Neuroscience: Brain Network Activity during resting states

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Abstract:
In this project we will analyse two datasets that contain EEG Motor movement/imagery data which is recorded from 64 electrodes using BCI2000 system with the subjects at rest in two conditions 1) Eyes Open[EO] 2) Eyes Closed[EC], particularly we will focus our analysis on subject S064. The dataset contains recorded data from S064R01.edf and S064R02.edf files. Our analysis is mainly focussed on connectivity graphs, graph theory indices, motif analysis and community detection. At each stage of above analysis, we focussed on the contrast between EO and EC states. For example, to estimate brain connectivity, we used MVAR estimators like Direct Transfer Function [DTF] and Partial Direct Coherence [PDC], from our analysis the latter approach tends to provide a bit more connectivity value than the first one.

Introduction:
Electroencephalography (EEG) is an electrophysiological monitoring method to record electrical activity of the brain. EEG measures voltage fluctuations resulting from ionic current within the neurons of the brain, Our human brain produces electrical signals when it is active that reach the surface of scalp, these signals are recorded and then used to reconstruct the patterns of brain activities by the sensors placed on the scalp, For this study we consider EEG signals, each sampled at 160 samples per second that are recorded from 64 high-density electrodes evenly spaced across the human scalp. These signals are used to obtain information about neural mechanisms and their cognitive reasoning with focus on neural oscillations called "Brain Waves" (e.g. the alpha waves) useful for coding specific information, modulating brain active states and study the communication between signals.

Methods:
The original dataset [1] consists of over 1500 one and two-minute EEG recordings, obtained from 109 volunteers which is provided in the EDF + Format and can be download from [1] And it also includes metadata, among which the sampling frequency and the channel labels containing 64- EEG signals each sampled at 160 samples for second from each subject in accordance with the study, the data for our analysis is targeted on subject S064.We consider the first two signals for our analysis with subject at rest with eyes open [EO] and another signal with subject at rest with eyes closed [EC].

1.1 Spectral Analysis:
We have conducted our analysis based on the conditions of subject with EO and EC and chose relevant channels based on specific situation. First, we defined a function to obtain a signal matrix of subject with conditions EO and EC to analyse our data from the raw input files. From [5] we understood that the alpha rhythms predominantly originate from the occipital lobe of the brain during wakeful relaxation with closed eyes and are reduced with open eyes, drowsiness and sleep. To understand our best channel that we can choose for our

analysis we want to estimate the power spectral density [PSD] of each channel present in occipital lobe and considering the channel with highest PSD [2] value with its corresponding frequency for the alpha rhythmic waves frequency range [i.e. between 8 and 13] as shown in [Figure 1], The choice of the parameters was basically done by considering the sample frequency of the signal, which in our case is 160 Hz that provides a good compromise between main lobe width and side lobe height as shown with estimations of the PSD.

1.2 Connectivity Graph

Brain connectivity can be estimated with the use of a spectral estimator based on the Multivariate Autoregressive model (MVAR). To understand the connectivity pattern for all channels, we implemented the Direct Transfer Function (DTF) that measures the effect of a channel on another one. The estimations of connectivity between signals were executed first with the implementation of the MVAR, since this method requires the selection of the order for the model, we used the Akaike information criterion for MVAR order estimation [3]

The frequency spectrum of each channel lies in the range 0-80Hz, we selected 100 as number of spectrum data points obtaining 100 connectivity matrices 64 by 64, each for a frequency band. The frequency selected is based on the alpha waves that have range between 8-13 Hz, with an observed peak in 10 Hz in the estimation of the Power Spectral Density. Hence the chosen matrix correspond to the 10th frequency, for this matrix we will apply a threshold for the construction of the adjacency matrix, if the estimated effect of the channel on another is bigger than the threshold, we consider connection between the two nodes, otherwise it will be considered as not connected. We can see a graphical representation of the adjacency matrices for both DTF and PDC at the rest conditions in the Figure 1.1 and Figure 1.3

Thresholds that guarantee a network density level to 20% for DTF and PDC are as follows.

```
DTF
 Subjects Eyes Open   Threshold: 0.128       Density: 20.0 %
 Subjects Eyes Closed Threshold: 0.132       Density: 20.0 %
PDC
 Subjects Eyes Open   Threshold: 0.102       Density: 20.0 %
 Subjects Eyes Closed Threshold: 0.108       Density: 20.0 %
```

The above procedure to obtain densities can be applied to 1%, 5%, 10%, 20%, 30%, 50% and is shown in the figures 1.3.

From the above figures we can infer that bigger is the density required for the network the smaller is the threshold. This is because for a smaller threshold we are going to consider a larger number of connections between channels, that makes the network denser.

Also, by considering a reduced subset of 19 channels, the estimation of this connectivity can be implemented using the PDC estimator. In order to keep the most significant values, a re-sampling procedure is applied; this statistical validation method returns the statistical significant values of the connectivity estimation [Figure 1.4]. The values that we must filter are the ones not significantly different from 0 and with a **pvalue** > 5%, so we are going to keep the significant connection between channels with p-value < 0.05. A topographical representation of the 19 channels shows the interactions between them [Figure 1.5].

2. Graph Theory Indices:

In order to construct global and local indices for the graph we need to consider binary connectivity matrices for both PDC and DTF from our connectivity graphs to calculate clustering coefficient and average path length between each channel. From our results, we have noticed that the average path length for EO & EC graph increases up to a density level 20% for PDC and decreases eventually up to a density level 50% with increase in connectivity, On the other hand for DTF, the average path length increases continuously from 1 to 50% with respective to increase in clustering coefficient for DTF, and the trend is more like an increase and decrease for PDC, the same can be observed in Table 2.1 with not much difference in average step to reach another channel among all other channels.

For local indices of the graph, we have calculated degree, in-degree and out-degree as the resulting graph is directed for both EO & EC conditions, For example in DTF, let's say at density level 20%, the channels that sent impulses are similar to some extent but are not totally similar. In particular we can find

10 channels which received more impulses for In-degree	**10 channels which sent more impulses for Out-degree**	**10 channels which exchanged more impulses for both In-degree and Out -degree**
For EO graph we have the below result:	For EO graph we have the below result:	For EO graph we have the below result:
F3, F5, Cp4, F1, Fz, Cpz, Cp3, Po3, Fc2, T9	Af7, Af8, Fp2, Af4, F8, Cp2, Fpz, F6, Fc6, C5	F5, F3, Cp4, F1, Fz, Cpz, Cp3, Po3, Fc2, Po4
For EC graph we have the below result:	For EC graph we have the below result:	For EC graph we have the below result:
F5, F3, O1, Poz, Fz, Cpz, Pz, Po3, Cz, Iz	Ft7, Fc4, Cp1, Cpz, Cp2, F8, Ft8, P1, Fc6, Cz	F5, F3, Cpz, Poz, Pz, O1, Fz, Cz, Po3, Cp1

3. Motif Analysis:

Network motifs are usually defined as patterns of interconnections occurring in complex networks at numbers that are significantly higher than those in randomized networks.
For networks, when the subject is at rest for conditions, EO and EC, we want to get the 3-nodes subgraph configuration and the relative frequencies and statistical significances as shown in Table 3.1 and. For 3-node connected subgraph we have 13 possible combinations of configurations[Figure 3.0]. Looking at the range of the frequencies for the random network we get the motif and anti-motif. The subgraphs that appear more in the real network rather than the random one are marked as motif. alternatively, the subgraph that appear more in the random network rather than the real one are marked as anti-motif, if the subgraphs have the frequency inside the interval of the random network, it means that the frequency in the real network is similar to a random network, so these subgraphs don't have any significance. The 3-node motif analysis for PDC [EO & EC] at 20% density is shown in figure 3.1. is done using a tool **mfinder** to obtain all subgraphs. Likewise, 4-node motif analysis is completed. We also analyse 3-node motif considering only parieto-occipital scalp region, and the result is shown in table 3.3. and figure 3.3.

4. Community Detection:

We use Louvain algorithm to detect high modularity partitions of large networks in short time and that unfolds a complete hierarchical community structure for the network, thereby giving access to different resolutions of community detection[4]. It is computed in two steps: 1)Small communities are found by optimizing modularity locally on all nodes;2)Each small community is grouped into one node and the first step is repeated, these steps are iterated until there are no more changes and a maximum of modularity is attained. The results of number of clusters and the composition of community for PDC are shown in table 4.1 and 4.2 along with graphical representation of community structure in figure 4.1 when the subject is EO and EC. The same steps are repeated for DTF and are shown in Table 4.3 and 4.4 and figure 4.2 respectively.

