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Research Article

A Segmental Approach with SWT Technique for Denoising the EOG Signal

Naga Rajesh

Department of Physics and Nanotechnology, Faculty of Engineering and Technology, SRM University, Kattankulathur, Kancheepuram, Tamil Nadu 603203, India

Correspondence should be addressed to Naga Rajesh; nagarajesh9@yahoo.co.in

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The Electrooculogram (EOG) signal is often contaminated with artifacts and power-line while recording. It is very much essential to denoise the EOG signal for quality diagnosis. The present study deals with denoising of noisy EOG signals using Stationary Wavelet Transformation (SWT) technique by two different approaches, namely, increasing segments of the EOG signal and different equal segments of the EOG signal. For performing the segmental denoising analysis, an EOG signal is simulated and added with controlled noise powers of 5 dB, 10 dB, 15 dB, 20 dB, and 25 dB so as to obtain five different noisy EOG signals. The results obtained after denoising them are extremely encouraging. Root Mean Square Error (RMSE) values between reference EOG signal and EOG signals with noise powers of 5 dB, 10 dB, and 15 dB are very less when compared with 20 dB and 25 dB noise powers. The findings suggest that the SWT technique can be used to denoise the noisy EOG signal with optimum noise powers ranging from 5 dB to 15 dB. This technique might be useful in quality diagnosis of various neurological or eye disorders.

1. Introduction

The electric field around the eye changes when it moves, producing an electrical signal known as Electrooculogram (EOG) signal. This is due to the formation of electric dipole, as the cornea and retina of the eye behave as positive and negative poles. In order to present an easy and accurate interpretation it is very much important to separate valid signal components from the noises caused by power-line interference and undesired artifacts [1]. To remove signal components from unwanted frequency ranges different types of digital filters are used. It is difficult to reduce artifacts caused by unexpected human behavior depending on the time, with fixed coefficients of the digital filters [2]. This problem can be overcome by adaptive filtering technique. The Recursive Least Squares (RLS) algorithm, whose convergence does not depend on the input signal, is the fastest of all conventional adaptive algorithms and it has been the best adaptive algorithm to denoise nonstationary signals like EOG, ECG, EMG, and so forth [3]. In analyzing the biomedical

signals like EOG, wavelet transform has emerged as one of the excellent techniques. For better understanding of the signal behavior the wavelet transform is capable of transforming a time domain signal into frequency localization [4]. A wavelet is a small wave which is oscillatory to discriminate between different frequencies and contains both the analyzed shape and the window [5].

In this paper, by the method of simulation, the performance of SWT technique is analyzed by the calculation of Root Mean Square Error (RMSE) values. The technique is also compared with the RLS adaptive filter algorithm which was proven to be suitable adaptive filter algorithm for EOG signal processing [3]. Therefore, the results of the study are presented.

2. SWT

SWT applies high and low pass filters to the data at each level. It does not decimate and modify the filter at each level, by padding them with zeros. It is computationally more

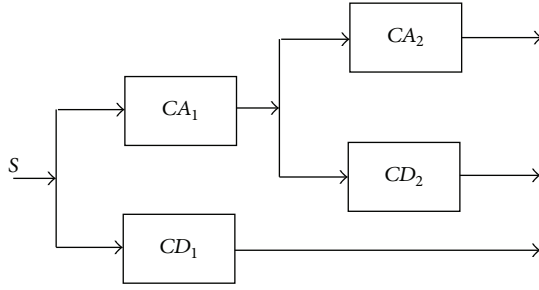


FIGURE 1: Wavelet decomposition scheme.

complex. The selection of subsets of the scales “ m ” and positions “ n ” of the mother wavelet $\psi(t)$ [6–8] is as follows:

$$\psi_{m,n}(t) = 2^{m/2} \psi(2^m t - n). \quad (1)$$

Dyadic scales and positions (m and n are integers) are based on powers of two. Wavelet for any function is built by dilation of function $\psi(t)$ with a coefficient 2^m (from (1)) resulting in the translated function interval on a grid proportional to 2^{-m} . By correlating the original signal with wavelet function of different sizes, the details of the signal are obtained at several scales. This hierarchical scheme called multiresolution decomposition separates the signals into “approximations” and “details” at different scales. The SWT preserves the property that a translation of original signal does not necessarily imply a translation of the corresponding wavelet coefficient [9–12]. The decomposition scheme is shown in Figure 1.

