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A Measure of Phase Locking of Cortico-cortical Brain Rhythms in Meditation EEG

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***Abstract*:** *The neural dynamics and its interpretation is a bit challenging task in the measure of synchronization. In this paper, in order to infer the neural mechanism in a different cognitive activity like meditation was observed through EEG signal and was investigated using Phase Synchrony (PS) estimation method. EEG signals are highly oscillating in nature. Its interpretation, on generalized phase synchrony, has studied to extract neural information transfer and neuronal dynamics of a complex system of the brain, which results from time-varying interactions of several subsystems. In this work, phase synchrony is used to study the simultaneous occurrences of peaks and valleys within EEG activities during meditation to obtain the transient spectral perturbation between different cortical areas. The result of both Phase Locking Value (PLV) and Improved Phase Locking Value (IPLV) has been shown and analyzed in meditation EEG signals. IPLV outperforms the results of PLV in EEG signal obtained from 23 meditators during meditation. Combining, we found that neural synchrony modulated the EEG signals independently. This finding has strong implication for interpretation of functional connectivity of EEG signal during meditation.*

Keywords: *phase locking value, EEG, meditation, Hilbert transform.*

1. Introduction

Electroencephalogram (EEG) is a unique and valuable measurement method to record the electrical activity of the brain. Because of its high temporal resolution, low cost and non-invasive way of measurement, it is most widely used, to measure the intensity of brain waves changes which depends on the internal brain activity [1]. Brain waves are time varying in nature, due to the various cognitive activity involved. Meditation and its effect on brain activity became a focus of collaborative research in neuroscience, psychology, and neurobiology in the latter half of the 20th century. Moreover, particular types of research on meditation practices [2], [3] are required to define the effect of meditation on EEG patterns. According to literature, alterations in brain activities during meditation can be stated in two categories: 1. State changes and 2. Trait changes and these are the outcomes of long-term meditation practitioners [4].

Synchronization is proved to be an important measure of neuroscience that gives the information about neural coordination or synchronization of a particular cognitive task [5]. Out of many synchronization measures, phase synchrony (PS) is an attractive mechanism to measure the directional neural oscillation that helps to infer the functional connectivity in neural signals. It is hypothesized to reflect the efficiency of information transfer between the signals and functional integration in different brain regions during the certain cognitive task [5]. In this paper, the study raises an attractive mechanism of neural oscillation during the cognitive task of meditation. It mainly refers to the interdependent relationship between the instantaneous phase of two signals just to enhance the EEG power as well as its amplitude. It also demonstrates the degree of leading as well as lagging relation between the EEG signals through electrode pair [5]. In the theory of phase synchronization, zero lag phase synchrony events are the primary interest of inferring the functional neural connectivity. Based on the number of inputs, phase synchronization can be measured both for bivariate as well as for multivariate signals. Several conventional signal processing approaches have developed to measure the EEG phase synchrony [6]. Modern signal processing methods such as time analysis, frequency analysis, and wavelet transform have been reported in the literature [6]. Apart from these above methods, the traditional method for measuring phase synchrony has also been developed which includes the detection of phase locking values (PLV) between the bivariate electrodes, simply by calculating the Instantaneous Phase (IP) using Hilbert Transform (HT) [6]. However, it was found that HT is suitable only for analyzing stationary signals. Because of non-linear and non-stationary nature of EEG signals, it is not suggestive to apply HT directly [7]. The improved method of calculating phase locking value is based on Hilbert-Huang transform (HHT). This approach has used the empirical mode decomposition (EMD) method to decompose any time-varying data into a finite set of functions called intrinsic mode function (IMF) [8]. It shows high precision rate than the traditional method, which also reduces the effect of spectral leakage and harmonic distortion by interweaving modulation.

This paper presents a comparative study between PLV and IPLV, deploy in HT and HHT based methods in the application of meditation EEG. PLV and IPLV are applied in EEG signals acquired during meditation, to measure the phase synchrony (PS) between different brain regions. One of the methodological issues of PS analysis, i.e. instantaneous phase (IP) and influence of measurement noise [9] cause the PS measure erroneous. The phase synchronization of the signal gives the information about the drift of the EEG signals at a particular instance of time irrespective of the amplitude of the signal. Calculating PLV for Time-frequency analysis using traditional method is not adaptive as compared to improved PLV method, as traditional requires an understanding of the hidden mathematical rules whereas improved PLV method avoids it.

