Noise Reduction of Electrocardiographic Signals using Wavelet Transforms

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***Abstract*—It has always been a critical issue to extract original signal having low signal-to-noise ratio (SNR) buried in heavy noise and interferences. Since the amplitude of the electrocardiogram (ECG) signal is smaller so while gathering and recording it may mix with various kinds of noises and interferences. In this paper, wavelet thresholding de-noising method based on stationary wavelet transform (SWT) is proposed in de-noising of ECG signal. In addition, this paper compares various de-noising methods to validate the proposed de-noising method. The improved de-noising method ensures that the geometrical characteristics of the original ECG are retained as well as efficiently suppresses additive noises. The experimental results reveal that the SWT method is better than traditional wavelet de-noising methods to maintain original shape of ECG waveform having improved SNR.**

***Index Terms*—Electrocardiogram, de-noising, noise, stationary wavelet transform, signal-to-noise ratio.**

I. INTRODUCTION

The electrocardiogram is measured on an instrument called Electrocardiograph. It is used by cardiologists to investigate the health condition of the heart [1], [2]. A typical electrocardiogram is shown in Fig. 1. The morphology of ECG signal has been used for recognizing much variability's of heart activity, so it is very important to get the parameters of ECG signal clear without noise.

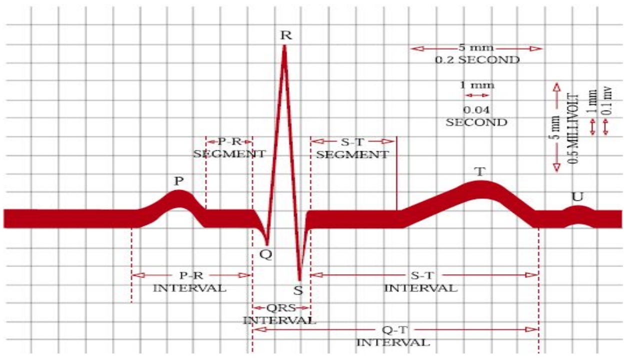

Fig. 1. Typical cycle of an electrocardiogram signature [2].

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Spatial filters have long been used as the traditional means of removing noise from images and signals. These filters usually smooth the data to reduce the noise, but, in the process, also blur the data. In the last decade, several new techniques have been developed that improve on spatial filters by removing the noise more effectively while preserving the edges in the data. An efficient technique for such a non-stationary signal processing is the wavelet transform. The factors which may cause interference in ECG signals can be the following [2]:

– Baseline Wander;
– Motion artifacts;
– AC 50 Hz power line frequency;
– Electromyography(EMG) signals;
– Additive Gaussian White noise (AWGN);
– Uniformly distributed White noise due to breathing.

Of the above interferences the most likely to present in the ECG signatures are the baseline wander, AC 50 Hz power line frequency, electromyography (EMG) signals and additive Gaussian white noise. These are present while capturing the ECG signature of the patient in static position; other interferences usually arise for certain tests when the patient is in motion during effort test or Holter recording. EMG interference provides a hard task for noise removal as EMG spectrum overlaps with that of the PQRST complex of ECG. Therefore QRS complex of ECG is highly affected by EMG noise spectrum [2].

II. METHODS FOR NOISE REMOVAL IN ECG

ECG and EMG signals were obtained from Physio Bank archives (archive of digital recordings of Physiologic signals). Noise-free ECG digitized data from MIT-BIH normal Sinus Rhythm recordings was selected. Digitized ECG sample file was converted into compatible format (a text file) to be imported for Matlab which was used for signal processing and wavelets processing [3]. Following interference signals were generated and added to the original noise-free ECG signal to simulate the real-life scenario where ECG is buried in a heavy noises and external interferences of varying frequencies and amplitudes with low

SNR [3], [4]. In principle, the following interferences may occur individually or together depending on the way of capturing ECG signatures and the environment:

– 50 Hz power line frequency generated inside Matlab;
– EMG signals taken from PhysioBank archieve Sleep EDF Database and converted to text file using software Polyman and Cygwin;
– AWGN generated inside Matlab.