5. Discussion:

We have listed the completed tasks clearly in Table 0, In this analysis we aimed at comparing different methods and their results, we have used parametric spectral analysis to estimate the PSD to identify the best frequency range for alpha waves which gives better results as compared to non-parametric which can be seen in Figure 1b with a peak in PSD and its corresponding frequency. This detection is important to capture the frequency and power fluctuations when the subject is tested for EO and EC conditions, also looking at the MVAR methods like DTF and PDC to estimate the brain connectivity, we observed the differences in connectivity especially for DTF as compared to PDC for various density levels by looking at their adjacency matrices. The same can be inferred from the graph's global indices where the clustering coefficient increases as the density increases and in the topological representations of graph indices at in-degree and out-degree conditions, analysing data with reduced set of 19 channels there is a high drop in degrees both in and out in the EC state as the impulses are less forwarded to and from other channels. In motif analysis, we noticed difference in motifs for 3-node and 4-node subgraphs for both EO and EC conditions. Also, from the motif A→B→C connection analysis, it is obvious that much signals are sent from inside to outside of brain. For parieto-occipital scalp region, we saw that signals are sent more actively on right-side brain. The difference can also be seen in community detection and it can be clearly noticed in the graphical representation of community structure. Looking at the EC condition, the communities are split into 3 parts, left-front, right-front and rear side. From our analysis we can infer that the brain connectivity is different for both eyes open and eyes closed states.

6. Conclusion:

From our analysis of the EEG signals data for brain connectivity, it is important to understand that different estimator yields different kind of results and we cannot baseline our observations as facts just by observing one subject, the study has to be broadened for various subjects and then we can draw statistical evidences comparing the results, we can further explore and improve this research to understand the interactions, patterns and correlations in the signals flow between channels amongst various sections of the brain.

7. References:

[1] https://physionet.org/physiobank/database/eegmmidb/
[2] http://www.ijete.org/wp-content/uploads/2014/09/IC-97.pdf
[3] http://connectivipy.readthedocs.io/en/latest/tutorial.html
[4] Blondel et al, J. Stat. Mech, 2008
[5] https://en.wikipedia.org/wiki/Alpha_wave

8. APPENDIX:

Table 0. list of tasks chosen for the project

Task	Class
1.1	Mandatory
1.2	A
1.3	A
1.4	D
1.5	C
2.1	Mandatory
2.3	B
2.4	C
2.5	B
3.1	Mandatory
3.2	C
3.3	C
3.4	E
4.1	Mandatory
4.2	B

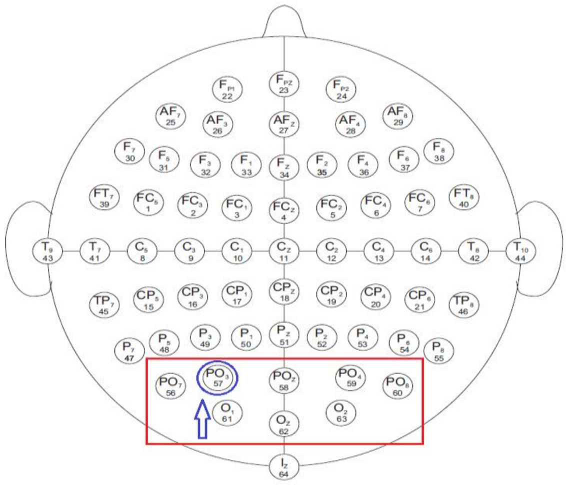


Figure 1a. Choosing a channel from occipital lobe that has maximum PSD

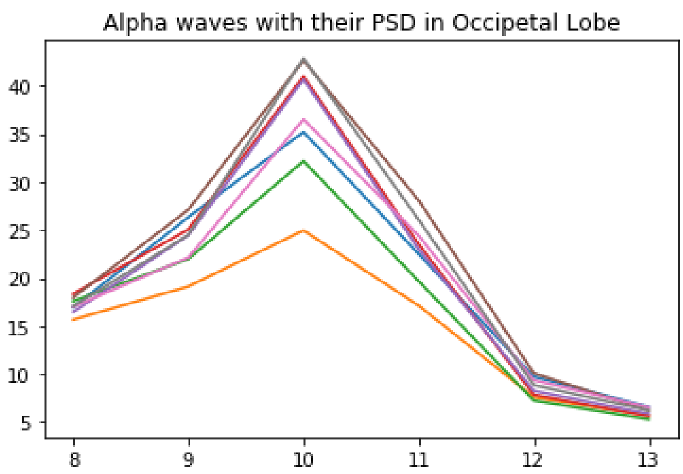


Figure 1b.

8.1. Connectivity Graphs

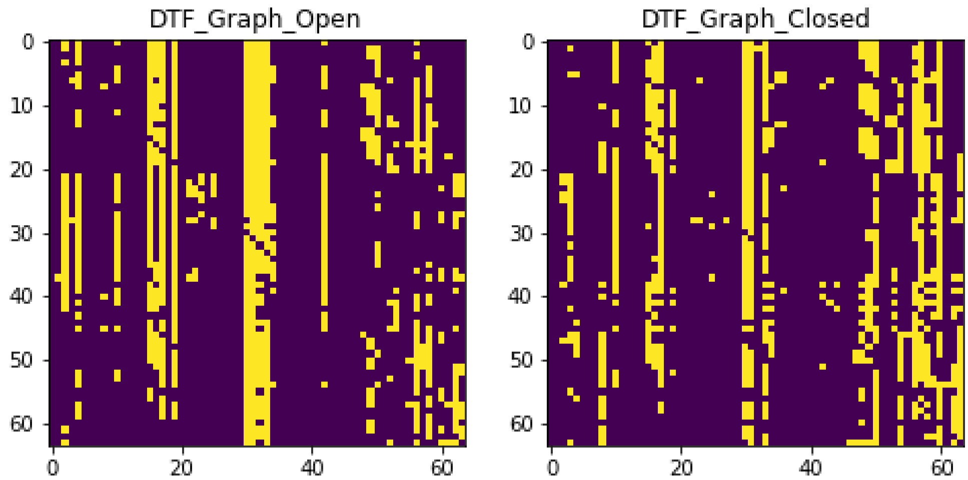


Figure 1.1.1. DTF Binary Connectivity Matrices

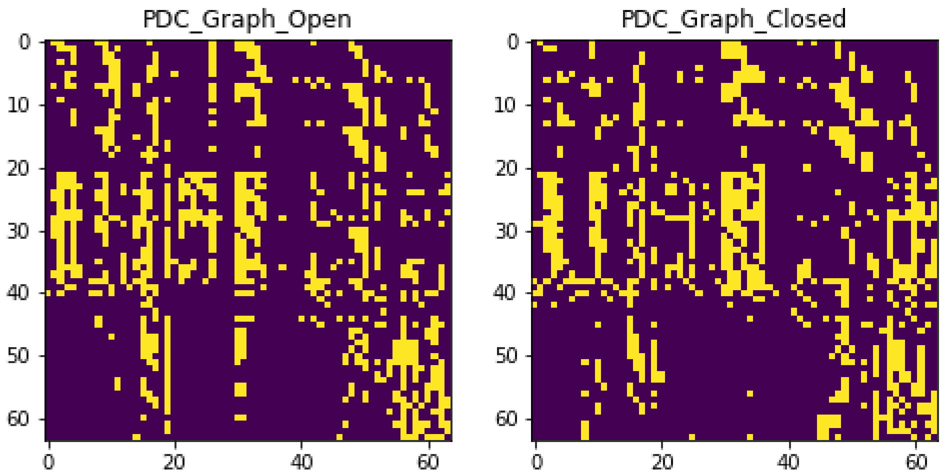
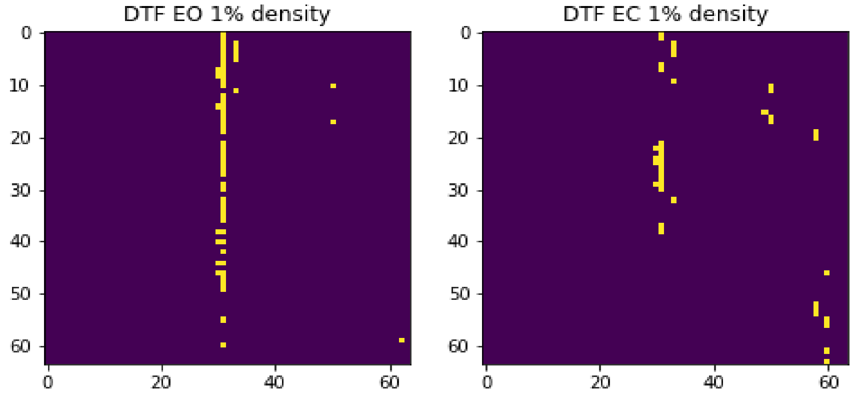
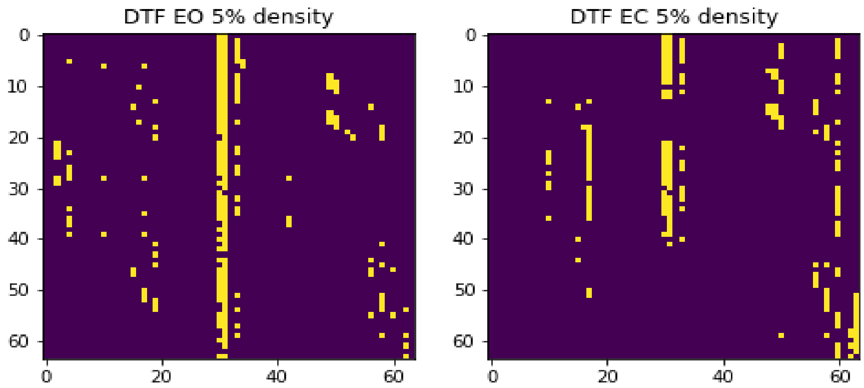


