

# Examination of Temporal Characteristics of Epileptic EEG Subbands Based on the Local Min-Max

Suparek Janjarasjitt and Kenneth A. Loparo

**Abstract**—Temporal characteristics of EEG signal provide insight into the state of the brain. In this work, temporal characteristics of spectral subbands of epileptic EEG data associated with different pathological states of the brain including  $\delta$ ,  $\theta$ ,  $\alpha$ ,  $\beta$  and  $\gamma$  subbands are examined using two features of local minima and local maxima, referred to the number of local min-max and the variance of local min-max intervals. The computational results show the substantial differences between the temporal characteristics of the epileptic EEG signal during an epileptic seizure activity and during a non-seizure period in any subband. Furthermore, the epileptic EEG signal during an epileptic seizure activity exhibits different temporal characteristics between the low and high frequency subbands as compared to the epileptic EEG signal during a non-seizure period.

**Index Terms**—electroencephalogram, epilepsy, seizure, local min-max, subbands.

## I. INTRODUCTION

EPILEPSY is a common brain disorder in which clusters of neurons signal abnormally [1]. More than 50 million individuals worldwide, about 1% of the world's population are affected by epilepsy [2]. In epilepsy, the normal pattern of neuronal activity is disturbed, causing strange sensations, emotions, and behavior, that sometimes include convulsions, muscle spasms, and loss of consciousness [1]. There are many possible causes for seizures ranging from illness to brain damage to abnormal brain development [1], and epileptic seizures are manifestations of epilepsy [3]. The electroencephalogram (EEG) is a signal that quantifies the electrical activity of the brain, usually from scalp recordings and is commonly used to assess and detect brain abnormalities, and is crucial for the diagnosis of epilepsy [1].

Temporal patterns of EEG signals can provide important information and such features can be obtained by visual inspection/analysis and using computational tools. Concepts and computational tools derived from the study of complex systems including nonlinear dynamics have gained increasing interest for applications in biology and medicine [4]. The correlation integral and dimension are common nonlinear dynamical analysis techniques that have been applied to EEG signal analysis [5] to study various aspects. Epilepsy is an important application for nonlinear EEG analysis [6], [7].

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In this paper, the temporal characteristics of epileptic EEG data are examined in terms of *local minima* and *local maxima*. There are a variety of different approaches to determining local minima and maxima and typically, local min-max detection algorithms rely on thresholding the magnitudes in a specified time window. The local minima (local maxima) here is defined as a point whose amplitude is less (greater) than its neighbors. The local minima and maxima thus specify extreme points of the signal where the magnitude changes direction. Previously, the characteristics of the local min-max of the epileptic EEG signals were investigated in [8]–[10]. Also, in [11], the characteristics of the local min-max were examined in the sleep EEG data associated with various sleep stages.

The features of the local minima and maxima examined in this paper are the total number of the local minima and maxima, referred to as the number of local min-max, and the variance of the sequence of distances between two consecutive local minima and maxima, referred to as the variance of local min-max intervals. In this paper, as compared to the full-spectrum of EEG signal investigated in [8]–[10], the temporal characteristics of five spectral subbands of intracranial EEG data obtained from epilepsy patients corresponding to different pathological states of the brain (i.e., during a non-seizure period and during an epileptic seizure activity) including  $\delta$  (1–4 Hz),  $\theta$  (4–8 Hz),  $\alpha$  (8–13 Hz),  $\beta$  (14–30 Hz), and  $\gamma$  (31–80 Hz) are examined.

From the computational results, it is shown that there are substantial differences between the temporal characteristics of the epileptic EEG signals during an epileptic seizure activity and during a non-seizure period in any subbands. Further, the number of local min-max  $N_\lambda$  of epileptic EEG signal during an epileptic seizure activity is significantly different from that during a non-seizure period at the  $\alpha$ ,  $\beta$  and  $\gamma$  subbands, and the variance of local min-max intervals  $V_\lambda$  of epileptic EEG signal during an epileptic seizure activity is significantly different from that during a non-seizure period at the  $\delta$ ,  $\alpha$  and  $\gamma$  subbands. Also, the epileptic EEG signal during an epileptic seizure activity corresponds to different temporal characteristics (i.e., the number of local min-max  $N_\lambda$  and the variance of local min-max intervals  $V_\lambda$ ) at the lower and higher frequency subbands as compared to that during a non-seizure period.