Symlet 8 as a mother wavelet having a good noise reduction performance was used in wavelet decomposition with a level of 6. Wavelet decomposition was performed on the original noisy signal using wavelet toolbox in Matlab. Noise estimation and reduction was applied using different noise thresholding schemes. Results of various thresholding and de-noising schemes were compared and scheme having best performance for reconstruction was selected and finally original interference free ECG was reconstructed [3].

The following techniques have been applied for the noise reduction and amplification of signal to noise ratio. They can be categorized into four groups depending upon the way in which they handle the time variance factor of ECG which are as follows [5]:

– Short Time Fourier Transform (STFT);
– Discrete Wavelet Transform (DWT);
– Wavelet Packet Transform (WPT);
– Stationary Wavelet Transform (SWT).

De-noising is achieved by thresholding the noise at certain levels. The thresholds are categorized as follows [5]. The hard thresholding is defined by the following mathematical function as [5]:

$$\hat{d}_{j,k} = \begin{cases} d_{j,k}, & \left|d_{j,k}\right| \geq t, \\ 0, & \left|d_{j,k}\right| \prec t. \end{cases} \tag{1}$$

where $^{\wedge}d_{j,k}$ is the estimated wavelet coefficients and t is the threshold value. According to the mathematical function the coefficients above a certain threshold level $d_{j,k}$ are forced to zero value. The soft thresholding is defined by the following mathematical function as [5]

$$\hat{d}_{j,k} = \begin{cases} \operatorname{sgn}(d_{j,k})(\left|d_{j,k}\right| - t, & \left|d_{j,k}\right| \geq t, \\ 0, & \left|d_{j,k}\right| \prec t. \end{cases} \tag{2}$$

where $^{\wedge}d_{j,k}$ is the estimated wavelet coefficients and t is the threshold value. According to the mathematical function the coefficients above a certain threshold level $d_{j,k}$ are shrinked to zero by the pattern of sgn function [5].

III. EXPERIMENTAL RESULTS AND DISCUSSION

Noise-free ECG digitized data from PhysioBank archive MIT-BIH Normal Sinus Rhythm recording No: 16272 was selected. This is the recording of a normal healthy patient. Data was extracted using website utility rdsamp-O-Matic which allows converting binary signal files from PhysioBank into text form. The original sample rate of this recording was 128 samples per second (128 Hz). Data was then converted into text file to be imported for Matlab. Figure 2 shows extracted ECG in Matlab [6]. To analyse ECG pattern in frequency domain a Matlab Simulink model was created.

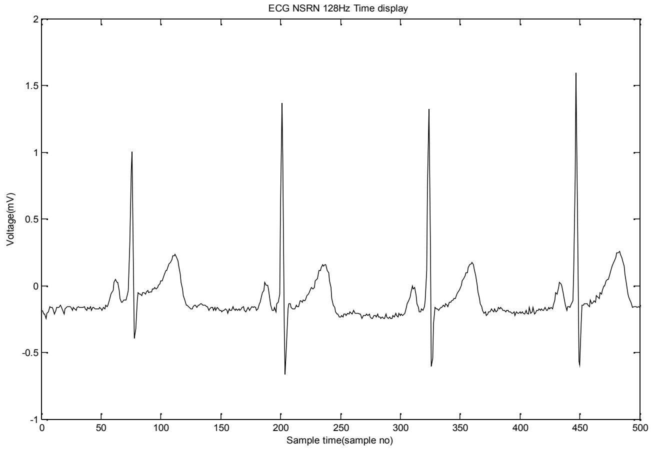

Fig. 2. Voltage (mV) vs sample time (sample no.) signature showing first four cycles of the extracted ECG [7].

From the spectrum it was found that the average value of ECG is not zero that is it contains an interference level for a frequency <=1.75 Hz which accounts for the presence of DC and baseline wander presence. A digital high pass finite impulse response (FIR) filter with cut-off frequency Wn = 1.75 Hz was applied to remove the interference without altering the original characteristics of ECG. Figure 3 shows high pass filtering [6].

