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Phase Synchrony in Subject-specific reactive band of EEG for Classification of Motor Imagery Tasks

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Abstract— **Recent works on brain functional analysis have highlighted the importance of distributed functional networks and synchronized activity between networks in mediating cognitive functions. The network perspective is fundamental to relate mechanisms of brain functions and the basis for classifying brain states. This work analyzes the network mechanisms related to motor imagery tasks based on synchronization measure (PLV (phase-locking value)) in EEG alpha-band for the BCI Competition IV Data Set. Based on network dissimilarities between motor imagery and rest tasks, important nodes and important channel pairs corresponding to tasks for all subjects are identified. The identified important channel pairs corresponding to tasks demonstrate significant PLV variation in line with the experiment protocol. With the selection of subject-specific reactive band, these channel pairs provide even more higher variation corresponding to tasks. This paper demonstrates the potential of these identified channel pairs in task classification for future BCI applications.**

I. Introduction

The Electroencephalographic (EEG) is a non-invasive measurement of brain's electrical activity which has a good temporal resolution. To understand brain cognition, connectivity plays an important role. In [1], structural properties, functional brain networks and effective cognitive connectivity patterns of human brain were analyzed using graph theory and networks. Network measures its importance in brain networks and mathematical definitions for both directed and undirected of binary and weighted graphs were discussed in [2].

Brain connectivity is generally analyzed by constructing a synchronization measure matrix. Recently, phase synchronization (phase locking value (PLV)) has been widely employed to study brain connectivity patterns. In [3], it was observed that phase in the rest period is different from activity and that can be used as a feature in BCI applications. Neuroscience literature suggests that phase may be more discriminative than amplitude and is a sensitive measure due to its relevant change in synchrony. Neuroscientists usually apply threshold to the PLV value in order to obtain a binary graph and focus on statistically significant connections. The transition between high and low level synchrony is discussed in [4], [5]. In [5], it was even proposed that a normal brain phase synchronization can occur at various time scales, various frequencies and with various coupling strengths.

It is well known that the motor imagery attenuates EEG alpha rhythm over sensorimotor cortices. In this paper, we study the brain synchrony related to motor activity. We identify the important electrode configurations that are subject and event specific. In [6], the subject reactive band is identified by using band limited multiple Fourier linear combiner (BMFLC). It was shown that by incorporating the reactive band, the classification is improved compared to traditional ERD based methods. A procedure to identify the subject-specific reactive band is formulated. With the phase-locking value and time-frequency mapping, most significant channel pairs corresponding to subject specific reactive band are then identified. It was shown that, the identified channel pairs corresponding to tasks demonstrative significant PLV changes in line with the protocol. Compared to ERD, the proposed method provides more variation that can be used for event classification in BCI applications.

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II. METHODS

A. Phase locking value

Phase locking value (PLV) is a measure for studying the synchronization phenomena in electroencephalographic (EEG) signals. It is similar to cross spectrum but, independent of amplitude of the two signals [7]. Making use of PLV, we can measure synchronization between all electrode pairs in EEG collection montage. Synchronization measure PLV, at time instant is defined as [7]:

$$PLV = \frac{1}{N}\left|\sum_{n=1}^{N} \exp(j\{\triangle\Phi(t,n)\})\right| \quad (1)$$

where N is number of total trails. $\triangle\Phi(t,n) = \Phi_1(t,n) - \Phi_2(t,n)$ is the instantaneous phase difference between pair of nodes. PLV of zero means that the phase of the two signals is not coupled and a PLV of one means that the signals are perfectly coupled. The decomposition of the signal into time-frequency mapping is achieved by convolving the signal with Morlet mother wavelet with a scaling and dilating parameter. For the ease of analysis, EEG alpha band is equally divided into 50 frequency bins by properly selecting the parameters.

Instantaneous phase difference ($\Delta\Phi(t,f)$) is calculated by taking the phase difference between two channels of EEG recordings. This gives the $\triangle\Phi(t,f)$ of all pairs of channels. For all combinations of time and frequency, instantaneous phase difference is computed. Then the average PLV for all trials and over time is obtained with (1).