## II. METHODS

### A. Data and Subjects

The intracranial EEG data of epilepsy patients examined in this study were obtained from the Department of Epileptology, University of Bonn (available online

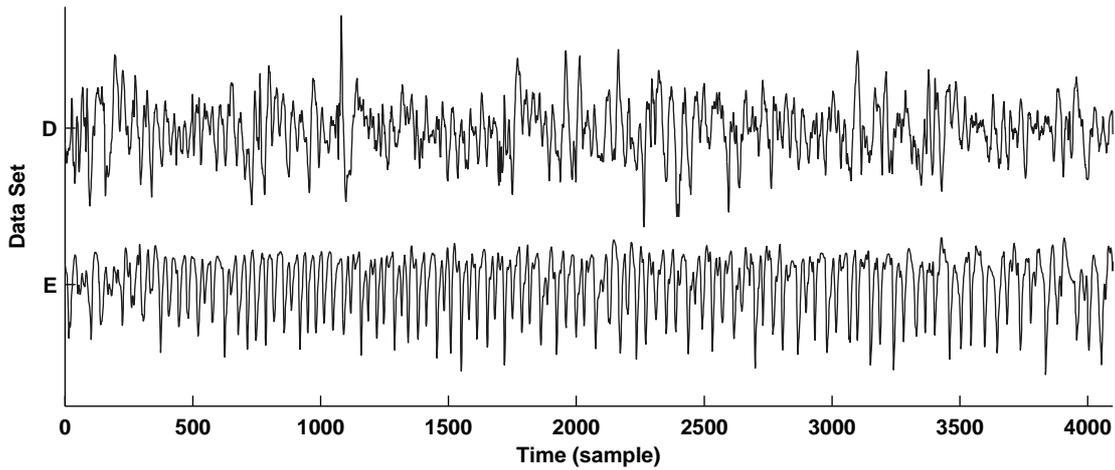


Fig. 1. Examples of intracranial EEG signals of the data sets *D* (non-seizure) and *E* (seizure).

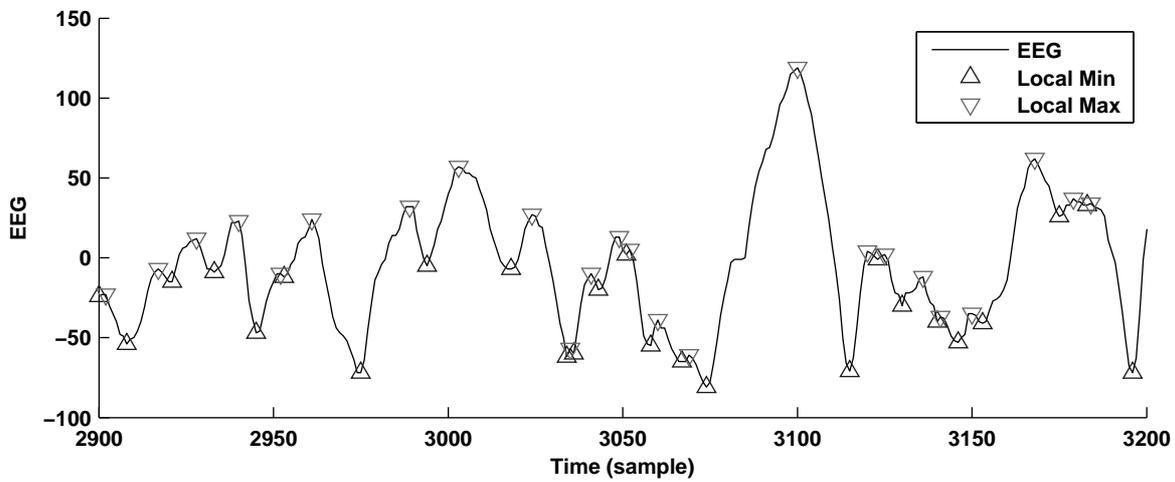


Fig. 2. Local minima  $\lambda_{\min}$  plotted in '△' and local maxima  $\lambda_{\max}$  plotted in '▽'.

at [http://epileptologie-bonn.de/cms/front\\_content.php?idcat=193&lang=3&changelang=3](http://epileptologie-bonn.de/cms/front_content.php?idcat=193&lang=3&changelang=3)) and originated from the study presented in [12]. Two sets of EEG data, referred to as sets *D* and *E*, were recorded using intracranial electrodes from five epilepsy patients. Both sets of EEG data were recorded from within the epileptogenic zone. Further, the EEG data in the set *D* corresponds to non-seizure periods while the EEG data in the set *E* were recorded during seizure activity.

