, the adaptive NLMS filter achieves the highest SNR and the lowest %PRD and MSE compared to the notch and RLS filters.

Results for record 105:

- **Notch Filter**: SNR = 21.91, PRD = 8.02%, MSE = 37.9328
- **RLS Filter**: SNR = 21.51, PRD = 8.40%, MSE = 41.5828
- **NLMS Filter**: SNR = 6.33, PRD = 48.23%, MSE = 1370.4278

To conclude, we assessed the effectiveness of different filtering techniques—notch, RLS, and NLMS—on noisy ECG signals. The notch and RLS filters provided substantial improvement in SNR while maintaining lower PRD and MSE values, making them effective for noise reduction without significantly altering the signal. On the other hand, while the NLMS filter achieved strong noise suppression, it resulted in higher PRD and MSE, suggesting some loss of signal quality. Overall, the notch and RLS filters proved to be more balanced in preserving the ECG signal's integrity while reducing noise,

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