B. Subject-event specific reactive band and Most Significant electrode pairs (MSP) identification

Reactive band is subject and event specific and hereafter referred as reactive band. To identify reactive band, we compute the difference of PLV between active and rest states

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for all electrode pairs in the range of 6-14 Hz. The difference-PLV, defined as:

$$PLV_{diff} = PLV_{MI} - PLV_{rest} \quad (2)$$

where, PLV$_{MI}$ is the average PLV during motor imagery activity 3s to 4.5s and PLV$_{rest}$ is average PLV during rest duration 0.5s to 2s are identified from the PLV time-frequency mapping. The range of frequencies within 6-14Hz where most of the electrodes have maximum PLV$_{diff}$ is identified as the reactive band for a specific task. Thus, the PLV difference mapping is formed.

The reactive band can be identified with the procedure suggested in [6]. Reactive band can also be identified as the range of frequency band that corresponds to the maximum PLV$_{diff}$. The pairs that corresponds to the maximum PLV$_{diff}$ can be identified as most significant pairs. Higher PLV$_{diff}$ points corresponds to the most significant pairs as they have the highest PLV difference between active and rest. The electrode pairs with the highest difference in PLV$_{diff}$ can be identified as the most significant pairs (MSP).

C. Subject-event specific threshold selection

A pair of nodes are said to be connected if the corresponding PLV is above a threshold level and its proper selection is crucial for the network formation. Setting threshold too low can give insignificant number of connections and setting too high can lead to too little connections losing important connections. To observe the dynamic changing connectivity pattern over time, the PLV of most significant pairs is averaged over the identified reactive band. In this paper, the threshold is obtained by averaging the PLV of active and rest periods. Thus the threshold value is subject-event specific. By applying the threshold, the binary graph is formed (above threshold is '1' and below threshold it is '0').

D. PLV of Most significant pairs in reactive band for classification

The PLV value of different motor imagery tasks of most significant pairs can be used as features for classification. The pairs that are selected for classification are based on PLV-difference mapping. By arranging the PLV-difference in descending order one can easily identify the most significant pairs for each event. For classification of motor imagery events, the PLV of identified subject specific significant pairs is averaged over full band and reactive band respectively. The threshold identified in the earlier section together with the most significant pairs PLV forms the basis for classification of tasks. The difference in PLV level after cue can be used for classification. Percentage increment of difference in PLV is defined as:

$$\%Increment = \frac{dPLV_{RB} - dPLV_{FB}}{dPLV_{FB}} \times 100 \quad (3)$$

where dPLV$_{FB}$ is difference in PLV of most significant pairs in full band and dPLV$_{RB}$ is difference in PLV of most significant pairs in reactive band.

III. Results

The BCI competition IV data set 2a is used for this study. The data set contains EEG data of 9 subjects. Four motor imagery tasks for which the data collected were: Imagination of movement of the left hand, right hand, both feet and tongue. The EEG data set signals were sampled with 250 Hz and band pass filtered between 0.5 Hz and 100 Hz. In order to obtain alpha band EEG, the data is further band pass filtered by using butterworth band pass filter of order 5. The timing scheme and the locations of the EEG recordings are shown in Fig. 1. All subjects data was analyzed. To visualize the connectivity graph over time, the graph is generated every 0.3s (total of 25 time epochs as data length is 7.5s). For illustration, the analysis of two tasks of subject #8 (S#8(LH) and S#8(RH)) are presented.