Figure 1.1.2. PDC Binary Connectivity Matrices

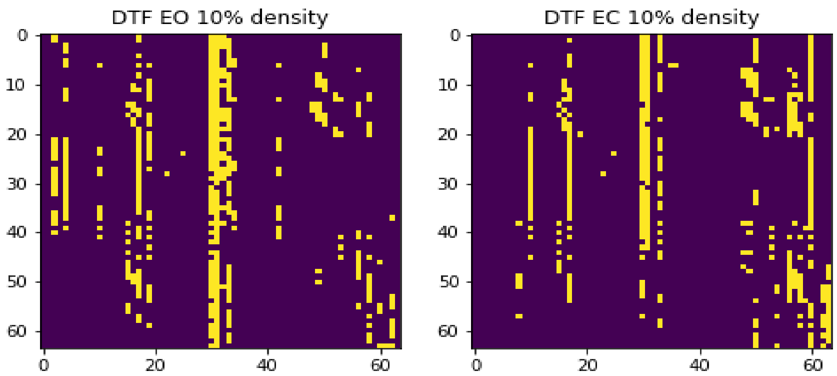
```
DTF Threshold with Density 1 %
 Subjects Eyes Open      Threshold: 0.368       Density: 1.0 %
 Subjects Eyes Closed    Threshold: 0.351       Density: 1.0 %
```



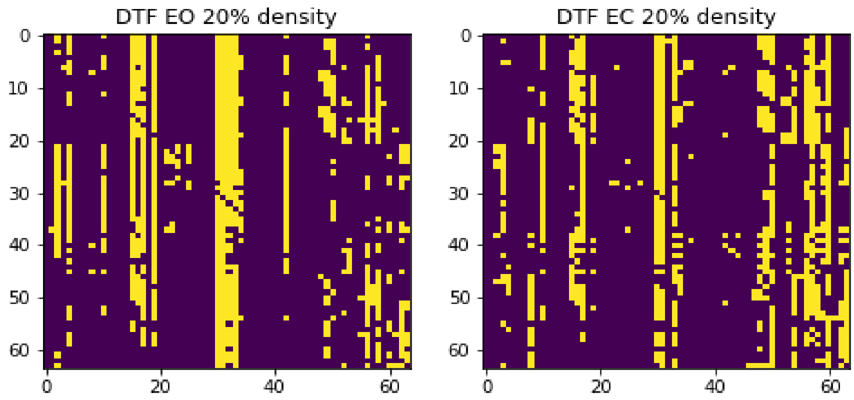

```
DTF Threshold with Density 5 %
 Subjects Eyes Open      Threshold: 0.231       Density: 5.0 %
 Subjects Eyes Closed    Threshold: 0.255       Density: 5.0 %
```



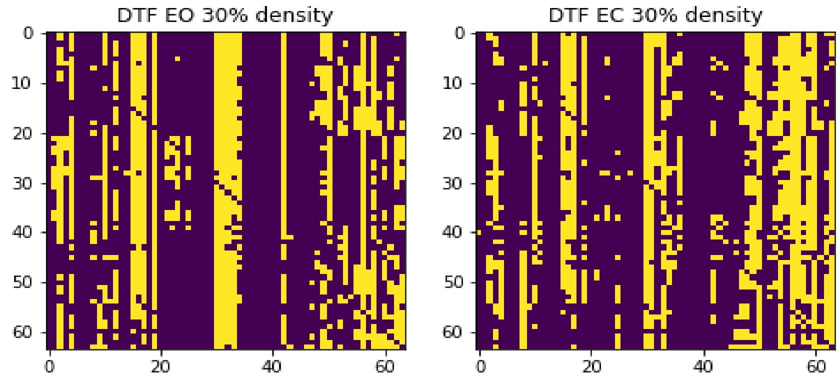

```
DTF Threshold with Density 10 %
 Subjects Eyes Open      Threshold: 0.179       Density: 10.0 %
 Subjects Eyes Closed    Threshold: 0.195       Density: 10.0 %
```



```
DTF Threshold with Density 20 %
 Subjects Eyes Open      Threshold: 0.128        Density: 20.0 %
 Subjects Eyes Closed    Threshold: 0.132        Density: 20.0 %
```




```
DTF Threshold with Density 30 %
 Subjects Eyes Open      Threshold: 0.094        Density: 30.0 %
 Subjects Eyes Closed    Threshold: 0.1          Density: 30.0 %
```




```
DTF Threshold with Density 50 %
 Subjects Eyes Open      Threshold: 0.055        Density: 50.0 %
 Subjects Eyes Closed    Threshold: 0.057        Density: 50.0 %
```

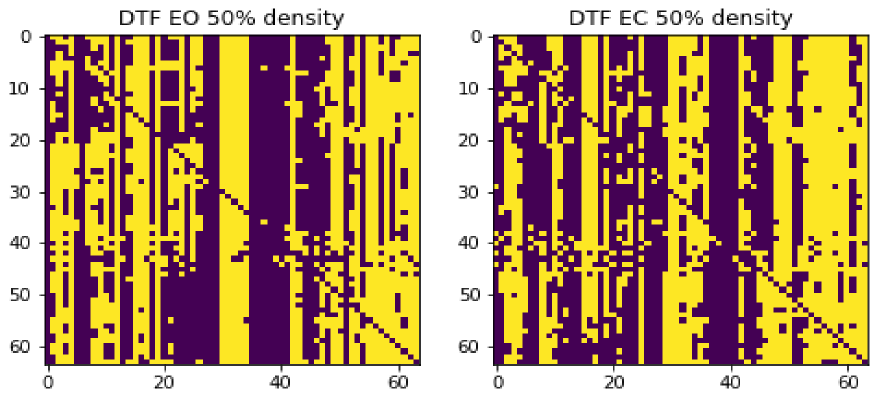
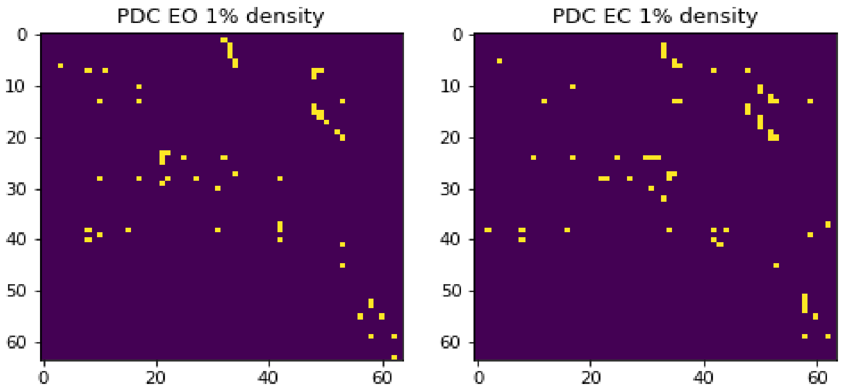
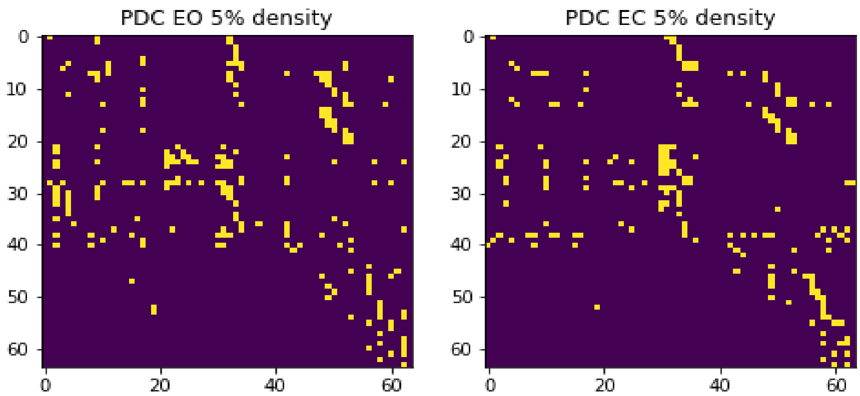


Figure 1.3.1 DTF with density levels at 1%, 5%, 10%, 20%, 30%, 50%

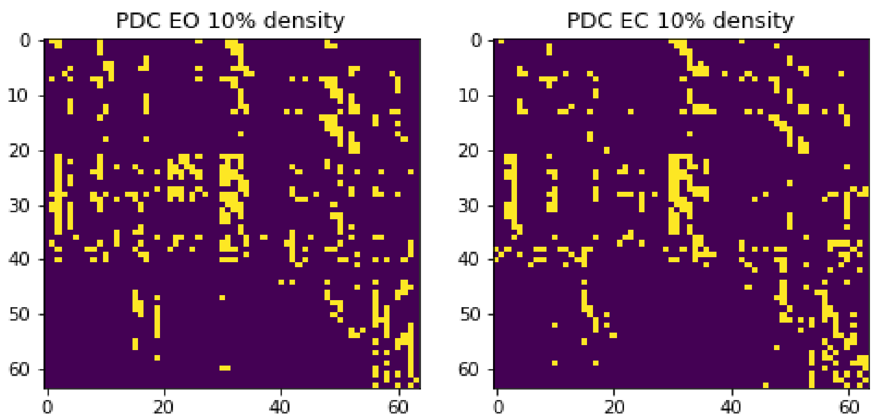
```
PDC Threshold with Density 1 %
 Subjects Eyes Open      Threshold: 0.248        Density: 1.0 %
 Subjects Eyes Closed    Threshold: 0.233        Density: 1.0 %
```