The motivation for using the improved method of calculating the phase locking value is that this approach is a unique indicator of functional integration than amplitude dependent measure such as energy. The PLV for synchronization of phase requires a complete phase information of the signal [10]. In traditional methods, the spectral analysis is performed using the HT followed by an instantaneous frequency computation to get the IP values which are suitable for analysing the stationary signals [10]. However, EEG like non-stationary signal, HT is not suggestive to apply directly. It was also found that the empirical approach using HHT can easily be applied to a dataset rather than using theoretical tools or proper mathematical calculations [11]. This method is useful to analyse any non-linear signal by generating the lower frequency content of any signal using HHT algorithm. Also, we can use the mathematical tool of HHT in one-dimensional signal processing as well as in two-dimensional image processing [12].

The phases of different brain units behaved as coupled oscillators which can be analysed and characterized to detect the synchronization regardless of the relation between signal amplitudes. The various aspects of brain connectivity can be reflected by using such frameworks, such as undirected measures of association (e.g. phase synchronization index, coherence, and mutual information,) and Granger causality based directed measures (e.g., transfer entropy and partial directed coherence) [13].

The paper is organized as follows. Section II presents the methods of experimentation, data acquisition, and pre-processing techniques. Section III gives the general concept of phase synchrony estimation. Section IV discusses the comparison between PLV and Improved PLV. Followed by, section V talks about their results and discussion. Finally, Section VI mentions the concluding remarks and suggestions for future scope of the phase synchrony of EEG signals.

2. Methods

The present work analyses the result of an experiment designed to obtain EEG signal during meditation (Kriya yoga) [14] to infer the neural dynamics of meditation EEG. The experimentation and data acquisition are mentioned in brief as below-

2.1. Experimentation and Design Protocol

The objective of the experiment is to capture the various physiological signal during meditation. The major concern is related to the measurement of EEG signals which is directly related to the human brain activity in meditation. Meditators are instructed by guided meditation and EEG data is being acquired during meditation. About 4.17mins of data has been analysed for the measure of PLV and IPLV based PS measure.

2.2. EEG Data Acquisition and Preprocessing

The EEG signals have been collected from 23 experienced meditators from Hariharanand Balashram, Odisha, India. A 32 channels EEG electrode cap has been used with standard international 10/20 electrode placement system [15]. The data has been acquired while the meditators were meditating, with sampling frequency of about 256Hz. A general block diagram of pre-processing and HT estimation is shown in Fig. 1.

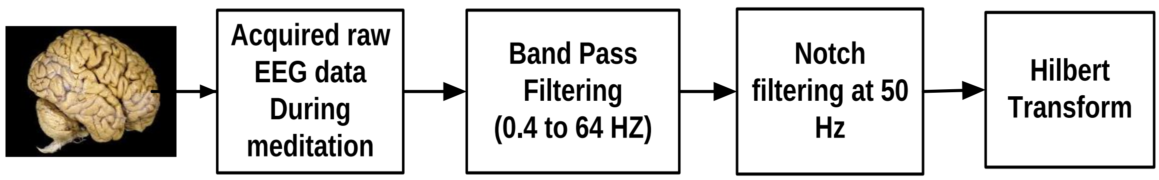


Fig. 1: General block diagram of phase locking value estimation.

The following pre-processing steps are considered

- Band pass filtering- The acquired raw EEG signal are band pass filtered from 0.4 to 64Hz to bring the signal to a particular band of interest.
- Notch filtering-Notch filter is used to remove the 50Hz power line interferences.
- Hilbert transform- It is used to get the phase information of a signal.

3. Phase Synchrony

Phase synchrony in the EEG signal can be defined as the phase oscillation occurs between two signals that oscillate in different frequency ranges over a limited period. The phase synchrony is a relation between the phase oscillations in various brain areas [15]. This phase can be estimated mainly by measuring the Phase locking value (PLV) of the signal using Hilbert transform (HT). The traditional method uses Hilbert Transform for the estimation of instantaneous phase after which the PLV can be calculated. In the improved one, a new method is proposed called Hilbert-Huang Transform (HHT) which has a significant impact on estimating the non-linearity and non-stationarity of EEG signal [16]. For this approach, empirical mode decomposition (EMD) is proved to be the key feature. EMD is used to decompose the complex set of data into some finite set which is called intrinsic mode function (IMF).