3. Adaptive Filter

Adaptive filter has “self-regulation” and “tracking” capacities. Its design does not require the prior knowledge of signal and noise characteristics, as it observes the statistical properties of the existing signal and in normal operation the parameters are adjusted automatically.

The input signal $x(n)$ is applied to the adaptive filter so as to produce output signal $y(n)$. Error signal $e(n)$ is the difference of desired signal $d(n)$ and the filter output $y(n)$. Therefore, adaptive filter automatically carries on a design based on the characteristic of the input signal $x(n)$ and the desired signal $d(n)$. RLS adaptive algorithm was considered as adaptive algorithm in Figure 2 [13].

4. RLS Algorithm

The RLS adaptive filter employs the following algorithm for prediction.

Here $(n) = [x(n-1) \ x(n-2) \ \dots \ x(n-p)]$ for an M order adaptive filter and $Xk = X(n)$ at $n = k$.

while |error| not less than a predefined $\epsilon > 0$

do begin

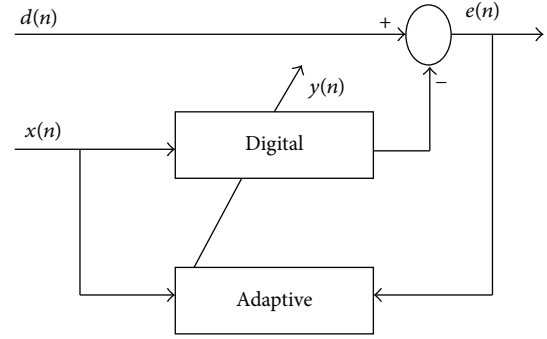


FIGURE 2: Principle of adaptive filter.

evaluate

$$\text{error } e(n) = d(n) - WTnX(n)$$

$$g(n) = (n-1) X * (n)$$

$$\{\lambda + X(n) P(n-1) X * (n)\}^{-1} \quad (2)$$

$$P(n) = \lambda^{-1} (n-1) - g(n) X T(n) \lambda^{-1} (n-1)$$

$$Wn = Wn-1 + e(n) g(n)$$

end While;

Here $P(n)$ is the inverse of the weighted autocorrelation matrix of Xk weighted by the forgetting factor λ .

That is, $P(n) = R x^{-1}(n)$, where

$$R x(n) = \sum \lambda(n-i) X * (i) X T(i). \quad (3)$$

$d(n)$ is desired signal, $e(n)$ is error, and $W(n)$ is weight vector all at time sample $t = n$.

With $W0 = 0$, $P(0) = \delta - 1I$, where I is a $(M+1)(M+1)$ identity matrix and λ is the forgetting factor which is equal to 0.99 [14].

5. Methodology

Figure 4(a) is an EOG signal comprising horizontal-vertical eye movements and blinks simulated and used as reference EOG signal throughout the analysis. The power of the reference EOG signal is found to be 44.11 dB.

Five noisy EOG signals are simulated by adding controlled noises of powers 5 dB, 10 dB, 15 dB, 20 dB, and 25 dB, respectively, to the reference EOG signal. The SNRs of the respective five noisy EOG signals are 39.04 dB, 33.92 dB, 29.02 dB, 24.12 dB, and 19.01 dB. The five noisy EOG signals are named as EOG5 dB, EOG10 dB, EOG15 dB, EOG20 dB, and EOG25 dB.

These noisy EOG signals are denoised using SWT technique. Bior 3.3 (Figure 3) wavelet is selected for the present analysis based on the promising results obtained in the previous published report [4].

