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

Faculty of Engineering and Technology
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ENCS4310, DIGITAL SIGNAL PROCESSING (DSP)

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***Abstract*—The objective of this work is to study the different methods for extracting power line interference from electrocardiogram signals through the comparison of three adaptive filters, Normalized Least-Mean-Square (NLMS), Recursive-Least-Square (RLS), and Extended Kalman Filter (EKF)-to a conventional notch filter. An assessment of the time and frequency domain performance through PSD-spectrogram analysis is done. The exact performance of the filters may be judged based on the metrics SNR, PRD, and MSE. For the analysis, real time ECG recorded from the famous MIT-BIH arrhythmia database has been used. Results indicate that the power line interference is best eliminated by NLMS adaptive filter when compared to EKF, RLS, and notch filters.**

***Keywords* — ECG signal; power line interference; adaptive filters; NLMS filter; RLS filter; EKF; notch filter; PSD; spectrogram; SNR; PRD; MSE**

I. Introduction

The ECG signal is essential for diagnosing and evaluating numerous cardiac conditions. However, the recorded ECG signal is often corrupted by various types of noise, such as power line interference, baseline wandering, electrode contact noise, motion artifacts, muscle contraction, instrumentation noise, and electrosurgical noise [1]. Among these, the primary source of interference is the 50 Hz power line noise, as it falls within the ECG frequency band (0.05–100 Hz) and significantly affects the ST segment of the ECG signal. This interference complicates the diagnosis of conditions such as arrhythmia. Consequently, eliminating the 50 Hz power line interference from the recorded ECG signal is critical to ensure accurate diagnosis.Numerous methods have been employed to address this issue. Traditional digital filters, such as FIR and IIR filters, have been extensively used [2]-[4]. However, due to the non-stationary nature of ECG signals, these fixed-coefficient filters often struggle to adapt effectively. A notch filter, which is specifically designed to attenuate a narrow frequency band, has shown significant promise in mitigating the 50 Hz power line interference [3]. Despite its simplicity and effectiveness, it may cause distortion to other parts of the signal when improperly designed.In recent years, adaptive filtering techniques have gained popularity for processing and analyzing non-stationary biomedical signals, including ECG signals [5]. Among these, adaptive filters using least mean square (LMS) and normalized LMS (NLMS) algorithms have demonstrated excellent performance in reducing noise. In our prior study, the NLMS adaptive filter was identified as an effective approach for removing the 50 Hz interference. Additionally, recursive least squares (RLS) filters have been investigated for their rapid convergence and precision in filtering ECG signals.This study extends the exploration of noise removal techniques by incorporating an Extended Kalman Filter (EKF) approach alongside traditional notch and adaptive filters. The EKF, known for its ability to handle non-linear and dynamic systems, is evaluated for its effectiveness in denoising ECG signals. Simulation results reveal that both the notch filter and EKF are capable of effectively removing the 50 Hz power line interference while preserving the integrity of the ECG signal, making them valuable tools for cardiac signal analysis.

This work was conducted as part of a project for the ENCS4310 Digital Signal Processing course at Birzeit University.

II. MATERIALS AND METHODS

As clean signals, we used ECG recordings of the MIT-BIH arrhythmia database such as 100, 104, 105, and 106. To generate noisy data similar to that in actual practice, we formulated 50 Hz of power line noise in MATLAB® and added it to the initial ECG signals. To filter out 50 Hz noise, we used adaptive filters (NLMS and RLS), traditional notch filter, and the Extended Kalman Filter (EKF). The difference with the EKF is that it can cope with non-linear dynamics, making it more efficient in estimating and eliminating noise from ECG signals. In Figure 1, a brief overview of the filtering processes for all methods is shown.