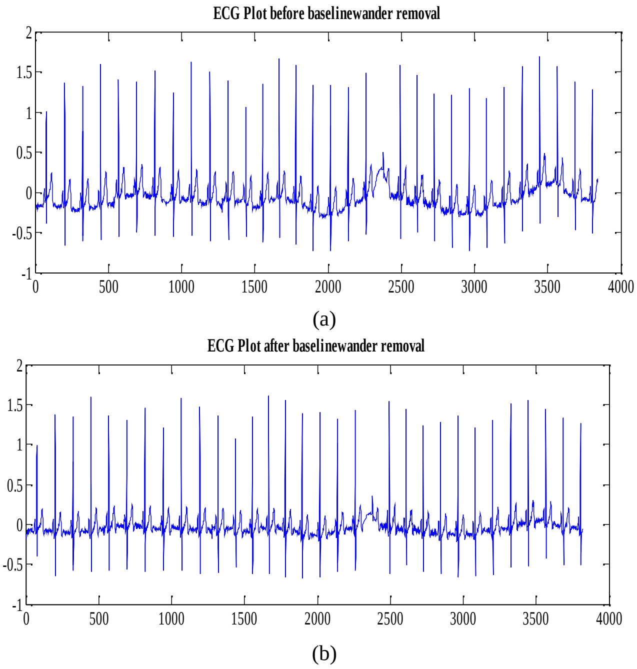

Fig. 3. ECG signature before baseline wander removal (a); ECG signature after baseline wander removal using high pass filtering [7] (b).

The original sampling rate of ECG 128 Hz was upsampled to 640 Hz gain an improved resolution of the RT interval variability measurement. Since T wave and U waves have low frequency as compared to QRS complex hence they result in poor time resolution and ending time of T wave is not obvious [6]. To compare the effectiveness of different ECG de-noising methods, different types of noises that is power line interference 50 Hz and Electromyogram (EMG)] and Additive Gaussian white Noise were added to the ECG signal [6]. Figure 4 shows ECG corrupted with AWGN, Sin 50 HZ and EMG signals.

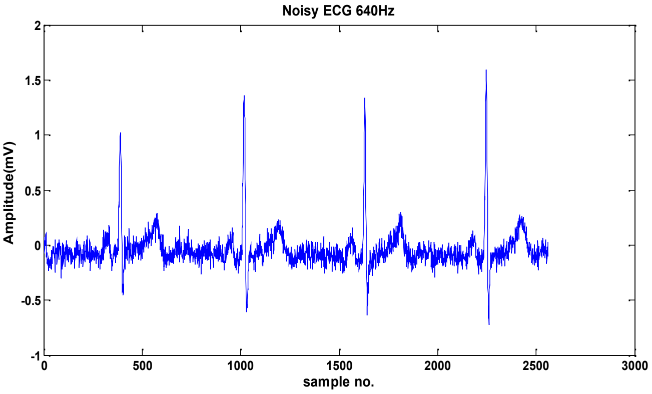

Fig. 4. ECG signature corrupted with interferences of AWGN, Sine 50 Hz and EMG signals.

A. *STFT De-noising*

In STFT de-noising a low pass FIR hamming window filter with a cutoff at 25 Hz was used to remove all noises in Matlab using Simulink model [7]. Figure 5 shows ECG signature using STFT (digital FIR low pass filtered method). After simulation signal extracted contained high content of noise. Minimum Mean Square Error (MMSE) b/w noise-free ECG and the extracted signal: 0.0676. This value is higher it is required that minimum mean square error should be very low [6]. The use of low pass filter has the disadvantage of reducing the amplitude of QRS Complex, because the high frequency components of the ECG describing high peaks of QRS signal are also removed since the low pass cut off frequency for EMG removal at 25 Hz removes some spectrum components of ECG falling after 25 Hz as the entire range of ECG spectrum is from 1.75 Hz to 30 Hz. Hence the method of low pass FIR filter is not so much successful in reducing EMG. The T and U waves of the signal are extremely distorted. The obtained SNR value is very low, this can be improved by introducing an amplifier but the distortions in the ECG signal will still be present [6].

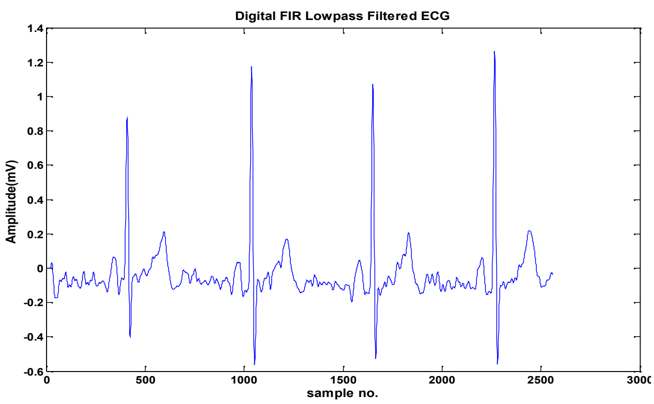

Fig. 5. De-noised ECG signature using STFT technique.