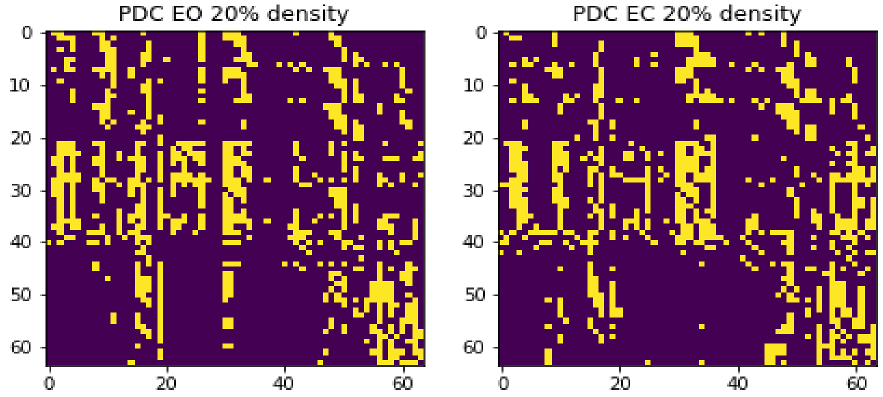

```
PDC Threshold with Density 5 %
 Subjects Eyes Open      Threshold: 0.168        Density: 5.0 %
 Subjects Eyes Closed    Threshold: 0.178        Density: 5.0 %
```



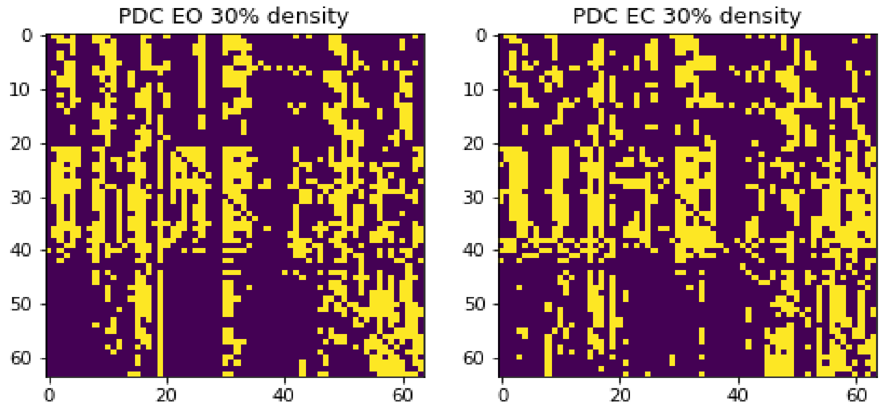

```
PDC Threshold with Density 10 %
 Subjects Eyes Open      Threshold: 0.132        Density: 10.0 %
 Subjects Eyes Closed    Threshold: 0.144        Density: 10.0 %
```



```
PDC Threshold with Density 20 %
 Subjects Eyes Open      Threshold: 0.102        Density: 20.0 %
 Subjects Eyes Closed    Threshold: 0.108        Density: 20.0 %
```




```
PDC Threshold with Density 30 %
 Subjects Eyes Open      Threshold: 0.082        Density: 30.0 %
 Subjects Eyes Closed    Threshold: 0.084        Density: 30.0 %
```




```
PDC Threshold with Density 50 %
 Subjects Eyes Open      Threshold: 0.053        Density: 50.0 %
 Subjects Eyes Closed    Threshold: 0.056        Density: 50.0 %
```

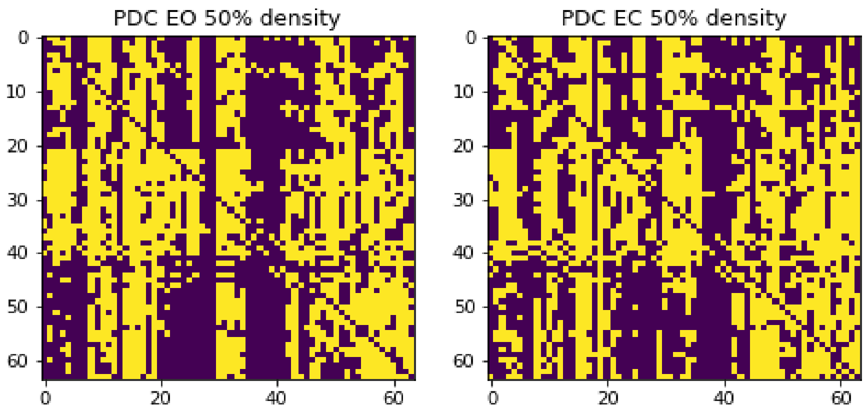


Figure 1.3.2 PDC with density levels at1%, 5%, 10%, 20%, 30%, 50%

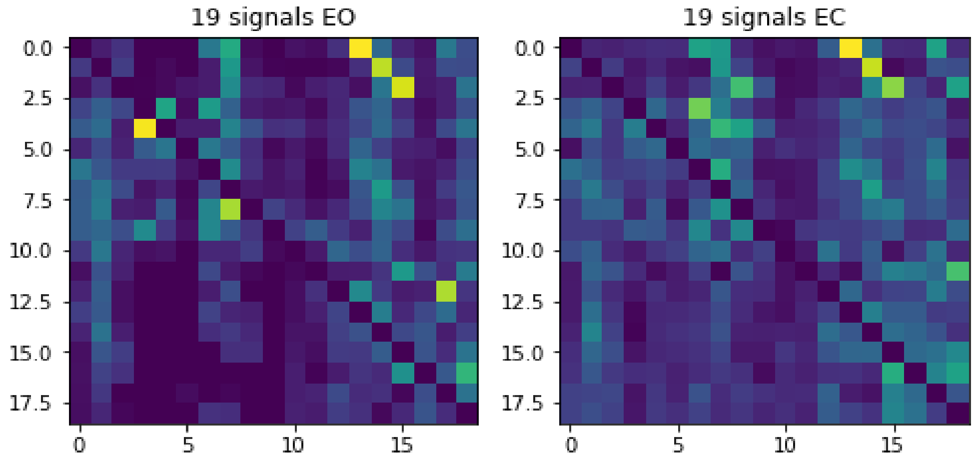


Figure 1.4.1. Considering the reduced set of 19 Channels and connectivity matrices

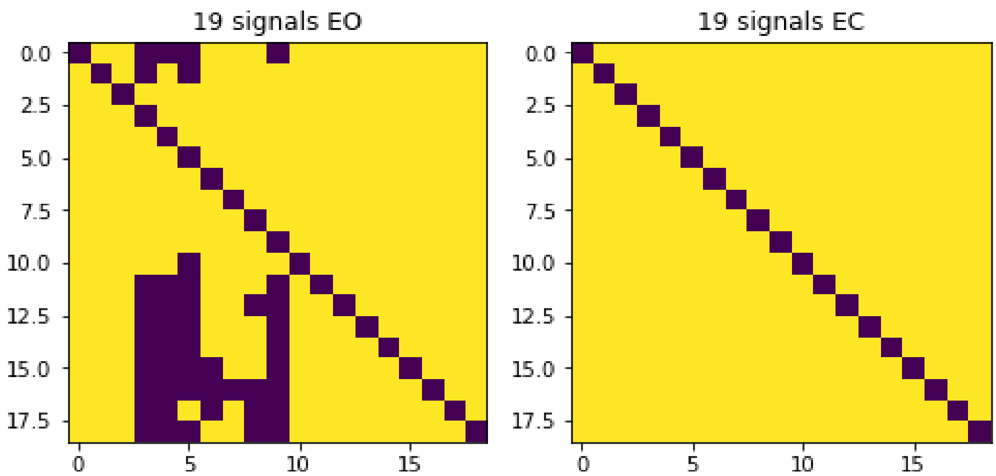


Figure 1.4.2. Considering the reduced set of 19 Channels and binary adjacency matrices