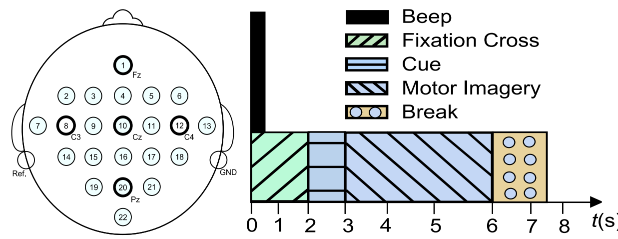

Fig. 1. Layout and timing scheme pattern of BCI competition data set IV

A. Phase locking value

For all the subjects, PLV mapping is calculated for all the possible electrode pairs. Similar to ERS (event related synchronization) pattern, the PLV has significant change with respect to the experiment cue. The PLV magnitude increased along time axis during the imagination compared to rest and the pattern is similar to inverse of the ERD pattern. For illustration, time-frequency PLV of a single Electrode pair 10-14 of subject #8 (RH) is shown in Fig. 2. For clarity only one pair was shown. The PLV variation can be identified in the certain frequency range in Fig. 2. Time-Frequency mapping of PLV values over alpha band for S#8 for all electrode pairs combination ($_{22}C_2$ pairs) are shown in Fig. 3. Further, existence of reactive band can be visually identified in Fig. 3. It is worth to note that most subjects displayed similar pattern and has narrow frequency band where significant changes in PLV can be observed. We can easily observe the PLV change from rest to activity exists in narrow frequency band 9-11 Hz. Similar pattern was observed in all the subjects.

B. Subject-event specific reactive band

As discussed in Methods, the difference between active and rest states for PLV are computed as defined in (2) for S#8(LH) and S#8(RH). Most of the events of all the subjects displayed subject-specific reactive band. A reactive band cannot be identified for Sub#2(LH, RH), Sub#5(LH), Sub#7(LH) tasks inline with earlier results [6]. For these subjects, one can select the complete band as reactive band. The reactive band for the subjects is selected to be 2 Hz in the paper. The reactive band can be visually identified as shown

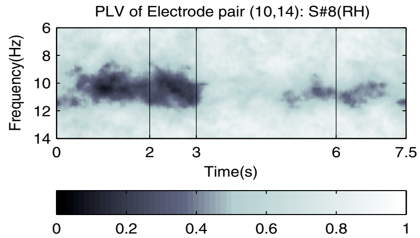

Fig. 2. S#8 (RH): PLV of Electrode pair (10,14)

in Fig. 3 or can adopt the method in [6] for identification. The PLV difference mapping for all electrode pairs of S#8 for both tasks are shown in Fig. 3. The identified reactive band is also marked in Fig. 3 as 9-11 Hz for both LH and RH tasks. Electrode pairs with high PLV-difference are crucial for task classification.

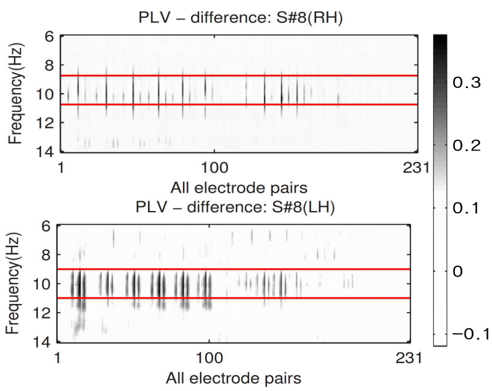

Fig. 3. All combinations of electrode pairs and identification of reactive band for Sub#8

C. Most Significant Pairs and Threshold Selection

Important pairs are the electrode pairs having high PLV-difference. The 5 most significant pairs (5 MSP) for each task are selected in this paper. The PLV of identified 5 most significant pairs (5 MSP) over time is shown in Fig. 4. Pattern similar to the experiment protocol can be observed. The PLV of electrode pairs has low PLV and they increase during the motor imagery period on the opposite side of the motor cortex region corresponding to the task. As 5 MSP lie in the contralateral part corresponding to task, we denote them as 5 MSP(LS) and 5 MSP(RS), where LS and RS corresponds to left side and right side of the brain. Threshold is computed by taking the average of both the rest and active period as discussed earlier in Section 2. The computed threshold is also shown in Fig. 4 for both tasks. Identified threshold line is shown as red dotted line in Fig. 4. The threshold identified for subject #8 (RH) is: 0.4467 and for subject #8 (LH) is: 0.4702. At every epoch, if the PLV of any pair is above threshold, it is considered as '1' else as '0' (1 means connection and 0 means no connection for the formation of the graph network).