The denoising analysis is performed by two methods:

- (i) increasing segments (in steps of 512 samples) from 1 to 8192 samples of noisy EOG signal (1:512, 1:1024, 1:1536, ...);

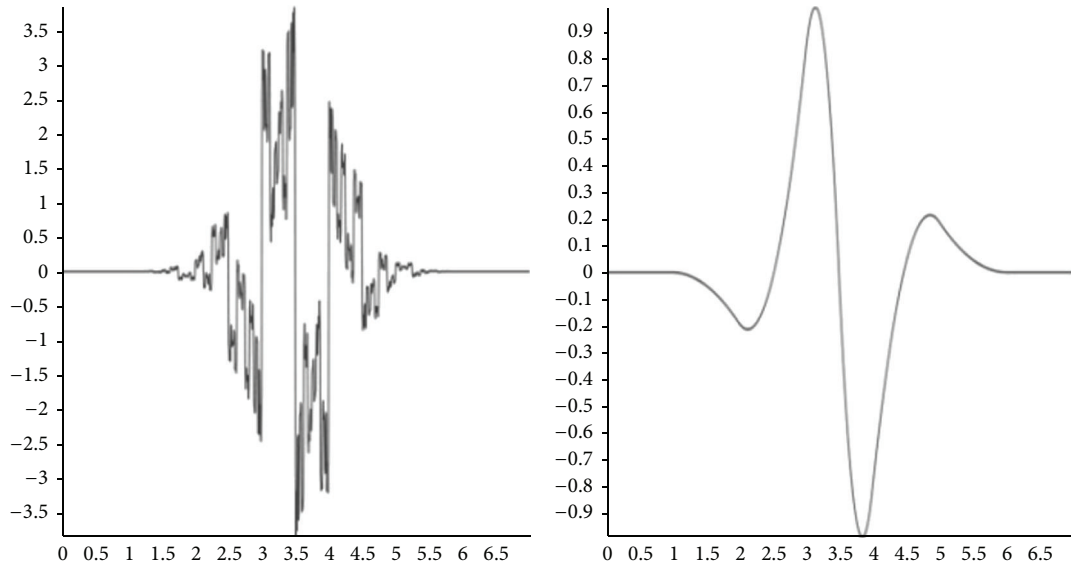


FIGURE 3: Biorthogonal 3.3 wavelet.