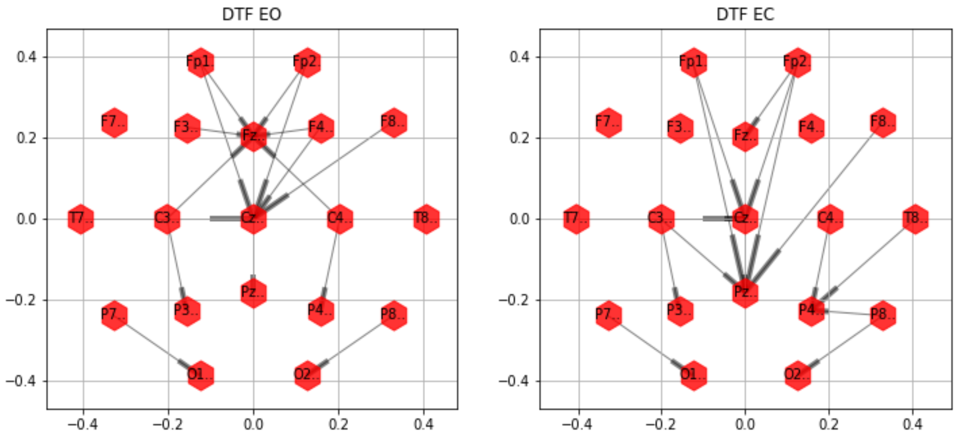


Figure 1.5.1 Topological representations of the networks for DTF

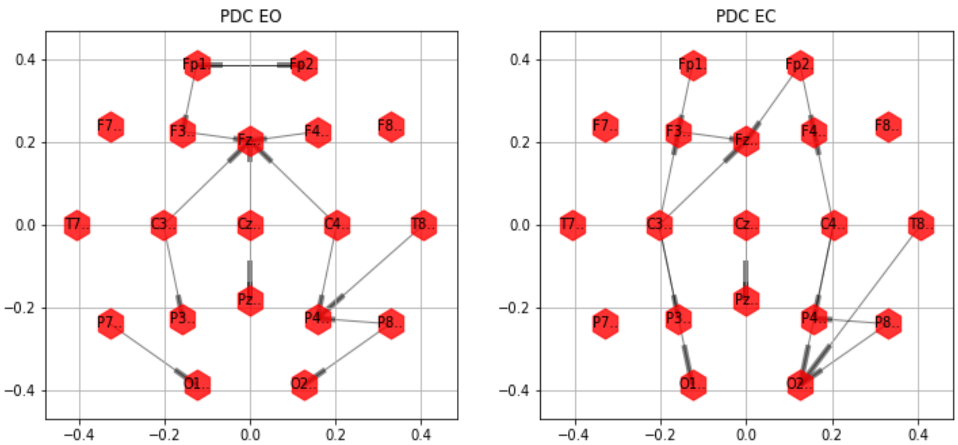


Figure 1.5.2. Topological representations of the networks for PDC

8.2. Graphs Indices:

Table 2.1.1. Global Indices

Estimator	Eyes	Density	Clustering_Coefficient	Path_Length
PDC	EO	50	0.803	1.581
PDC	EO	30	0.602	1.812
PDC	EO	20	0.497	1.911
PDC	EO	10	0.381	1.077
PDC	EO	5	0.274	0.372
PDC	EO	1	0.048	not fully connected
PDC	EC	50	0.799	1.557
PDC	EC	30	0.62	2.001
PDC	EC	20	0.506	2.23
PDC	EC	10	0.4	1.402
PDC	EC	5	0.314	0.32
PDC	EC	1	0.087	not fully connected
DTF	EO	50	0.859	1.232
DTF	EO	30	0.783	1.079
DTF	EO	20	0.734	0.676
DTF	EO	10	0.683	0.593
DTF	EO	5	0.707	0.123
DTF	EO	1	0.18	not fully connected
DTF	EC	50	0.85	1.376
DTF	EC	30	0.738	1.086
DTF	EC	20	0.722	0.936
DTF	EC	10	0.635	0.603
DTF	EC	5	0.555	0.237
DTF	EC	1	0.069	not fully connected

Table 2.1.2. Local Indices for PDC

Estimator	Eyes	Density	High_Degree	High_In-Degree	High_Out-Degree
PDC	EO	50	F5, F1, F3, Pz, C3, F2, Cpz, Po3, Cp1, Cp3	Cp1, Cp4, C3, Cp3, F5, Cpz, Pz, Po3, Cp5, F3	Af8, Af7, F6, Fp2, F4, Af4, Af3, Fp1, F5, T7
PDC	EO	30	F5, F3, Cp4, Pz, Cp3, Cp1, Afz, P1, Po3, F1	Cp4, Cp1, F5, Pz, Cp3, F3, Po3, P1, P4, Fc2	Af8, Af7, F6, F4, Af4, F7, F5, F8, T7, Fp1
PDC	EO	20	F5, Pz, F3, Cp4, Cp1, Afz, Po3, Cp3, Cpz, Fz	Cp4, Pz, F5, Cp1, F3, Cp3, Po3, Fc2, Afz, P4	Af8, Af7, F6, Fp1, F4, Fp2, Af4, F8, F7, Ft7
PDC	EO	10	F3, Fz, F5, Pz, Af8, F1, Fc1, Fp2, Po3, Af7	Fz, Pz, Fc1, F3, Po3, F5, F1, P4, O2, C1	Af8, Af7, C5, Fp2, F6, Ft7, T7, F7, C6, F8
PDC	EO	5	Af8, Af7, F3, F1, Fc1, C1, Cpz, Fp2, Fz, P1	Fc1, F1, F3, Fz, C1, Cpz, P1, P4, O2, T9	Af8, Af7, C5, Ft7, T7, Fc4, Fp2, C6, F8, C3
PDC	EO	1	Af8, P6, C5, C3, Cz, Cpz, Fp1, Ft7, T9, P3	Fp1, T9, P3, P6, C3, Cz, Cpz, Fz, F2, P1	Af8, C5, Ft7, C6, Af7, Fc6, Cp3, Fp2, T7, Po7
PDC	EC	50	P1, Cp4, Cpz, F5, Po3, Cp3, Fz, O1, F4, F2	Cp3, P1, Cp4, Cpz, O1, Cp1, Po3, P3, Cz, O2	Ft7, C6, Fp2, F8, Ft8, Afz, Af8, Af7, Af4, F4
PDC	EC	30	Po3, Cpz, F5, Fz, F3, F6, P1, O1, F2, F1	Cpz, Po3, P1, Cp3, O1, Cp4, Cp1, Cz, Fz, Poz	Ft7, Af8, Af7, Af4, F6, Ft8, F8, C6, Fp2, F4
PDC	EC	20	F6, Po3, Fz, Cpz, F3, O1, F1, P1, F5, F4	Po3, Cpz, O1, P1, Cz, Fz, F3, Cp1, F6, F5	Af8, Ft7, C6, Af4, F6, Fp2, F8, Ft8, Afz, Fc6
PDC	EC	10	F3, F5, Fz, Pz, F6, Af8, C6, F1, F2, Ft7	Fz, F3, O1, F5, Fcz, Pz, Cpz, F6, P1, Po3	Af8, Ft7, C6, Af7, T7, Fc6, Af4, F7, Ft8, F8
PDC	EC	5	Ft7, C6, Fz, F5, F3, F1, P1, Pz, Po4, Cz	F3, Fz, F5, Po4, F2, P1, Cz, Pz, O2, F1	Ft7, C6, Af8, Af7, C5, F7, Fp1, Fp2, Af3, Af4
PDC	EC	1	C6, Af7, Ft7, Pz, P4, Po4, Af8, Fz, F4, P6	Pz, Po4, Fz, F4, P4, F2, T9, P3, P6, C3	C6, Af7, Ft7, Af8, Fc4, Fc6, C5, Cz, Cp6, Af4