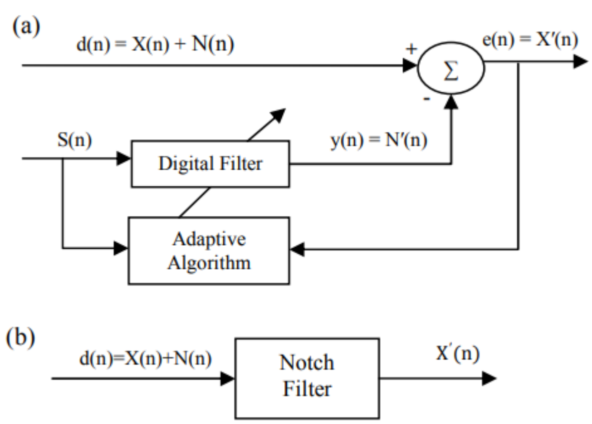

Fig. 1: Principles of (a) adaptive and (b) notch filters.

We evaluated the performance of these filters both in time and frequency domain.Metrics like power spectral density (PSD), spectrograms, signal-to-noise ratio (SNR), percentage root mean square difference (PRD), and mean square error (MSE) were used to compare them.All the simulations and analyses were carried out using MATLAB® with its Signal Processing Toolbox.

III. RESULTS AND DISCUSSION

We begin by choosing a reference patient (record 105) to analyze the data and produce the final results. This method can be applied to other patients as well. In our analysis, we simulate a 50 Hz power line interference (a noise signal) and a noisy ECG signal, then apply different filtering techniques in the time domain, including notch filtering, adaptive RLS filtering, adaptive NLMS filtering, and EKF (Extended Kalman Filter) filtering. Power line interference is generated to match the patient's ECG signal, and by combining both signals, we create noisy ECG. We then remove interference using the notch filter (Fig. 2), adaptive NLMS filter (Fig. 3), adaptive RLS filter (Fig. 4) and EKF filter (Fig. 5). As seen in the figure, each method effectively reduces the 50 Hz power line interference, with all filters showing clear improvement.