Each epileptic EEG data set contains 100 epochs of a single-channel that were selected to be free of artifacts such as muscle activity and eye movements. The length of each epoch is 23.6 seconds (4097 samples). In addition, the epochs of the EEG signal satisfied the weak stationarity criterion given in [12]. The sampling rate of the data is 173.61 Hz and a bandpass filter with passband between 0.50 Hz and 85 Hz was used during signal acquisition. Examples of the epileptic EEG signals for each data set are depicted in Fig. 1.

### B. Local Minima and Local Maxima

Let the sequence  $\{x[n]\}$  be samples from a signal for  $n = 0, 1, \dots, N - 1$ , where  $N$  is the length of signal. The local minima  $\lambda_{\min}$  of the signal  $x$  are defined as point whose amplitude is less than that of its consecutive preceding and

succeeding points while the local maxima  $\lambda_{\max}$  are defined as point whose amplitude is greater than that of its consecutive preceding and succeeding points.

Computationally, the local minima  $\lambda_{\min}$  and maxima  $\lambda_{\max}$  are given by

$$\lambda_{\min} = \left\{ n = \left\lceil \frac{s+t}{2} \right\rceil \mid x[s-1] > x[n] \text{ and } x[t+1] > x[n] \right\} \quad (1)$$

and

$$\lambda_{\max} = \left\{ n = \left\lceil \frac{s+t}{2} \right\rceil \mid x[s-1] < x[n] \text{ and } x[t+1] < x[n] \right\} \quad (2)$$

where  $x[s] = x[s+1] = \dots = x[n] = x[n+1] = \dots = x[t]$ . The local minima and maxima of an EEG signal are depicted in Fig. 2.

### C. Local Min-Max Characteristics

Temporal characteristics of the spectral subbands of the EEG signals are examined based on two features quantified