3.1. Phase Locking Value (PLV)

The phase locking value (PLV) has calculated simply by using the Hilbert transform (HT) in the traditional method. In this process, HT gives the instantaneous phase of the corresponding signal from which the PLV can be calculated. However, there are still some shortcomings in this method. The problem is that the HT is suitable only for the stationary signals, and the EEG signals are highly non-stationary in nature. And the component of the signal analysed from different parts of the brain is a narrow band signal. So it is necessary to filter the signal first. Thus, another method comes into picture which can estimate the phase locking value of the non-linear and non-stationary signals which is explained further in the content [15] [16].

Steps for traditional Method to calculate PLV

- Band-pass filter is applied to get the frequency band of interest.
- Computing of instantaneous phase.

$$\Phi_{ij}(t) = \Phi_i(t) - \Phi_j(t)$$

- Computing PLV.

The PLV between time sequence x_i and x_j within a given time period is defined as

$$PLV(i,j)=\left|\frac{1}{N}\sum_{k=1}^{n}\exp(j\phi_{ij}t_k)\right|$$

$\Phi(t)$ is the phase difference between two signals at particular time instance. PLV measures the phase lock activity as a function of time and frequency.

3.2. Improved Phase Locking Value (IPLV)

In this paper, an improved method has been demonstrated which uses HHT to generate instantaneous phase locking value of EEG signal. EMD (Empirical Mode Decomposition) used to decompose the signal into a finite set of functions called Intrinsic Mode Function (IMF) [17]. This IMF provides useful signal information for every component separately. EMD is a data-driven approach that doesn't require any prior knowledge of signal, and thus it is entirely adaptive in nature. This method highly depends on the quality of EMD algorithm that uses in the decomposition process for getting the IMFs. The decomposition indicated on the local characteristic time scale of the data; it can employ to nonlinear and nonstationary processes.

This HHT algorithm helps to generate the lower frequency content of any signal as the next IMF comes step by step. It also reduces the spectral leakage as well as the effect of harmonic distortion [18]. The HHT follows a standard process to obtain the IMF. The peaks and bottom of the incoming sequence need to be found out and then calculate the spline of the peaks and the bottom. The mean of the two spline is computed to obtain the original signal and subtract them to get the signal for next iteration.

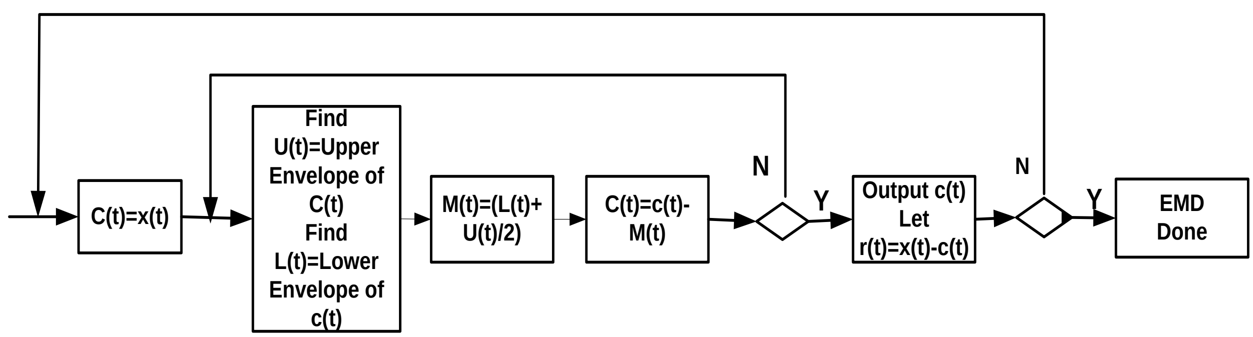


Fig. 2: Flowchart of shifting Process of EMD.

Empirical Mode Decomposition (EMD) is a process which can separate the signal into several finite set of elemental functions called Intrinsic Mode Function (IMF) [17]. We calculate the energy and instantaneous frequency of the IMF, simply by applying Hilbert Transform as previously applied in the traditional method [18]. The block diagram for the EMD shifting process for PS estimation using improved method is shown in Fig. 2.