In Fig. 5, for both right and left hand motor imagery the connectivity map at for epochs at selected time instants for subject #8 are shown. The experimental time line is presented in the left side of the same figure. The most significant pair identified for subject #8 of right hand motor imagery is (10,14) pair (most significant pair is marked for LH and RH tasks) and it is mostly seen during imagery duration. Similarly (1,18) pair is identified as MSP for LH imagery. The connection pattern can be visualized in the Fig. 5 and (1,18) pair is mostly seen during imagery duration. Similar pattern was observed in 6 subjects out of 9 subjects. For left hand and right hand motor imagery tasks shown in Fig. 5, the significant pairs are present in its contralateral part of the brain. For all subjects connectivity changes corresponding to right hand imagery movement were observed in left side of brain and vice versa.

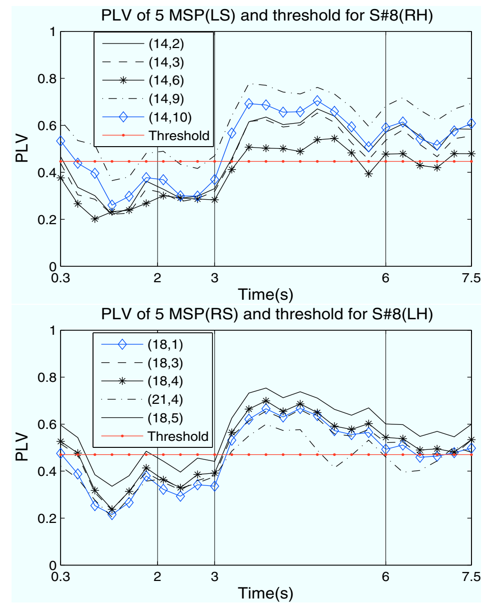

Fig. 4. PLV of 5-most significant pair (5 MSP) and selected threshold: Sub#8

D. Classification of Tasks

For classification, we select the 5 MSP(LS) and 5 MSP(RS). The average PLV of these pairs over time for RH task and LH task for Sub#8 full band (6-14 Hz) are shown in Fig. 6(a)-6(c). The average PLV of 5 MSP(LS) on contra-lateral part corresponding to RH imagery show increase, where as the 5 MSP(RS) on the same side show decrease in PLV. By comparing the PLV variation between 5 MSP(LS) and 5 MSP(RS) one can easily classify the task.

With the selection of subject-specific and event-specific reactive band, a remarkable increase in separation can be observed between 5 MSP(LS) and 5 MSP(RS) as shown in Fig. 6(b)-6(d). The %increment (3) in PLV difference with selection of reactive band for all subjects is tabulated in Table I. The identified reactive band, most significant pair and PLV differences for all subjects and tasks are shown. For four tasks in three subjects without reactive band, full band was used for calculation and hence zero increment was obtained. The % increase in PLV clearly highlights the improvement with the selection of subject-specific reactive band in rest of