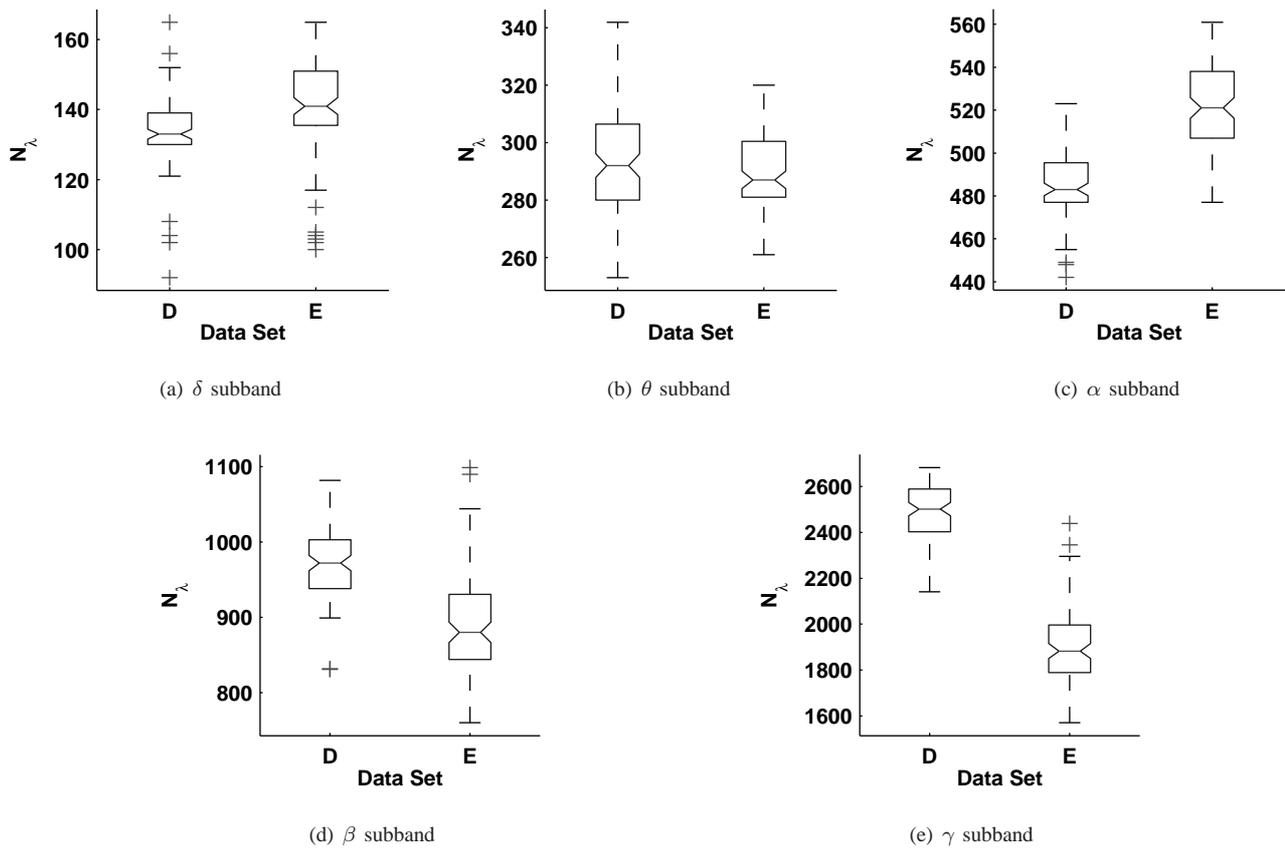


Fig. 3. Comparison of the number of local min-max  $N_\lambda$  of the spectral subbands of the EEG data of sets  $D$  and  $E$ .

from the local minima  $\lambda_{\min}$  and the local maxima  $\lambda_{\max}$  defined as follows:

1) *Number of local min-max:*

The number of local min-max  $N_\lambda$  is the total number of both local minima  $\lambda_{\min}$  and local maxima  $\lambda_{\max}$  of the EEG signal.

2) *Variance of local min-max intervals:*

The variance of local min-max intervals  $V_\lambda$  is the variance of the sequence of distances between two consecutive local minima and maxima  $i_\lambda$ .

*D. Analytical Framework*

In this study, the intracranial EEG signal of the EEG data of sets  $D$  and  $E$  is divided into five spectral subbands:  $\delta$  (1–4 Hz),  $\theta$  (4–8 Hz),  $\alpha$  (8–13 Hz),  $\beta$  (14–30 Hz), and  $\gamma$  (31–80 Hz). The temporal characteristics, i.e., the number of local min-max  $N_\lambda$  and the variance of local min-max intervals  $V_\lambda$ , of all five spectral subbands including the  $\delta$ ,  $\theta$ ,  $\alpha$ ,  $\beta$  and  $\gamma$  subbands are examined. The two-sample  $t$ -test is performed to determine whether both local min-max characteristics of each spectral subbands of EEG data set  $D$  significantly differs from that of the data set  $E$ .

III. RESULTS

The box plots shown in Fig. 3(a), Fig. 3(b), Fig. 3(c), Fig. 3(d) and Fig. 3(e), respectively, compare the number of local min-max  $N_\lambda$  of the  $\delta$ ,  $\theta$ ,  $\alpha$ ,  $\beta$  and  $\gamma$  subbands of the epileptic EEG data sets  $D$  and  $E$ . The variance of local min-max intervals  $V_\lambda$  of the  $\delta$ ,  $\theta$ ,  $\alpha$ ,  $\beta$  and  $\gamma$  subbands of the

epileptic EEG data sets  $D$  and  $E$  are compared in Fig. 4(a), Fig. 4(b), Fig. 4(c), Fig. 4(d) and Fig. 4(e), respectively. The central mark of each box is the median mark while the edges of the box are the 25th and 75th percentiles. In addition, the mean, median and standard deviation of both local min-max characteristics, i.e.,  $N_\lambda$  and  $V_\lambda$ , of the EEG subbands are summarized in Table I. Evidently, the epileptic EEG data of sets  $D$  and  $E$  associate with different characteristics of the local min-max of various spectral subbands, i.e.,  $\delta$ ,  $\theta$ ,  $\alpha$ ,  $\beta$  and  $\gamma$ . The number of local min-max  $N_\lambda$  of the epileptic EEG data of both sets  $D$  and  $E$  tends to increase with higher frequency subbands while the variance of local min-max intervals  $V_\lambda$  of the epileptic EEG data of both sets  $D$  and  $E$  tends to decrease with higher frequency subbands.