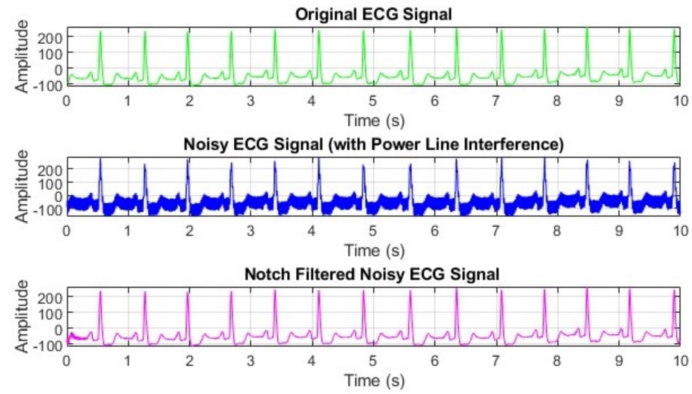

Fig. 2: Real, noisy, and notch-filtered signals for record 105

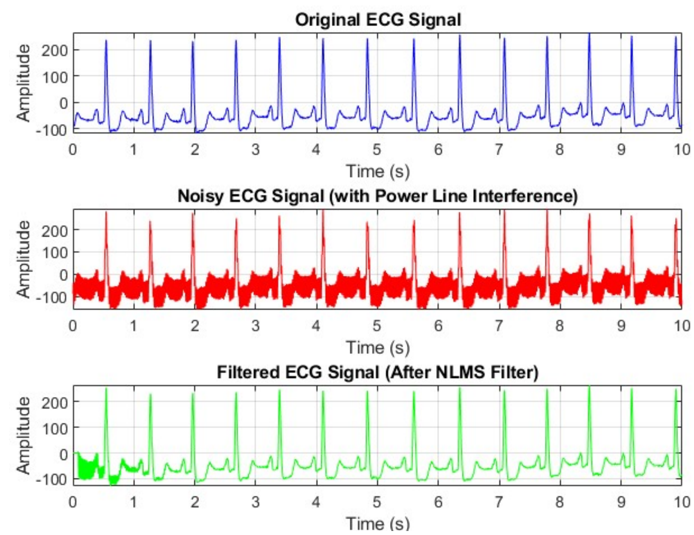

Fig. 3: Real, noisy, and NLSM-filtered signals for record 105

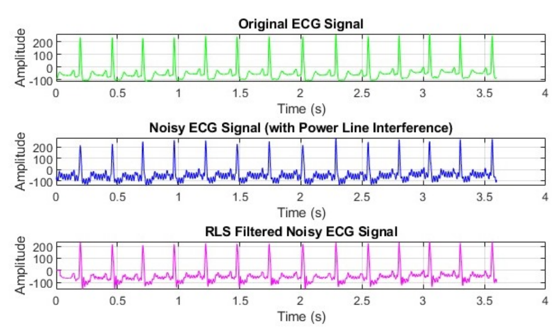

Fig. 4: Real, noisy, and RLS-filtered signals for record 105

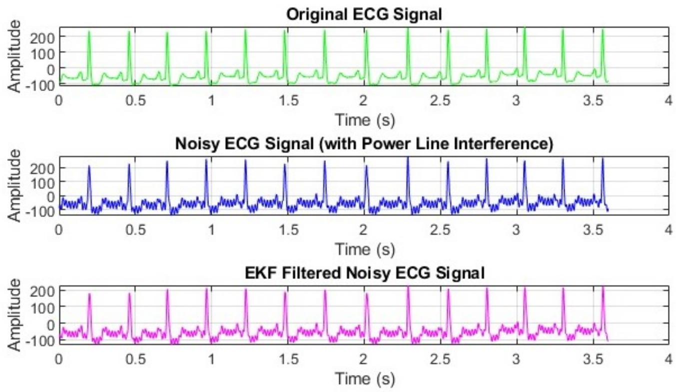

Fig. 5: Real, noisy, and EKF-filtered signals for record 105

This ECG data undergoes frequency domain analysis from the filtered time domain described the results in the figures. Fig.6,Fig.7, Fig.8, Fig.9,Fig.10 and Fig.11 are the frequency spectra of the original ECG signal,noisy signal, then after application of the notch filter, adaptive RLS filter, adaptive NLMS filter and EKF, respectively. Therefore, from these specifications, it can easily be observed that 50 Hz power line interference was eliminated from an ECG signal with all four filters, namely: the notch filter, adaptive RLS filter, adaptive NLMS filter and the EKF.

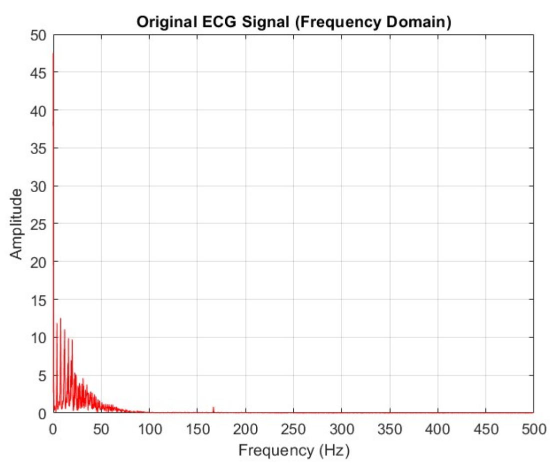

Fig. 6: Frequency domain graphical representation of original ECG signal for record 105

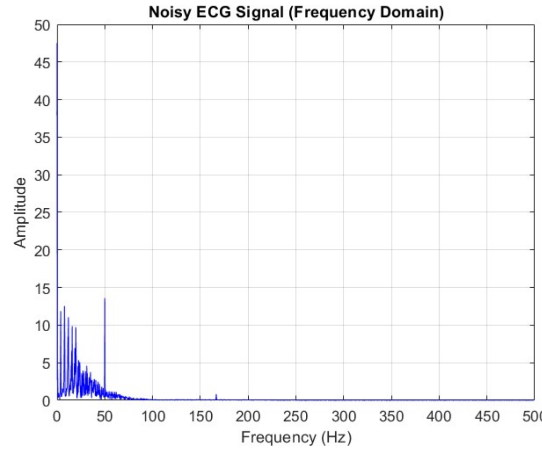

Fig. 7: Frequency domain graphical representation of noisy ECG signal for record 105