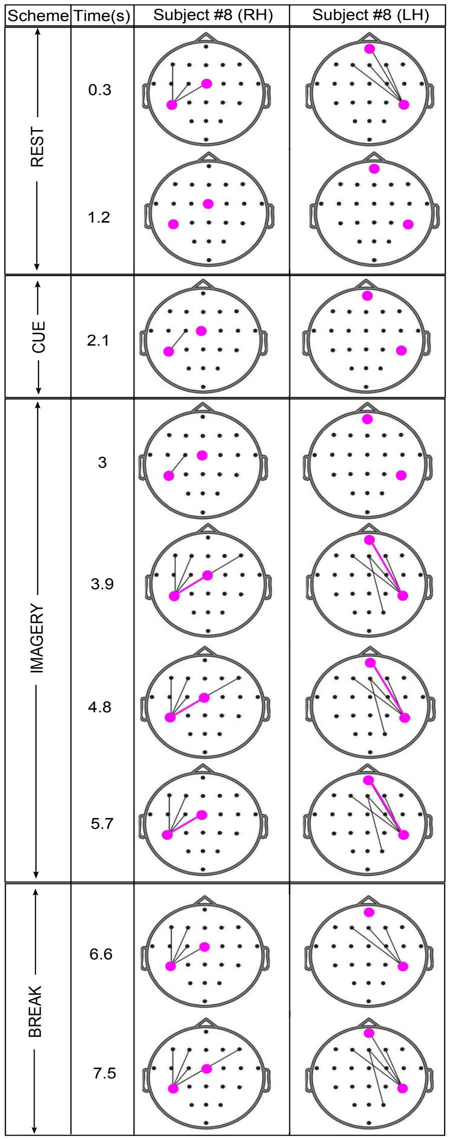

Fig. 5. Sub#8: 5 most significant pairs connectivity for both tasks. The most significant pair of top5 is highlighted.

TABLE I

COMPARISON OF PLV DIFFERENCE IN FULL BAND AND REACTIVE BAND

Subject	Identified reactive band	MSP	Difference in PLV		
			Full band	Reactive band	%Incr-ement
S#1(RH)	10.5-12.5	(5,14)	0.1	0.1	68
S#1(LH)	9.5-11.5	(6,19)	0.0	0.0	0
S#2(RH)	6-14(No band)	(7,18)	0.0	0.0	0
S#2(LH)	6-14(No band)	(5,14)	0.1	0.1	0
S#3(RH)	9-13	(1,14)	0.0	0.0	176
S#3(LH)	11-13	(1,13)	0.2	0.3	93
S#4(RH)	10-12	(1,14)	0.0	0.0	19
S#4(LH)	10-12	(1,18)	0.2	0.2	20
S#5(RH)	10-12	(1,14)	0.0	0.0	22
S#5(LH)	6-14(No band)	(14,18)	0.1	0.1	0
S#6(RH)	8-10	(1,18)	0.0	0.0	0
S#6(LH)	9-11	(10,18)	0.0	0.1	216
S#7(RH)	11-13	(7,18)	0.0	0.0	174
S#7(LH)	6-14(No band)	(1,14)	0.0	0.0	0
S#8(RH)	9-11	(10,14)	0.2	0.3	77
S#8(LH)	9-11	(1,18)	0.1	0.4	211
S#9(RH)	9.5-11.5	(10,14)	0.1	0.2	105
S#9(LH)	10-12	(1,12)	0.0	0.1	483

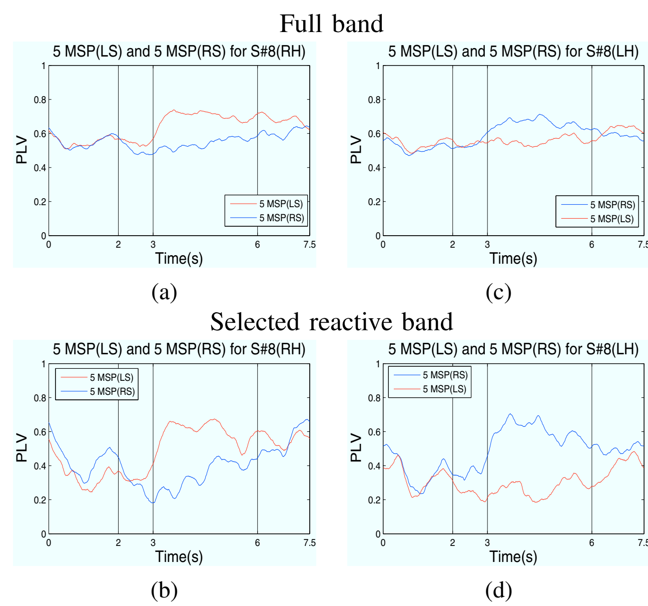

Fig. 6. MSP comparison of S#8 in full band and selected reactive band for 5 most significant pairs (5 MSP)

the subjects. An average increase of 138% was obtained with selection of reactive band compared to full band.

Together with the selection of reactive band, the proposed method even provides improved performance as shown in Fig. 6(b)-6(d). The proposed approach demonstrates the potential for BCI applications. Future work will focus on real-time task classification with single trial data.

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