The number of local min-max  $N_\lambda$  of the  $\delta$  and  $\theta$  subbands of the epileptic EEG data of set  $E$  tends to be higher than that of the data set  $D$ . On the contrary, the number of local min-max  $N_\lambda$  of the  $\beta$  and  $\gamma$  subbands of the epileptic EEG data of set  $E$  tends to be less than that of the data set  $D$ . Also, the variance of local min-max intervals  $V_\lambda$  of the epileptic EEG data of set  $E$  tends to be lower than that of the data set  $D$  at the lower frequency subbands (i.e.,  $\delta$ ,  $\theta$  and  $\alpha$ ) while, at the higher frequency subbands (i.e.,  $\beta$  and  $\gamma$ ), the variance of local min-max intervals  $V_\lambda$  of the epileptic EEG data of set  $E$  tends to be higher than that of the data set  $D$ . Note that the degree of difference between the number of local min-max  $N_\lambda$  of the spectral subbands of the epileptic EEG data sets tends to increase with higher frequency subbands.

The results of the two-sample  $t$ -test comparing between the local min-max characteristics, i.e.,  $N_\lambda$  and  $V_\lambda$ , of the

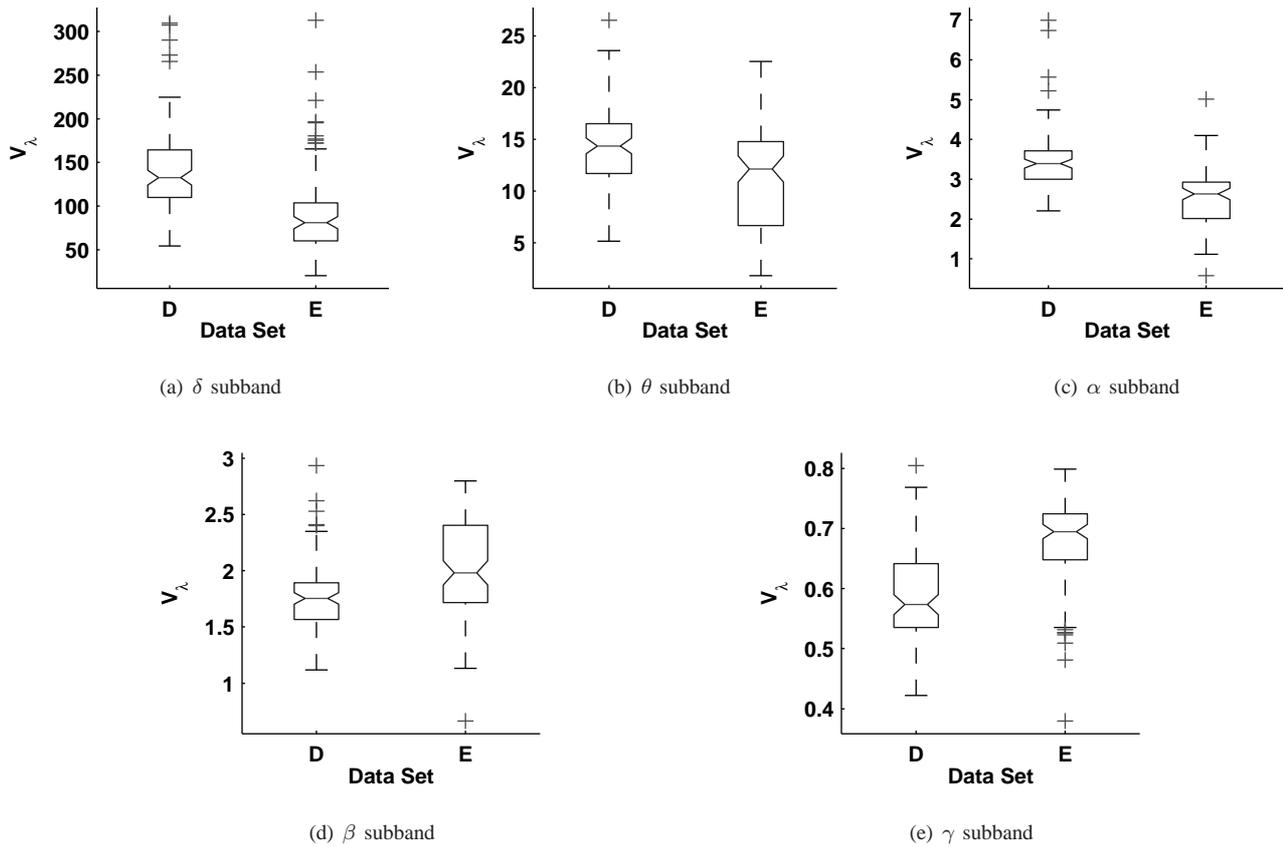


Fig. 4. Comparison of the variance of local min-max intervals  $V_\lambda$  of the spectral subbands of the EEG data of sets  $D$  and  $E$ .

TABLE I  
STATISTICAL VALUES OF THE LOCAL MIN-MAX CHARACTERISTICS OF THE SPECTRAL SUBBANDS OF THE EEG DATA OF SETS  $D$  AND  $E$ .

Feature	Data Set	Subband	Mean	Median	S. D.
$N_\lambda$	$D$	$\delta$	133.19	133.00	9.90
$N_\lambda$	$D$	$\theta$	293.74	292.00	20.58
$N_\lambda$	$D$	$\alpha$	483.87	483.00	15.57
$N_\lambda$	$D$	$\beta$	970.55	972.00	47.11
$N_\lambda$	$D$	$\gamma$	2477.78	2502.00	131.03
$N_\lambda$	$E$	$\delta$	140.26	141.00	14.60
$N_\lambda$	$E$	$\theta$	290.06	287.00	12.83
$N_\lambda$	$E$	$\alpha$	520.74	521.00	18.63
$N_\lambda$	$E$	$\beta$	889.32	880.00	70.88
$N_\lambda$	$E$	$\gamma$	1903.43	1883.00	160.84
$V_\lambda$	$D$	$\delta$	139.79	132.64	50.51
$V_\lambda$	$D$	$\theta$	14.34	14.36	4.10
$V_\lambda$	$D$	$\alpha$	3.48	3.39	0.75
$V_\lambda$	$D$	$\beta$	1.78	1.75	0.31
$V_\lambda$	$D$	$\gamma$	0.59	0.57	0.08
$V_\lambda$	$E$	$\delta$	91.63	81.07	49.84