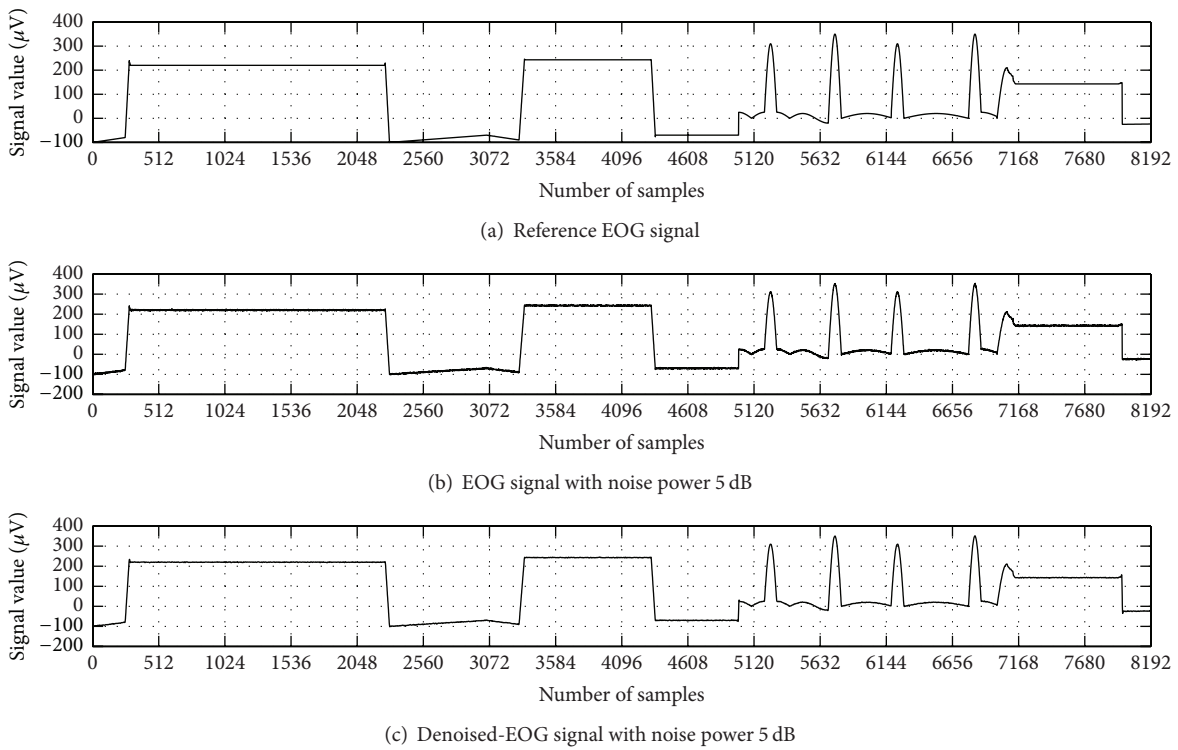


FIGURE 4: (a) Reference EOG signal, (b) EOG signal with noise power 5 dB, and (c) denoised-EOG signal with noise power 5 dB.

(ii) different equal segments of 8192 samples of noisy EOG signal (1:512, 513:1024, 1025:1536, ...). Here one segment is equal to 512 samples.

The RMSE values for each segment are calculated between the reference EOG signal and the denoised-EOG signal in both methods.

Further, the maximum, minimum, mean, and standard deviation values are also calculated from the obtained RMSE values.

Estimation of Root Mean Square Error (RMSE). Consider

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (x(i) - \bar{x}(i))^2}, \quad (4)$$

TABLE 1: RMSE values obtained between reference EOG signal and denoised EOG signals by increasing segments approach using SWT technique.

S. number	Segment of the signal (samples)	EOG5 dB	EOG10 dB	EOG15 dB	EOG20 dB	EOG25 dB
		SNR = 39.04 dB RMSE (μV)	SNR = 33.92 dB RMSE (μV)	SNR = 29.02 dB RMSE (μV)	SNR = 24.12 dB RMSE (μV)	SNR = 19.01 dB RMSE (μV)
1	1:512	8.38	8.39	8.81	9.78	10.92
2	1:1024	5.94	6.05	6.63	7.52	9.35
3	1:1536	4.88	5.02	5.61	6.71	9.06
4	1:2048	4.25	4.41	5.05	6.25	8.91
5	1:2560	0.91	1.56	2.79	4.61	7.81
6	1:3072	0.94	1.57	2.78	4.60	7.89
7	1:3584	3.48	3.69	4.36	5.77	8.60
8	1:4096	3.27	3.49	4.20	5.60	8.49
9	1:4608	0.92	1.55	2.75	4.59	7.96
10	1:5120	1.46	1.93	2.97	4.73	8.04
11	1:5632	1.34	1.84	2.88	4.68	8.05
12	1:6144	1.38	1.87	2.91	4.70	8.07
13	1:6656	1.39	1.87	2.89	4.68	8.12
14	1:7168	2.03	2.37	3.23	4.95	8.25
15	1:7680	1.97	2.33	3.20	4.91	8.29
16	1:8192	1.53	1.99	2.94	4.79	8.22
Maximum value		8.38	8.39	8.81	9.78	10.92
Minimum value		0.91	1.55	2.75	4.59	7.81
Mean (μV)		2.75	3.12	4.00	5.55	8.50
Standard deviation (μV)		2.15	1.97	1.74	1.43	0.78

where N is the length of the EOG signal, $x(i)$ is the reference EOG signal, and $\bar{x}(i)$ is the denoised-EOG signal.