B. *DWT De-noising*

DWT was performed on the original noisy signal using Wavelet 1-D utility of Wavelet toolbox in Matlab. The signal was loaded and then decomposed using Symlet 8, at level 6 decomposition. Unscaled white noise model was used [6]. The de-noising technique in DWT was achieved by applying Global Soft Fixed Form, Global Soft Heruistic and Global Soft Rigsure thresholding techniques [6]. Fig. 6 shows de-noised ECG signature using different DWT techniques. Plots of Rigrous and Heuristic SURE are both noisy and contains distortions overall the waveform. Plots for Minimax, Hard and Variance adaptive are less noisy but contains spikes, impulses and distortions in T wave. Soft Threshold Fixed Form plot is good and smooth. The characteristics of ECG waveform are also retained except that the tip of T wave is a little distorted. The peaks of Q and S waves are also uneven and irregular showing Pseudo Gibbs phenomena. The SNR ratio is smaller as compared to other methods due to slightly reduced amplitude of R waves. But this factor can be ignored in extracted ECG as it is still higher than the original noisy ECG signal.

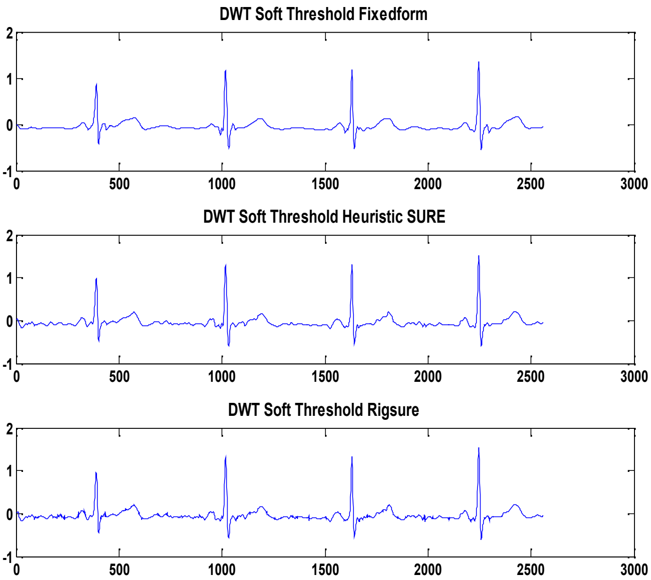

Fig. 6. De-noised ECG signature obtained from 1 dim DWT de-noising tool in Matlab Wavelet Toolbox [7].

C. *Wavelet Packet De-noising*

Wavelet Packet de-noising was achieved using Matlab Wavelet Packet 1-D de-noising utility in Wavelet Toolbox. The threshold criterion selected was Soft Threshold Fixed Form and unscaled white noise. The signal was loaded and then decomposed using Symlet 8, at level 6 decomposition.

The SNR value for WPT de-noising was 12.4575 which is greater than obtained from DWT de-noising soft Threshold Fixed Form method. The shape of the de-noised waveform obtained is same as of DWT. The characteristics of ECG waveform are also retained except that the tip of T wave was little distorted [7].

D. *SWT De-noising*

SWT analysis on original noisy ECG signal was performed using Matlab Wavelet Toolbox SWT de-noising 1-D feature using Symlet 8, at level 6 decomposition. Unscaled white noise model was used [7]. The Thresholding methods adopted in SWT were Soft Threshold Fixed Form, Soft Threshold Heuristic SURE and Hard Threshold Fixed Form. Figure 7 shows de-noised ECG signature obtained using different methods of SWT technique [6].

Plots of Heuristic SURE are noisy and contains distortions overall the waveform. Plots for Hard Threshold Fixed Form are less noisy but contains spikes, impulses and distortions in T wave. Soft Threshold Fixed Form has upper hand over other two methods as the plot is good and smooth. The characteristics of ECG waveform are also retained. T wave is also smooth and not distorted as was in DWT.