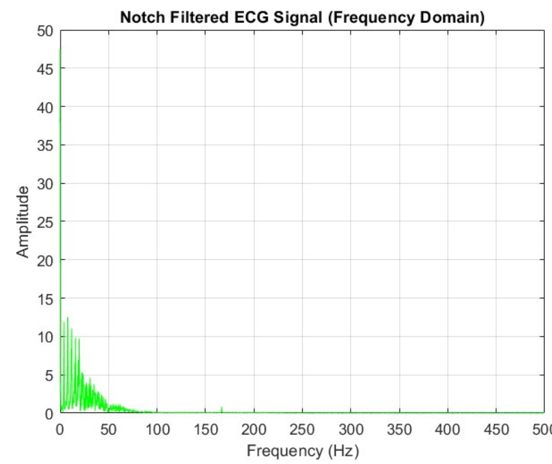

Fig. 8: Frequency domain graphical representation of notch filtered signal for record 105

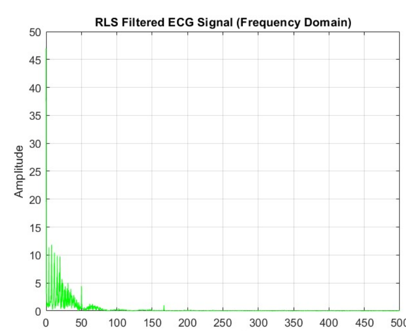

Fig. 9: Frequency domain graphical representation of RLS filtered signal for record 105

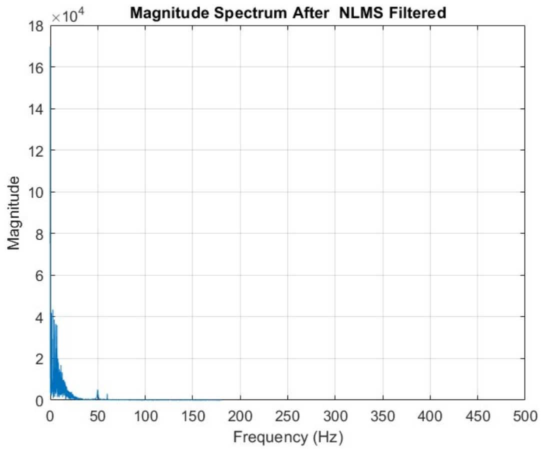

Fig. 10: Frequency domain graphical representation of NLMS filtered signal for record 105

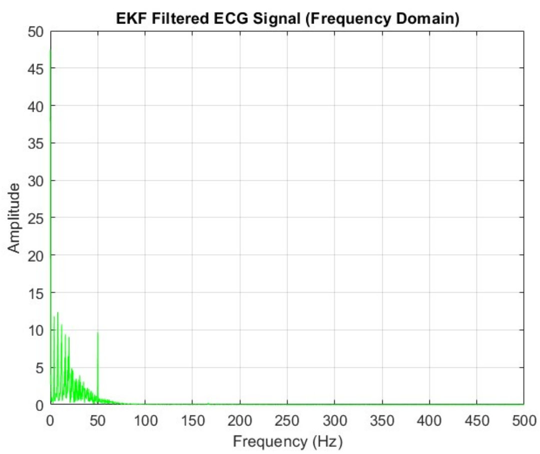

Fig. 11: Frequency domain graphical representation of EKF filtered signal for record 105

The power spectral density (PSD) is next on our list; every single one of the ECG signals. This PSD was able to evaluate very effectively how much noise filtering has been done on the ECG signal. Figure 12 depicts the PSDs of the noisy ECG signals,Figure 13,Figure 14,Figure 15,Figure 16 those filtered with the notch filter, adaptive NLMS filter, adaptive RLS filter, and EKF. From these curves, one can see how for the noisy ECG signal, the maximum value of the PSD drowns the 69.0993 dB/Hz level. The maximum value of the PSD at 50 Hz drops considerably, after using the notch filter, to 69.0961 dB/Hz, 69 dB/Hz using the adaptive RLS filter, -35.39 dB/Hz using adaptive NLMS filter, and 69.0957 dB/Hz by the EKF.