6. Results and Discussions

Let us consider the denoising analysis for the increasing segments of the five noisy EOG signals EOG5 dB, EOG10 dB, EOG15 dB, EOG20 dB, and EOG25 dB. By denoising these noisy EOG signals with SWT technique, the maximum RMSE values obtained are between $8.38 \mu V$ and $10.92 \mu V$. All these maximum values obtained are for the 1:512 samples segment. These high values are due to the less concentration of the EOG signal as shown in Figure 4(b). The minimum RMSE values obtained are between $0.91 \mu V$ and $7.81 \mu V$. But the minimum RMSE values $4.59 \mu V$ and $7.81 \mu V$ obtained by denoising EOG20 dB and EOG25 dB signals are comparatively higher values over the minimum RMSE values obtained by denoising EOG5 dB, EOG10 dB, and EOG15 dB signals. By denoising 16 segments in this method, the mean and standard deviations for the obtained RMSE values are found to be ($2.75 \mu V$ and $2.15 \mu V$, $3.12 \mu V$ and $1.97 \mu V$, and $4.00 \mu V$ and $1.74 \mu V$) for EOG5 dB, EOG10 dB, and EOG15 dB signals. From Table 1, these values are considerably better when compared with EOG20 dB and EOG25 dB signals ($5.55 \mu V$ and $1.43 \mu V$, and $8.50 \mu V$ and $0.78 \mu V$).

Again by denoising all the five noisy EOG signals with RLS adaptive filtering technique, the maximum RMSE values obtained are between $35.92 \mu V$ and $36.49 \mu V$. All these maximum values obtained are for the 1 : 512 samples segment. These high values are due to the less concentration of the EOG

signal as already stated. The minimum RMSE values obtained are between $17.97 \mu V$ and $18.38 \mu V$ as given in Table 2. But these statistical values are very large when compared with the values obtained by SWT technique as given in Table 1.

From the analysis of the different equal segments of the considered noisy EOG signals with SWT technique, the maximum RMSE values obtained are between $8.38 \mu V$ and $11.73 \mu V$ in the segment of 1:512 samples except for the maximum RMSE value $11.73 \mu V$ obtained for the segment of 4097:4068 samples. This is negligible when compared with RMSE value $10.92 \mu V$ obtained for the segment of 1:512 samples. The minimum RMSE values are between $0.75 \mu V$ and $2.44 \mu V$, respectively, for EOG5 dB, EOG10 dB, and EOG15 dB signals which are very less when compared with $4.16 \mu V$ and $7.28 \mu V$ RMSE values obtained by denoising EOG20 dB and EOG25 dB signals. For EOG5 dB, EOG10 dB, and EOG15 dB signals analysis, the mean and standard deviations are found to be $3.35 \mu V$ and $3.21 \mu V$, $3.77 \mu V$ and $2.97 \mu V$, and $3.99 \mu V$ and $2.61 \mu V$. These values are considerably better when compared with EOG20 dB and EOG25 dB signals which are $6.11 \mu V$ and $2.23 \mu V$, and $9.17 \mu V$ and $1.44 \mu V$ as given in Table 3.

For RLS adaptive filtering technique, the maximum RMSE values obtained are between $49.52 \mu V$ and $50.60 \mu V$. The minimum RMSE values are between $13.97 \mu V$ and $14.45 \mu V$, respectively. The mean and standard deviations which are obtained are extremely large when compared with the values obtained by SWT technique as given in Tables 3 and 4.

The denoised-EOG5 dB (Figure 4(c)) and denoised-EOG20 dB (Figure 5(c)) signals with SWT technique are

TABLE 2: RMSE values obtained between reference EOG signal and denoised EOG signals by increasing segments approach using RLS adaptive filtering technique.