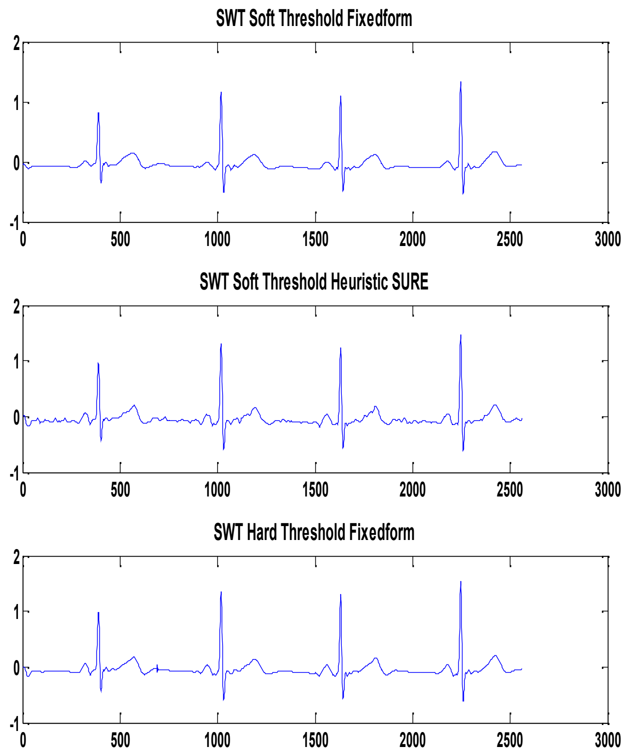

Fig. 7. De-noised ECG signatures obtained using different methods of SWT technique [7].

E. *Comparison of Different Methods*

SWT has improved SNR ratio than its WPT and DWT counterpart for Soft Threshold Fixed Form method.

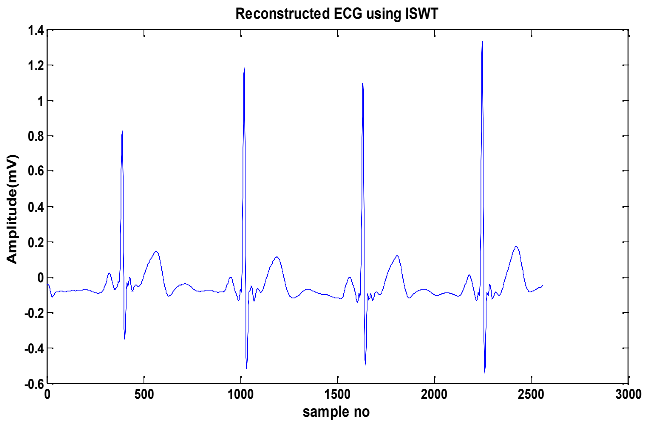

Fig. 8. Reconstructed ECG signature [7].

ECG signature using SWT technique is smoother and closer to original noise-free ECG waveform than the signatures obtained using DWT and WPT techniques [7].

After comparison of all four aforementioned de-noising schemes, SWT was found to be a superior de-noising algorithm among all. Among the Thresholding techniques Soft Threshold Fixed Form was found to evaluate the best performance. The signal was reconstructed using Inverse Stationary Wavelet Transform (ISWT) to get the original signal back as shown in Fig. 8.

IV. CONCLUSIONS

The ECG signatures are usually corrupted with different types of noises and interferences, which severely effect on the accuracy of the results. To enhance the reliability of the results, ECG signatures should be de-noised. To select a suitable de-noising technique and threshold producing a noise-free ECG signature depends upon the nature of signals in terms of its frequency contents and amplitude. Among available techniques, SWT technique using Soft Thresholding with Fixed Threshold method provides a better extracted de-noised signal than the other methods keeping in view SNR, precision and speed. The important considerations for SWT analysis are selecting wavelet family and number of decomposition levels. In this paper, Symlet 8 mother wavelet has been selected up to 6 decomposition levels. The analytical procedure involved in the proposed technique may provide a cost effective solution resulting in smaller size of the noise reduction equipment and lower power consumption when implemented using a digital signal processor with SWT algorithm.

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