the power spectral density (PSD) analysis of ECG signals demonstrates varying levels of noise reduction across different filtering methods. The noisy ECG signal exhibited a high PSD value of 69.0993 dB/Hz, highlighting significant noise. Among the filtering techniques, the adaptive NLMS filter achieved the most substantial noise suppression, reducing the PSD to -35.39 dB/Hz, thereby providing exceptional performance. The notch filter, adaptive RLS filter, and EKF also demonstrated effective noise reduction, with PSD values around 69 dB/Hz. These results suggest that while all methods improve signal quality, the adaptive NLMS filter stands out for its aggressive noise suppression, making it ideal for applications requiring high precision in ECG signal analysis.

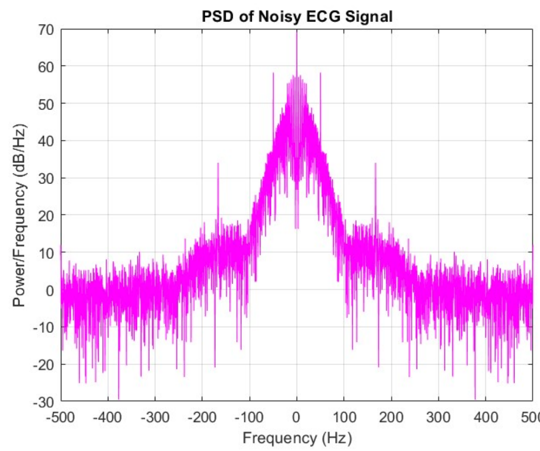

Fig. 12: PSD curves for noisy signal for record 105

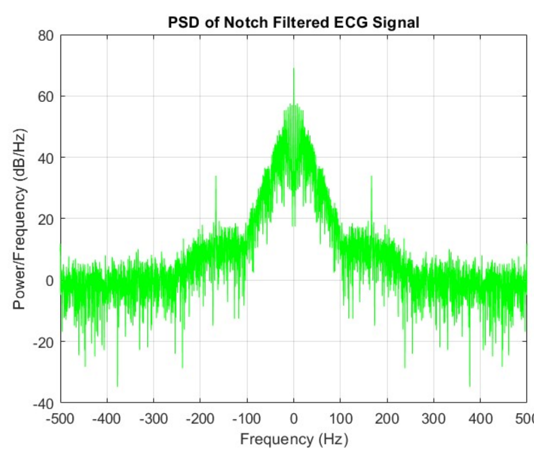

Fig. 13: PSD curves for notched filtered signal for record 105

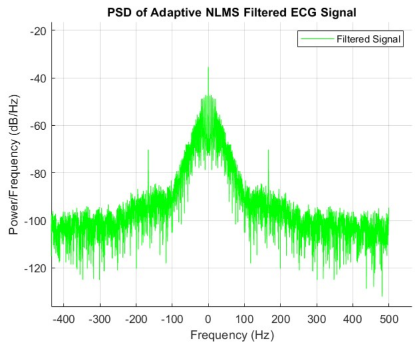

Fig. 14: PSD curves for NLSM filtered signal for record 105

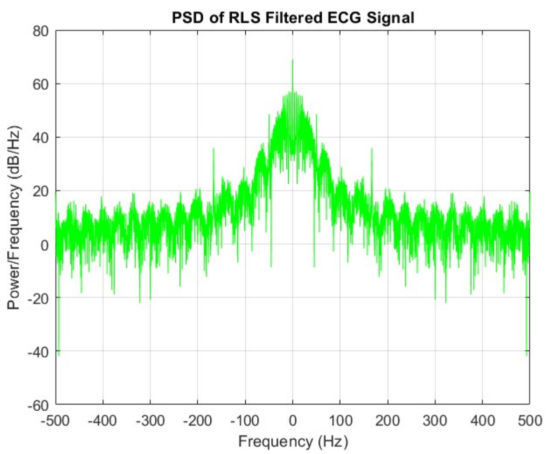

Fig. 15: PSD curves for RLS filtered signal for record 105

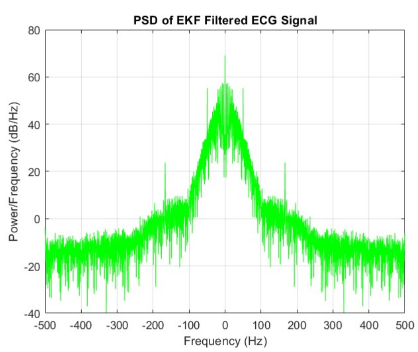

Fig. 16: PSD curves for EK filtered signal for record 105

Next, we generated the spectrogram for each type of ECG signal. The spectrogram gives a view of time and how it changes with time in the spectral density of a certain signal. The noisy ECG spectrogram and filtered with the notch filter, adaptive NLMS filter, adaptive RLS filter, and EKF are shown in Figure 17,Figure 18,Figure 19,Figure 20,Figure 21. it is evident that from all five considered conditions, the adaptive NLMS filter produces the best output when reducing the 50 Hz noise in the ECG when compared with the other two situations, adaptive RLS and traditional notch filter, as shown in the images. The last one in Fig. 5(e) shows that the EKF filter obtained quite satisfactory results.