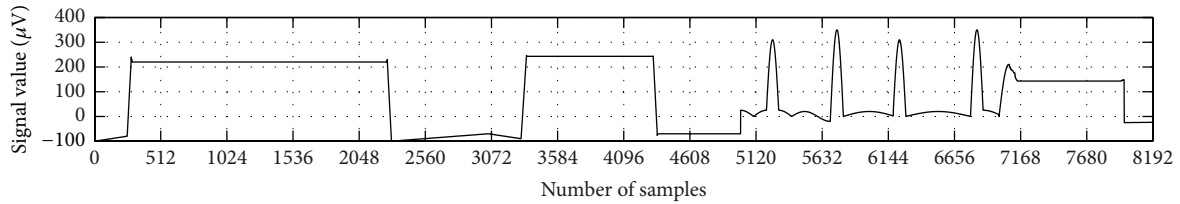
S. number	Segment of the signal (samples)	EOG5 dB	EOG10 dB	EOG15 dB	EOG20 dB	EOG25 dB
		SNR = 39.04 dB	SNR = 33.92 dB	SNR = 29.02 dB	SNR = 24.12 dB	SNR = 19.01 dB
		RMSE (μV)	RMSE (μV)	RMSE (μV)	RMSE (μV)	RMSE (μV)
1	1:512	36.12	35.92	36.42	36.49	36.20
2	1:1024	25.54	25.40	25.76	25.84	25.71
3	1:1536	20.85	20.75	21.05	21.13	21.12
4	1:2048	18.06	17.97	18.24	18.33	18.38
5	1:2560	22.00	21.93	22.16	22.18	22.15
6	1:3072	22.09	20.03	20.23	20.26	20.28
7	1:3584	22.05	21.99	22.12	22.19	22.11
8	1:4096	20.63	20.57	20.69	20.77	20.72
9	1:4608	22.30	22.32	22.40	22.57	22.51
10	1:5120	21.63	21.65	21.74	21.88	21.86
11	1:5632	23.80	23.81	23.94	24.11	23.98
12	1:6144	26.69	26.69	26.83	27.04	26.87
13	1:6656	28.13	28.15	28.22	28.50	28.31
14	1:7168	30.08	30.13	30.21	30.44	30.32
15	1:7680	29.06	29.10	29.19	29.41	29.31
16	1:8192	28.87	28.91	28.98	29.16	29.10
Maximum value		36.12	35.92	36.42	36.49	36.20
Minimum value		18.06	17.97	18.24	18.33	18.38
Mean (μV)		24.87	24.71	24.89	25.02	24.93
Standard deviation (μV)		4.65	4.76	4.78	4.81	4.74

TABLE 3: RMSE values obtained between reference EOG signal and denoised EOG signals by different equal segments approach using SWT technique.

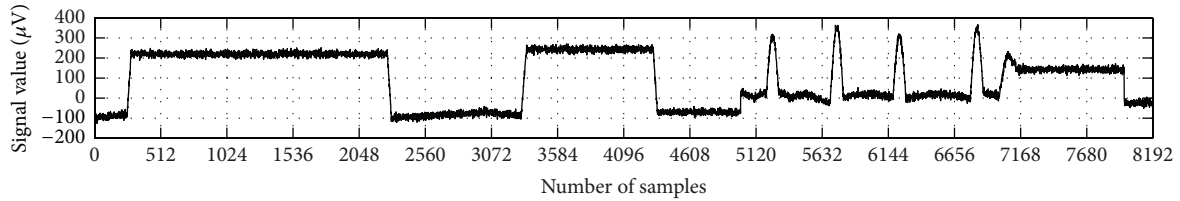
S. number	Segment of the signal (samples)	EOG5 dB	EOG10 dB	EOG15 dB	EOG20 dB	EOG25 dB
		SNR = 39.04 dB	SNR = 33.92 dB	SNR = 29.02 dB	SNR = 24.12 dB	SNR = 19.01 dB
		RMSE (μV)	RMSE (μV)	RMSE (μV)	RMSE (μV)	RMSE (μV)
1	1:512	8.38	8.39	8.81	9.78	10.92
2	513:1024	0.75	1.56	3.06	4.34	7.28
3	1025:1536	0.88	1.57	2.82	4.50	7.93
4	1537:2048	0.82	1.46	2.47	4.66	8.35
5	2049:2560	8.05	8.18	8.50	9.52	11.15
6	2561:3072	0.96	1.54	2.68	4.58	8.28
7	3073:3584	8.21	8.32	8.66	9.49	11.54
8	3585:4096	0.81	1.39	2.71	4.32	7.89
9	4097:4608	8.18	8.27	8.55	9.28	11.73
10	4609:5120	3.27	3.55	4.10	5.46	8.70
11	5121:5632	0.95	1.59	2.44	4.58	8.24
12	5633:6144	1.05	1.62	2.87	4.79	8.27
13	6145:6656	1.06	1.59	2.49	4.16	8.59
14	6657:7168	3.53	3.76	4.16	6.10	8.81
15	7169:7680	0.84	1.49	2.61	4.31	8.64
16	7681:8192	5.89	6.09	6.36	7.84	10.31
Maximum value		8.38	8.39	8.81	9.78	11.73
Minimum value		0.75	1.39	2.44	4.16	7.28
Mean (μV)		3.35	3.77	3.99	6.11	9.17
Standard deviation (μV)		3.21	2.97	2.61	2.23	1.44

TABLE 4: RMSE values obtained between reference EOG signal and denoised EOG signals by different equal segments approach using RLS adaptive filtering technique.