Table 2.1.3. Local Indices for DTF

Estimator	Eyes	Density	High_Degree	High_In-Degree	High_Out-Degree
DTF	EO	50	Iz, Cp4, Po7, F5, C4, F3, Fc2, Po3, Po4, Cpz	Fc2, C4, Cp3, Cp4, F5, F3, T9, Po3, Po4, F1	Fc6, Fp2, F8, Ft8, T8, C6, Af7, Af4, F7, F6
DTF	EO	30	Cp4, F5, F3, Po3, Cp3, Cpz, F1, Cp1, Fz, T9	F3, Po3, F5, Cp4, F1, Cp3, Cpz, Fz, T9, Cp1	Af4, Fp2, F7, F6, F8, Cp2, Fp1, Fpz, Af8, Af7
DTF	EO	20	F5, F3, Cp4, F1, Fz, Cpz, Cp3, Po3, Fc2, Po4	F3, F5, Cp4, F1, Fz, Cpz, Cp3, Po3, Fc2, T9	Af7, Af8, Fp2, Af4, F8, Cp2, Fpz, F6, Fc6, C5
DTF	EO	10	F3, F5, Fz, Cpz, Cp4, Fc2, F1, Fc1, Cp3, Po4	F3, F5, Fz, Cpz, Cp4, Fc2, F1, Fc1, Po4, T9	Af4, C6, Cp1, F6, Fc6, Cp3, Fp1, Fp2, Af7, Af8
DTF	EO	5	F3, F5, Fz, Cpz, Cp4, Fc2, Po4, Fc1, Cz, Pz	F3, F5, Fz, Po4, Fc2, Cp4, Cpz, Fc1, P1, Pz	Cz, Cpz, Af8, Fc4, Fc6, C1, Cp2, Fp2, P7, P2
DTF	EO	1	F3, F5, Fz, Fc1, Fcz, Fc2, Fc4, C5, C3, Cz	F3, F5, Fz, Pz, O2, Fc5, Fc3, Fc1, Fcz, Fc2	Fc1, Fcz, Fc2, Fc4, C5, C3, Cz, Cp5, Cpz, Ft7
DTF	EC	50	P8, Cp3, P3, Pz, Poz, P1, Po3, Fz, Iz, Cpz	F5, F3, O1, Fz, Po3, Poz, Iz, P3, P1, Pz	P2, Fc6, Cp5, Cp3, P5, C5, Af4, Ft7, Tp8, P4
DTF	EC	30	F5, F3, Pz, Po3, Poz, Cpz, P8, O1, Fz, P1	F5, F3, Po3, O1, Poz, Pz, Cpz, Fz, P8, Cp3	Fc6, P2, Fc4, F8, C4, Ft8, Tp8, Cp2, Af8, Ft7
DTF	EC	20	F5, F3, Cpz, Poz, Pz, O1, Fz, Cz, Po3, Cp1	F5, F3, O1, Poz, Fz, Cpz, Pz, Po3, Cz, Iz	Ft7, Fc4, Cp1, Cpz, Cp2, F8, Ft8, P1, Fc6, Cz
DTF	EC	10	F5, F3, O1, Cpz, Fz, Cz, Pz, Po3, Poz, Po4	F5, O1, F3, Cpz, Fz, Cz, Pz, Po3, Po4, Iz	C6, Cp1, Cp4, C4, Cpz, Ft7, P2, C3, Cz, Cp6
DTF	EC	5	F3, F5, O1, Cpz, Fz, Iz, Pz, Po4, Po3, Cz	F3, O1, F5, Cpz, Fz, Iz, Pz, Po4, Cz, Po3	Af3, Fc1, Fcz, Fc2, C3, C1, C2, Fp2, Afz, F5
DTF	EC	1	F3, F5, Fz, Po4, O1, Pz, Fpz, Af7, Af3, F7	F3, Fz, Po4, O1, F5, Pz, P1, Fc5, Fc3, Fc1	Fpz, Af7, Af3, F7, Fc5, Fc3, Fc1, Fcz, Fc2, Fc6

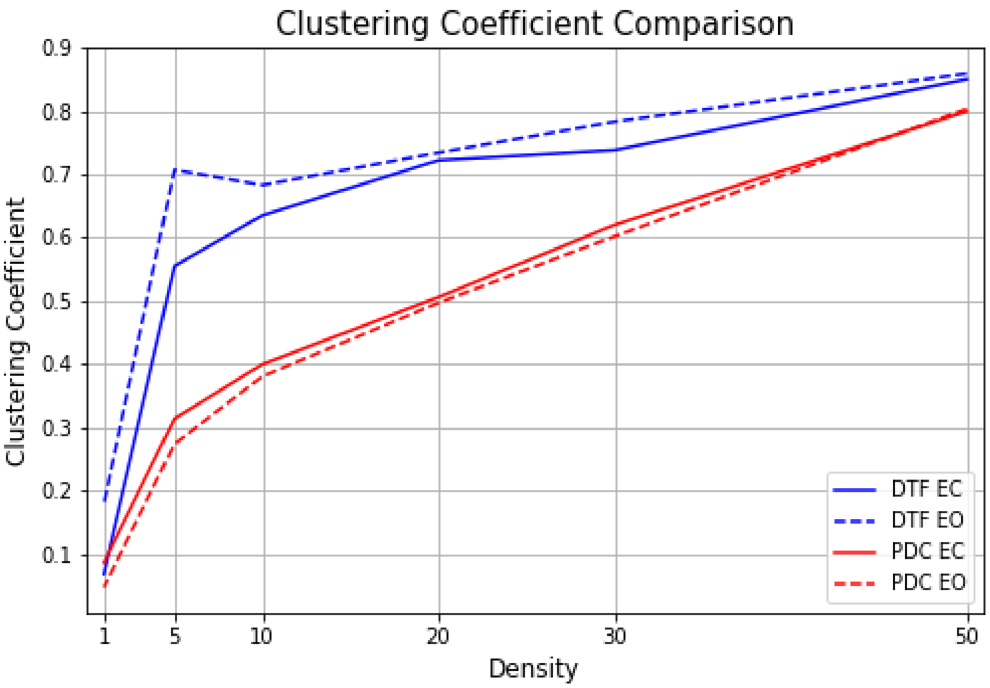


Figure 2.3.1. Comparison of clustering coefficient

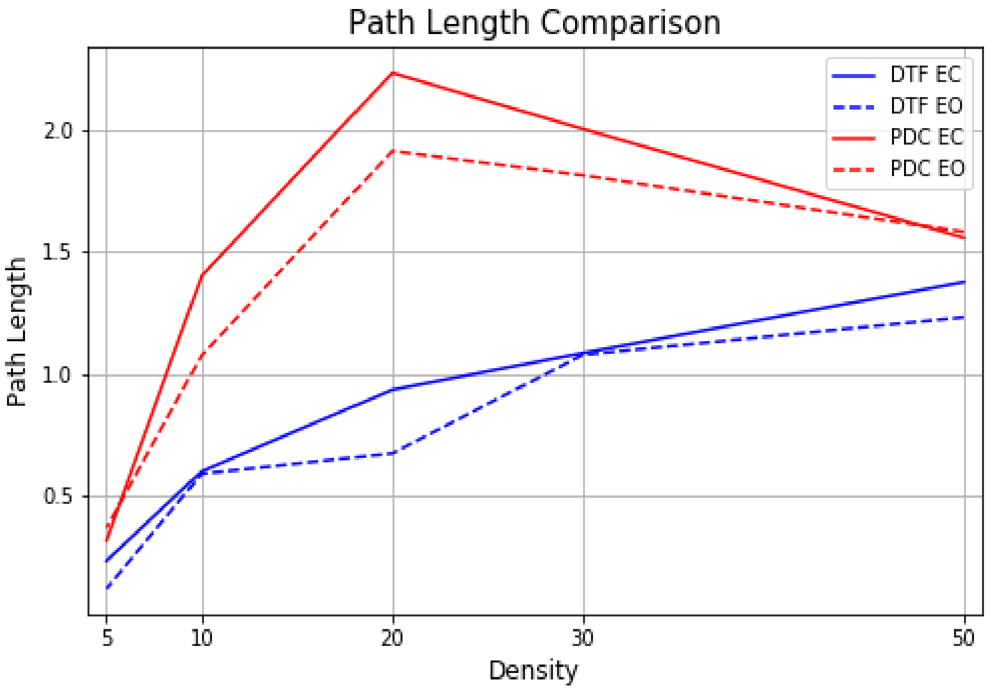


Figure 2.3.2. Comparison of path length

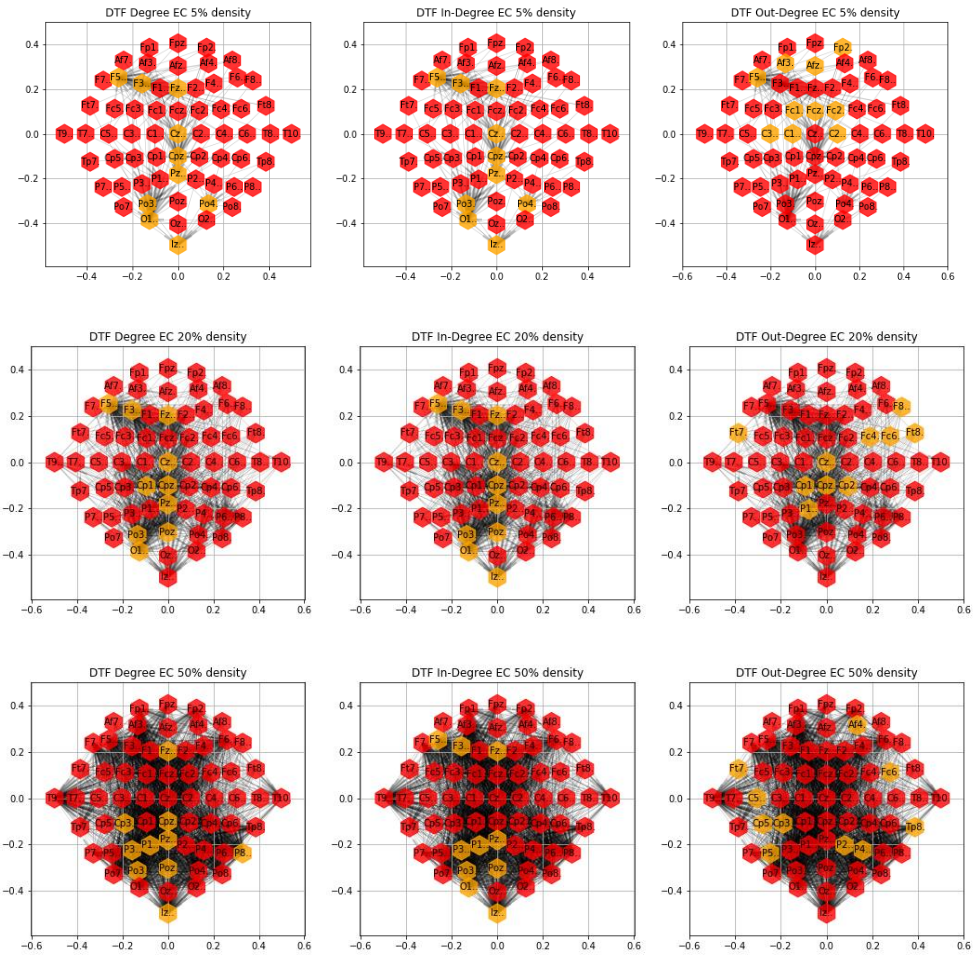


Figure 2.5.1. Topological representations of Local Indices (DTF EC)