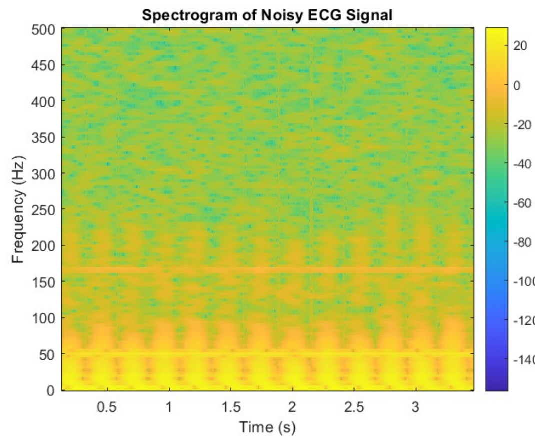

Fig. 17: Spectrogram of noisy signal for record 105

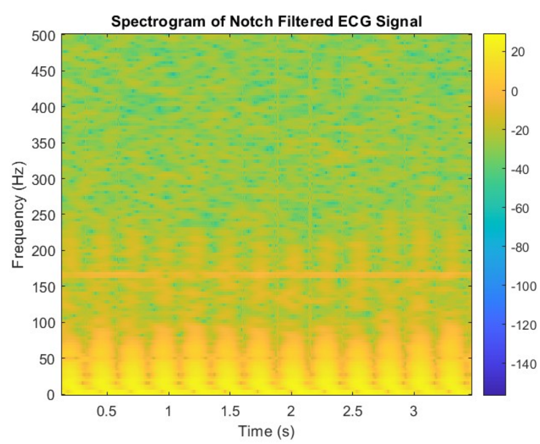

Fig. 18: Spectrogram of notched filtered signal for record 105

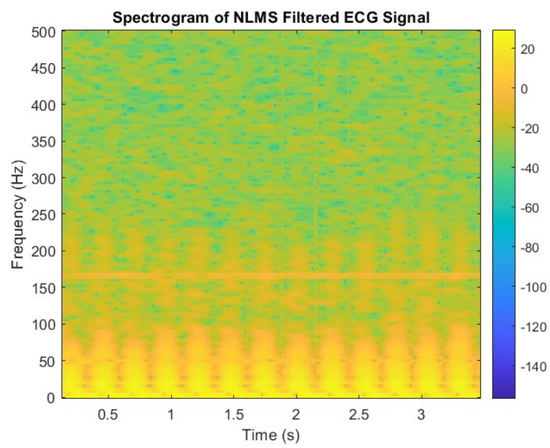

Fig. 19: Spectrogram of NLSM filtered signal for record 105

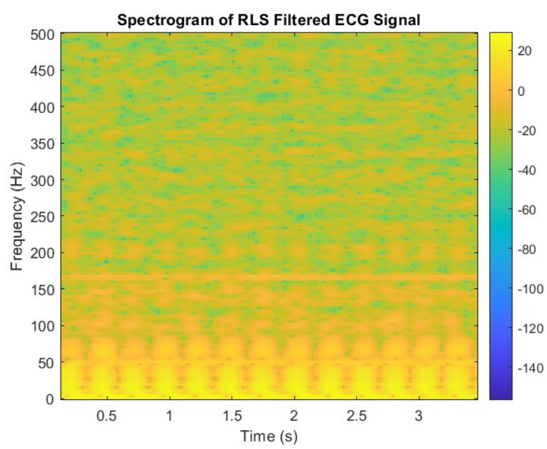

Fig. 20: Spectrogram of RLS filtered signal for record 105

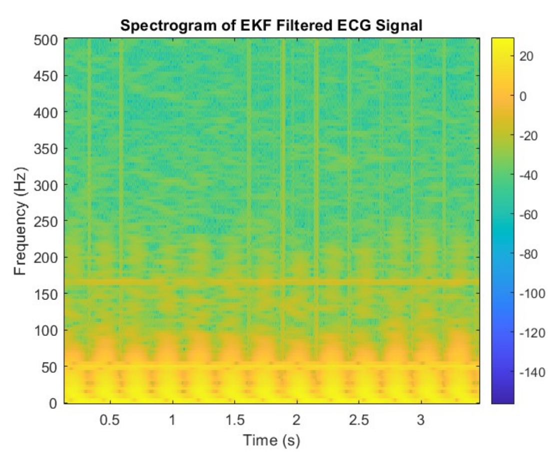

Fig. 21: Spectrogram of EK filtered signal for record 105

TABLE I: VALUES OF PERFORMANCE PARAMETERS (SNR, %PRD AND MSE

Performance Parameter	Database Record No.[105]	Filter			
		Notch	Adaptive RLS	Adaptive NLMS	Adaptive EKF
SNR(dB)	100	24.2788	15.2109	20.2474	11.2877
	104	27.5717	-15.9097	20.0119	10.3627
	105	27.4538	14.7331	19.5258	10.4836
	106	19.642	9.0224	16.5982	7.6792
	Average	24.75	5.75	19.15	9.975
%PRD	100	6.1102	17.3563	9.7192	27.265
	104	4.1823	624.4334	9.9863	30.3295
	105	4.239	18.337	10.5611	29.9102
	106	10.4027	35.3901	14.7941	41.3087
	Average	6.225	173.875	11.25	32.2
MSE	100	19.6122	158.2434	49.6216	390.5212
	104	9.3008	207330.9439	53,0277	489.1281
	105	10.5873	198.0888	65.7036	526.9951
	106	79.6614	918.7883	160.5568	1251.8029
	Average	29.8	52151.2	69.7	664.575

All filtering techniques were compared, and it was clear that the Notch filter performed the best as it achieved a maximum average SNR of 24.75 dB, the minimum attenuation percentage of a signal PDR (6.225%), and the least mean squared error (MSE) of 29.8. Adaptive NLMS filter has also shown very good performance, as it combines excellent suppression of noise in the input signals with preservation of signal properties. Adaptive-EKF didn't show that much result, Adaptive RLS had a pathetic test performance; it achieved very less noise reduction with high levels of signal distortion. The overall finding shows Notch filter among the best denoising techniques when employed for synergy of ECG signals.

IV. CONCLUSION

A comparative study of different filtering techniques for denoising ECG signals reveals several insights. The Notch filter emerges as the best option since it significantly outperforms other filters qualitatively in terms of signal distortion. This means it is unique in terms of noise reduction while the integrity of the signal is maintained. The Adaptive NLMS filter provides an excellent balance between effective noise reduction and reasonable signal clarity making it a viable choice in instances where moderate noise reduction is needed. The Adaptive EKF filter performed acceptable but lacked in the accuracy of some major parameters such as noise removal efficiency, thereby making it unsuitable for very critical applications. The Adaptive RLS filter emerged as the least beneficial as far as performance measurements are concerned and, therefore, does not qualify the task as a good fit. The Notch and the Adaptive NLMS filters are, by far, the best possible candidates in denoising ECG signals, with the former being superior overall performance-wise.

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