$V_\lambda$	$E$	$\theta$	11.09	12.13	5.27
$V_\lambda$	$E$	$\alpha$	2.50	2.63	0.77
$V_\lambda$	$E$	$\beta$	2.01	1.98	0.43
$V_\lambda$	$E$	$\gamma$	0.68	0.69	0.08

spectral subbands, i.e.,  $\delta$ ,  $\theta$ ,  $\alpha$ ,  $\beta$  and  $\gamma$ , of the epileptic EEG data of sets  $D$  and  $E$  are summarized in Table II. From the two-sample  $t$ -test for the number of local min-max  $N_\lambda$ , the results suggest that there are statistically significant differences between the number of local min-max  $N_\lambda$  of the  $\alpha$ ,  $\beta$  and  $\gamma$  subbands of the epileptic EEG data of sets  $D$  and  $E$  with a  $p$ -value of 0.000001. Furthermore, the results of two-sample  $t$ -test for the variance of local min-max intervals  $V_\lambda$  suggest that there are statistically significant differences between the variance of local min-max intervals  $V_\lambda$  of the  $\delta$ ,  $\alpha$  and  $\gamma$  subbands of the epileptic EEG data of sets  $D$  and  $E$  with a  $p$ -value of 0.000001.

#### IV. CONCLUSIONS AND DISCUSSION

In this paper, the temporal characteristics of the spectral subbands of epileptic EEG data as quantified from the local minima and maxima are examined. The epileptic EEGs were divided into five subbands:  $\delta$ ,  $\theta$ ,  $\alpha$ ,  $\beta$ , and  $\gamma$ . Two local min-max characteristics of the subbands of epileptic EEG data examined are referred to as the number of local min-max  $N_\lambda$  and the variance of local min-max intervals  $V_\lambda$ . In [9], [10], it was shown that the number of local min-max  $N_\lambda$  of the full-spectrum EEG signal during an epileptic seizure activity tends to be lower than that during a non-seizure period while the variance of local min-max intervals  $V_\lambda$  of the full-spectrum EEG signal during an epileptic seizure activity tends to be higher than that during a non-seizure period. Moreover, a decrease of the number of local min-max  $N_\lambda$  and an increase of the variance of local min-max intervals

TABLE II  
RESULTS OF  $t$ -TEST OF THE LOCAL MIN-MAX CHARACTERISTICS OF  
THE SPECTRAL SUBBANDS OF THE EEG DATA OF SETS  $D$  AND  $E$ .