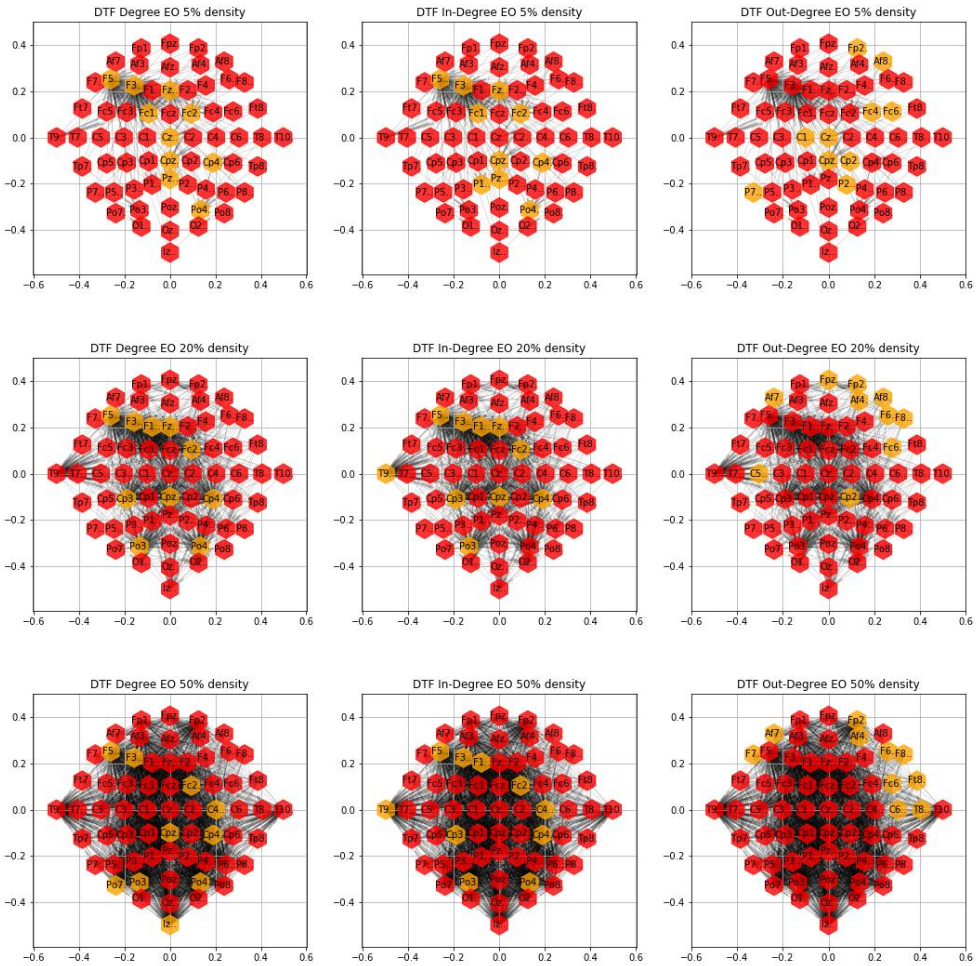


Figure 2.5.2. Topological representations of Local Indices (DTF EO)

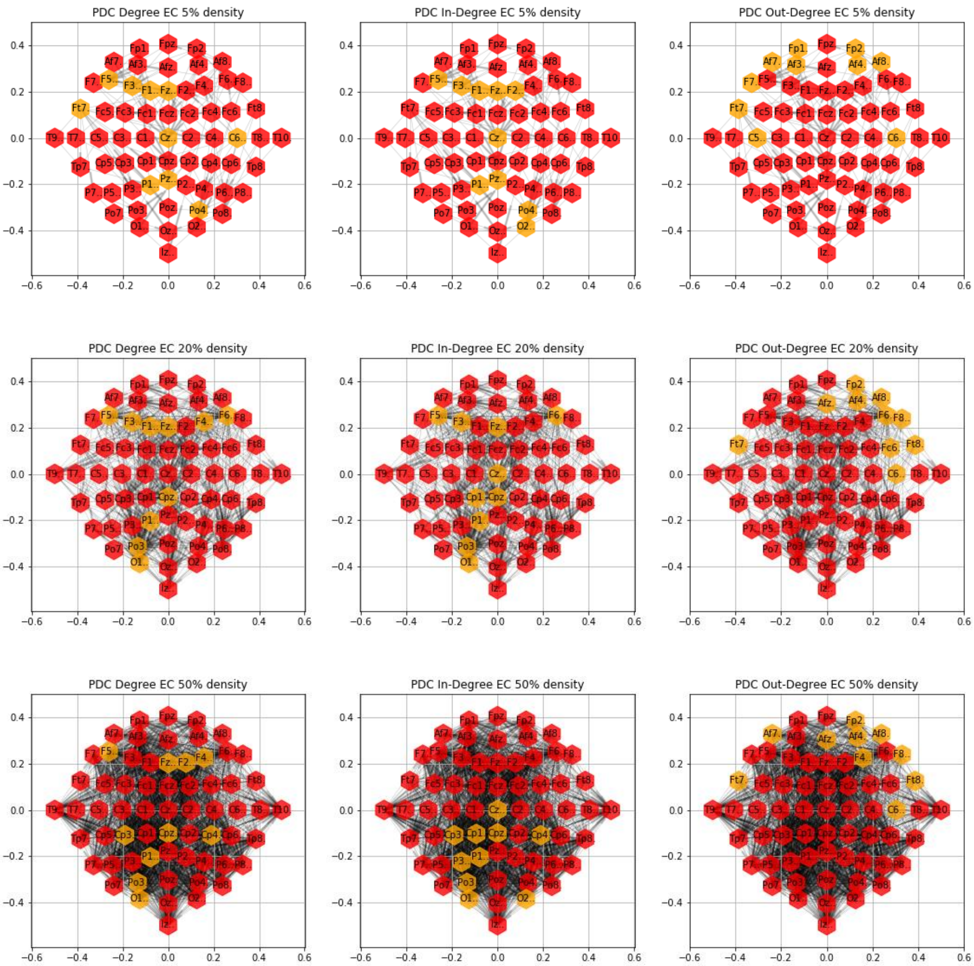


Figure 2.5.3. Topological representations of Local Indices (PDC EC)

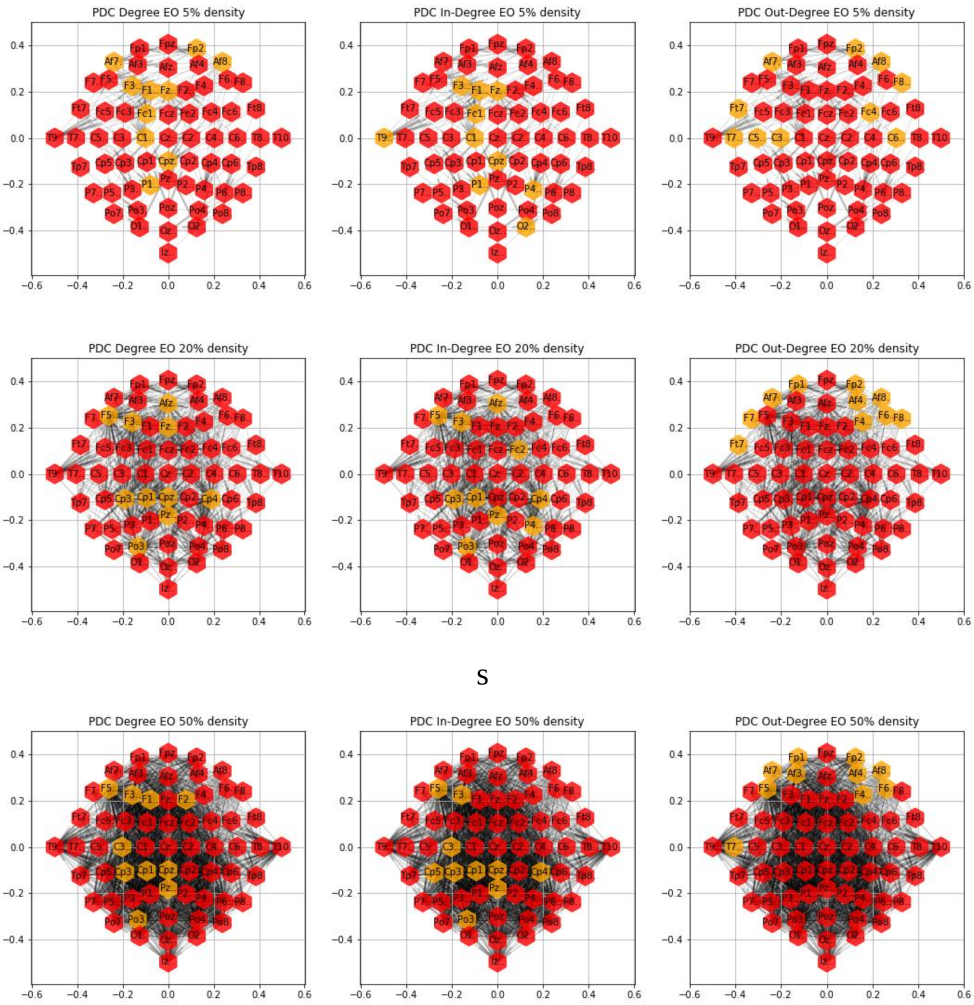


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Figure 2.5.4. Topological representations of Local Indices (PDC EO)