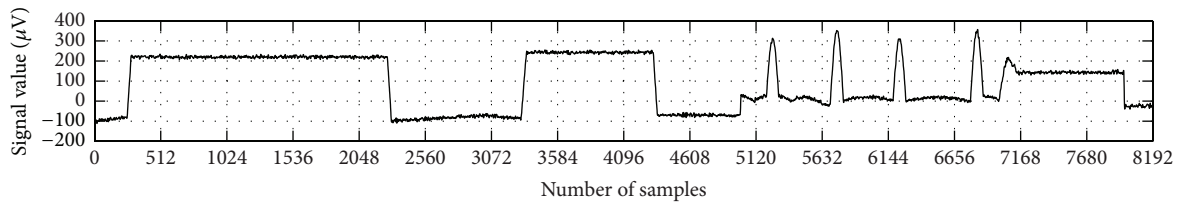
S. number	Segment of the signal (samples)	EOG5 dB	EOG10 dB	EOG15 dB	EOG20 dB	EOG25 dB
		SNR = 39.04 dB RMSE (μV)	SNR = 33.92 dB RMSE (μV)	SNR = 29.02 dB RMSE (μV)	SNR = 24.12 dB RMSE (μV)	SNR = 19.01 dB RMSE (μV)
2	513:1024	34.47	34.48	34.39	34.60	34.45
3	1025:1536	34.45	34.39	34.35	34.60	34.65
4	1537:2048	34.42	34.43	34.49	34.38	34.60
5	2049:2560	47.94	47.92	48.07	48.10	47.87
6	2561:3072	13.97	13.99	14.07	14.00	14.45
7	3073:3584	24.27	33.29	33.09	33.37	33.01
8	3585:4096	38.03	38.03	38.08	37.97	38.31
9	4097:4608	50.17	50.43	50.28	35.88	50.60
10	4609:5120	18.06	18.04	18.24	18.01	18.45
11	5121:5632	39.40	39.41	39.75	40.14	39.33
12	5633:6144	48.21	48.09	48.39	48.80	48.37
13	6145:6656	41.69	41.89	41.43	41.85	41.92
14	6657:7168	48.86	19.08	49.26	49.52	49.54
15	7169:7680	22.41	22.33	22.40	22.59	23.02
16	7681:8192	34.11	34.12	34.10	33.49	33.95
Maximum value		50.17	50.43	50.28	49.52	50.60
Minimum value		13.97	13.99	14.07	14.00	14.45
Mean (μV)		35.36	34.00	36.02	35.15	36.17
Standard deviation (μV)		11.46	11.29	11.11	10.51	11.03



(a) Reference EOG signal



(b) EOG signal with noise power 20 dB



(c) Denoised-EOG signal with noise power 20 dB

FIGURE 5: (a) Reference EOG signal, (b) EOG signal with noise power 20 dB, and (c) denoised-EOG signal with noise power 20 dB.

shown in Figures 4 and 5 along with reference EOG signals (Figures 4(a) and 5(a)).

7. Conclusion

The present study deals with the optimization of SWT technique in denoising the EOG signals with respect to different levels of noise power. The findings suggest that SWT technique is a suitable technique to denoise the EOG signal with noise powers up to 15 dB in terms of RMSE values. Any noise power more than the 15 dB will not give us quality output. The results obtained are remarkable with very low RMSE values at simulation level for considerable noise powers. Even when the results are compared with RLS adaptive filtering technique analysis, which was proven to be the best adaptive filter algorithm for EOG signal processing [3], the SWT technique yielded better results. Thus it may be concluded that, by the proposed method of denoising, the quality EOG signal can be useful in the field of medicine for effective diagnosis of various neurological and eye disorders.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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