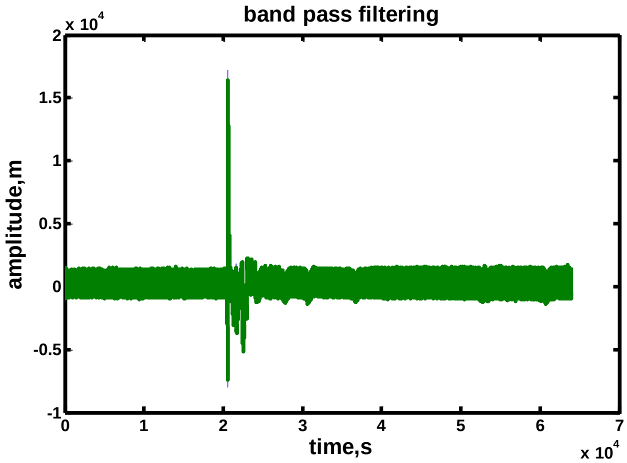
4. Comparison Between PLV and IPLV

The main difference between PLV and IPLV is that PLV is based on the assumption that the signal is stationary and linear whereas IPLV applies to both non-stationary and nonlinear signal. PLV is non-adaptive in nature whereas IPLV is posteriori-defined basis means and it is data dependent adaptive in nature [10-12].

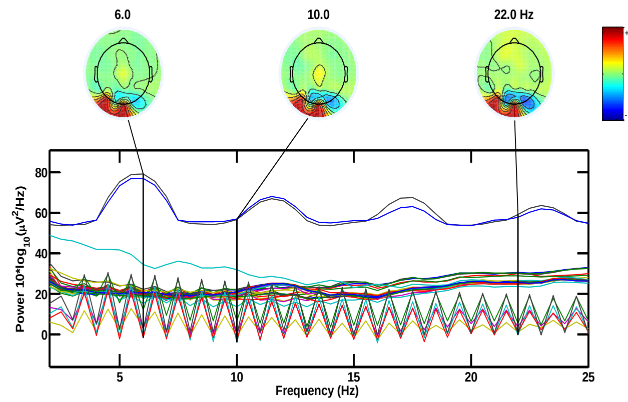
4.1. Advantages of IPLV over PLV in EEG Phase synchrony estimation

From HHT, we are getting the energy-frequency-time distribution of the signal. Frequency evolution for each mode can be analysed as one-dimensional (1D) Signal. HHT preserves the characteristic of variation of frequency in the time domain (as during decomposition the length of IMFs is same as that of the original signal). It generates low-frequency content of any signal using HHT algorithms. Using EMD, the base of HHT used for the decomposition of the signal represents the local property of the signal. It reduces spectral leakage and replaces the effect of harmonic distortion.

5. Results and Discussion

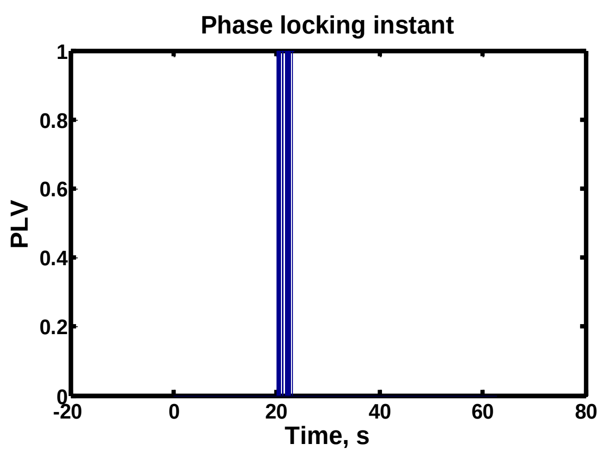


(a): Phase locking value of bivariate signal after band pass filtering.

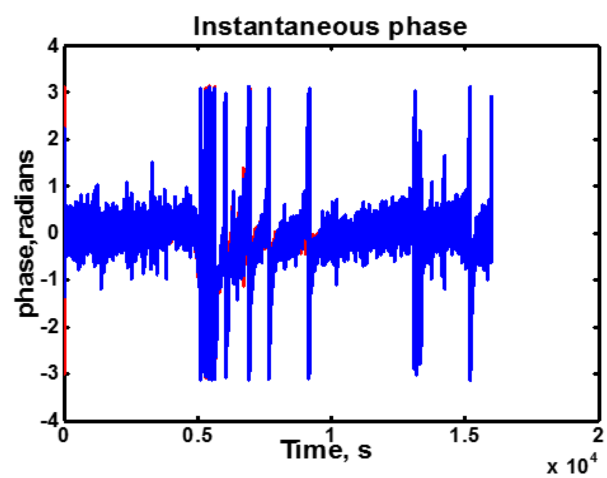


(b): A spectopographic () plot using EEGLAB. The components are shown for the largest portion of 10Hz activity at POz (middle scalp map). The power spectrum of the selected channel (top black trace), the activity spectra of the projection to that channel of each of the 32 components (lower traces), and the scalp power maps of the four largest contributing components (4, 5, 7, 10).