Feature	Subband	Hypothesis	$p$ -value
$N_\lambda$	$\delta$	$H_0$ cannot be rejected	$p = 0.000087$
$N_\lambda$	$\theta$	$H_0$ cannot be rejected	$p = 0.130718$
$N_\lambda$	$\alpha$	$H_0$ can be rejected	$p \ll 0.000001$
$N_\lambda$	$\beta$	$H_0$ can be rejected	$p \ll 0.000001$
$N_\lambda$	$\gamma$	$H_0$ can be rejected	$p \ll 0.000001$
$V_\lambda$	$\delta$	$H_0$ can be rejected	$p < 0.000001$
$V_\lambda$	$\theta$	$H_0$ cannot be rejected	$p = 0.000002$
$V_\lambda$	$\alpha$	$H_0$ can be rejected	$p \ll 0.000001$
$V_\lambda$	$\beta$	$H_0$ cannot be rejected	$p = 0.000028$
$V_\lambda$	$\gamma$	$H_0$ can be rejected	$p \ll 0.000001$

$V_\lambda$  of the full-spectrum long-term electrocorticogram (ECoG) signal during a seizure onset were shown in [8].

From the computational results, it is shown that both the number of local min-max  $N_\lambda$  and the variance of local min-max intervals  $V_\lambda$  of various subbands of the epileptic EEG data for both non-seizure and seizure periods are substantially different. The number of local min-max  $N_\lambda$  increases while the variance of local min-max intervals  $V_\lambda$  with a higher frequency subband. This is as expected since at a higher-frequency subband the EEG signal contains faster oscillating components. As a result, the amplitude of EEG signal varies faster and the interval between extrema of EEG signal becomes narrower. Further, the temporal characteristics of the epileptic EEG signals during an epileptic seizure activity and a non-seizure period are also basically different for each subbands.

At the low frequency subbands (i.e.,  $\delta$  and  $\alpha$ ) the number of local min-max  $N_\lambda$  of the epileptic EEG data of set  $D$  tends to be higher than that of set  $E$  but the number of local min-max  $N_\lambda$  of the epileptic EEG data of set  $D$  at the high frequency subbands (i.e.,  $\beta$  and  $\gamma$ ) tends to be lower than that of set  $E$ . This indicates that there is a higher rate of amplitude variation of the low frequency contents of EEG signal during an epileptic seizure activity than that during a non-seizure period. On the other hand, the rate of amplitude variation of the high frequency contents of EEG signal during a non-seizure period tends to be higher than that during an epileptic seizure activity.

In addition, the variance of local min-max intervals  $V_\lambda$  of the epileptic EEG data of set  $D$  at the low frequency subbands (i.e.,  $\delta$ ,  $\theta$  and  $\alpha$ ) tends to be lower than that of

set  $E$  but at the high frequency subbands (i.e.,  $\beta$  and  $\gamma$ ) the variance of local min-max intervals  $V_\lambda$  of the epileptic EEG data of set  $D$  tends to be higher than that of set  $E$ . This indicates that the regularity of amplitude variation of the low frequency contents of the epileptic EEG signal during an epileptic seizure activity is lower than that during a non-seizure period. The regularity of amplitude variation of the high frequency contents of the epileptic EEG signal during an epileptic seizure activity is higher than that during a non-seizure period.

Therefore, as quantified using the local minima and maxima, at the low frequency subbands the rate of amplitude variation of epileptic EEG signal during an epileptic seizure activity is higher but its temporal variability is less as compared to that during a non-seizure period. This is however reversed at the high frequency subbands. The rate of amplitude variation of epileptic EEG signal during an epileptic seizure activity is lower while the regularity of amplitude variation is less as compared to that during a non-seizure period.

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