Fig. 3: (a) and (b)



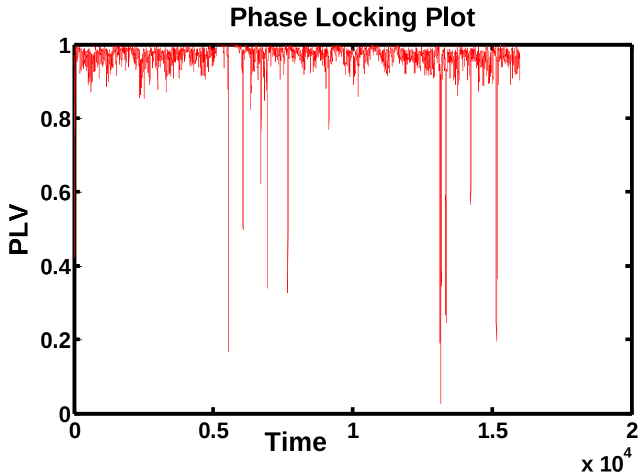
(a) Plot of phase locking value at particular instance of time of one of the meditator subiect.



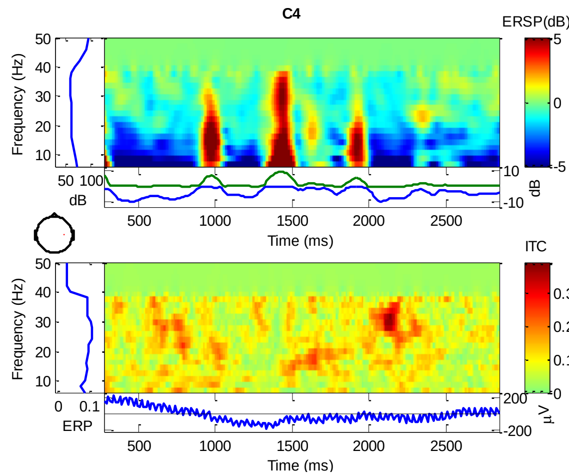
(b) Instantaneous phase estimation using EMD of one the meditator subject.

Fig. 4: (a) and (b)

Fig. 4(a) shows the phase locking instance of the bivariate meditative EEG signals. The instantaneous phase of those bivariate EEG signals has shown in Fig. 4(b). The phase locking plot of bivariate EEG signal has shown in Fig. 5(a). If both the EEG time series have fully coupled with zero phase lag, then the value signifies 1. If those bivariate signals are fully uncoupled and have some phase lag, then the PLV values indicate zero.



(a) Phase locking plot of bivariate EEG signal of channels Fp2 and Fp1 of one of the meditator subject.



(b) Improved phase coherence plot in a particular Channel i.e. C4 in one of the meditator subject.

Fig. 5: (a) and (b)

This paper presents a study on the use of phase synchronization measures, in the framework of functional connectivity of meditative brain signal. The performance of the PLV, IPLV and the phase coherence using EEGLAB [19] for finding the cortico-cortical phase locking instance is evaluated, and the results are shown in the Fig. 3(a), Fig. 3(b) and Fig. 5(b) respectively.

There are significant differences between these measures shown in Fig. 3(a), Fig. 3(b) and Fig. 5(b). In general, IPLV yielded better results than PLV (see Fig. 5(b)). This may be because synchronization is more restrictive than coherence. The signals of two synchronized systems are correlated, but increased coherence does not necessarily imply synchronization [20]. We demonstrated that from PLV and IPLV, computed from broadband signals, interesting features can be derived, containing relevant information on functional connectivity of EEG during meditation [21]. From the results obtained from PLV, shown in Fig. 5(a). The phase coherence obtained in channel C4 is shown in Fig. 5(b).

6. Conclusion

In summary, a new PLV based phase estimation method known as improved PLV (IPLV) is proposed. The performance of the both phase estimator i.e. PLV and IPLV evaluated, and their corresponding synchrony measures has shown in the application of meditative brain signal. The meditative signal shows enhanced phase synchrony in the alpha frequency during meditation which may improve functional integration. Phase synchrony is one the most important methods to infer the functional connectivity of the neural signal such as meditative EEG signal. The most striking topographical alteration was the synchronization of anterior and posterior channels. Therefore, EEG records from meditators practicing Kriya Yoga, distinguish the meditative brain state from other states of consciousness. The combination of sequential EEG changes about topographical alterations produces a particular pattern. Future studies with participants of wider ranges using robust phase synchrony measures infusion with other EEG connectivity techniques will help to understand better the neuro-dynamical changes during meditation.

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