8.3. Motif Analysis:

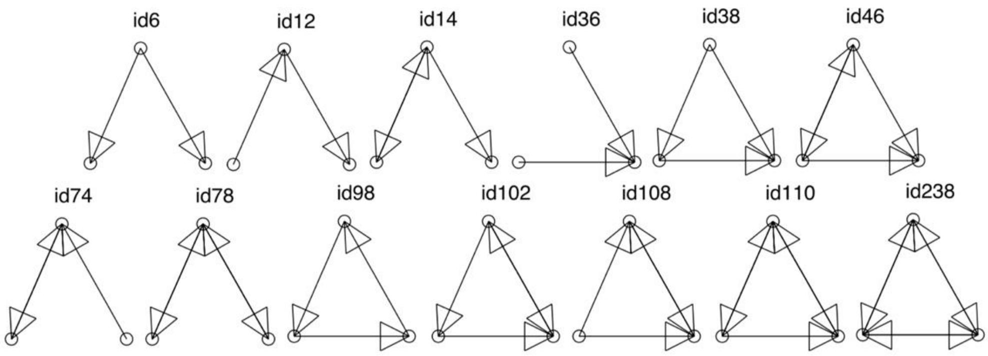

Figure 3.0.1. Description of 3-node motifs

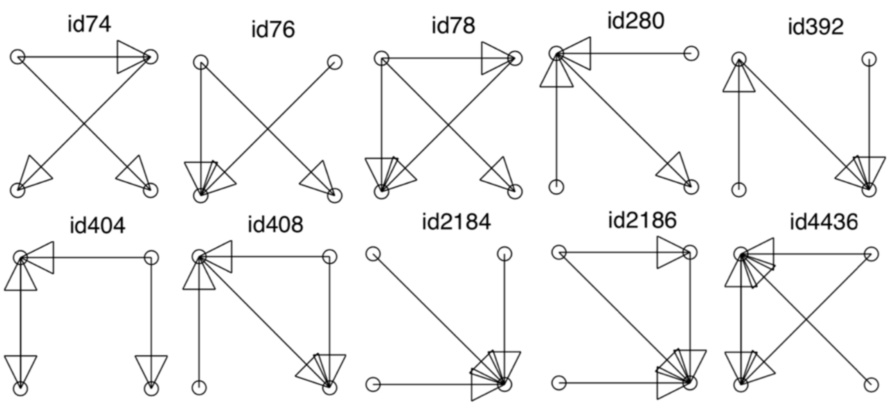

Figure 3.0.2. Description of top 10 4-node motifs seen this project

Table 3.1.1. 3-node motif analysis PDC EO for 20% density

Motif ID	Frequency	Statistical Significance
6	2028	anti-motif
12	1789	anti-motif
14	375	anti-motif
36	3115	anti-motif
38	1573	motif
46	223	motif
74	1223	anti-motif
78	63	anti-motif
98	22	anti-motif
102	107	anti-motif
108	553	motif
110	187	motif
238	35	motif

Table 3.1.2. 3-node motif analysis PDC EC for 20% density

Motif ID	Frequency	Statistical Significance
6	2046	anti-motif
12	2072	not significant
14	539	anti-motif
36	2680	anti-motif
38	1462	motif
46	261	motif
74	1130	anti-motif
78	80	anti-motif
98	30	anti-motif
102	126	anti-motif
108	510	motif
110	139	not significant
238	45	motif

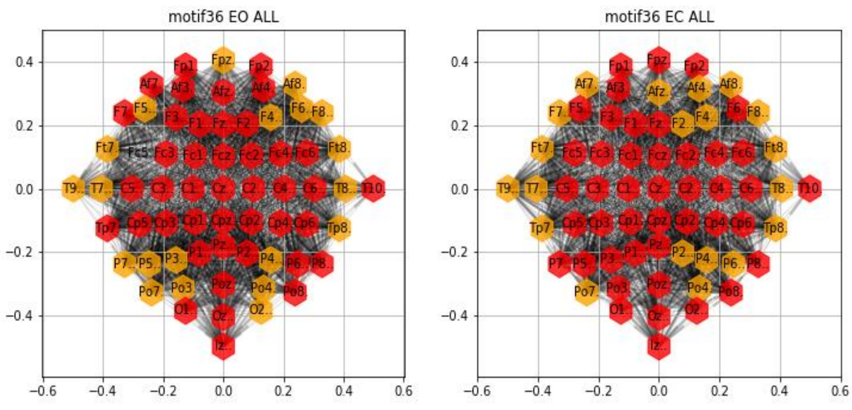

Figure 3.2. Topographical representation of the networks with connections $A \rightarrow B \leftarrow C$

Table 3.3.1. 3-node motif analysis for only PO scalp region of PDC EO for 20% density

Motif ID	Frequency	Statistical Significance
6	54	motif
12	232	motif
14	67	not significant
36	408	not significant
38	16	not significant
46	10	not significant
74	234	not significant
78	19	not significant
98	0	not significant
102	4	anti-motif
108	25	not significant
110	16	not significant
238	4	not significant

Table 3.3.2. 3-node motif analysis for only PO scalp region of PDC EC for 20% density

Motif ID	Frequency	Statistical Significance
6	41	motif
12	253	motif
14	68	not significant
36	562	not significant
38	17	anti-motif
46	9	not significant
74	322	not significant
78	36	not significant
98	0	not significant
102	3	not significant
108	24	not significant
110	12	not significant
238	4	not significant

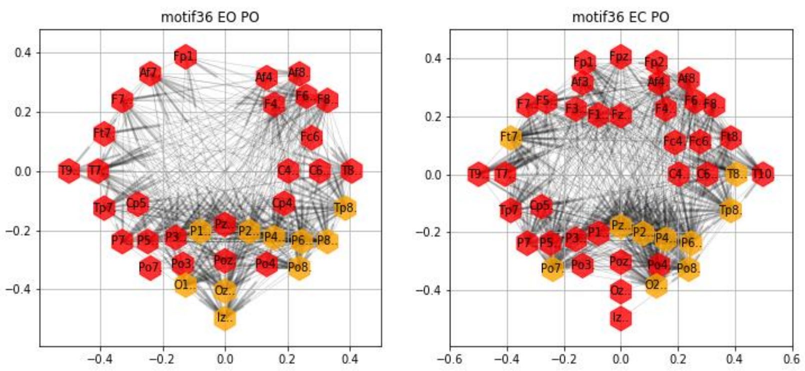

Figure 3.3. Topographical representation of the networks with connections $A \longrightarrow B \longleftarrow C$

Table 3.4.1. 4-node motif TOP 10 analysis PDC EO for 20% density

Motif ID	Frequency	Statistical Significance
76	23213	anti-motif
392	12807	motif
2186	11220	not-significant
2184	8476	anti-motif
74	7929	not-significant
78	7064	not-significant
408	6004	not-significant
4436	5600	anti-motif
404	4404	anti-motif
280	4264	anti-motif

Table 3.4.2. 4-node motif TOP 10 analysis PDC EC for 20% density

Motif ID	Frequency	Statistical Significance
76	20395	anti-motif
392	12571	motif
74	9102	not-significant
2186	9091	not-significant
78	6514	anti-motif
2184	6349	anti-motif
408	5455	not-significant
280	4849	not-significant
404	4713	anti-motif
4436	4616	anti-motif

8.4. Community Detection:

PDC

Table 4.1.1. Communities using Louvain for graph of PDC EO 30% density

Community ID	Number of nodes	Channels
0	14	Fc5, C5, C3, Cp5, F5, F3, F1, F4, Ft, T7, T9, Tp7, P3, P1
1	22	Fc3, Fc, Fcz, Fc2, Fc4, C1, C2, C4, Fp1, Fpz, Fp2, Af7, Af3, Afz, Af4, Af8, Fz, F2, F6, F8, Pz, P4
2	10	Fc6, Cz, C6, Cp1, Cpz, Cp2, Cp6, Ft8, T8, T10
3	18	Cp3, Cp4, F7, Tp8, P7, P5, P2, P6, P8, Po7, Po3, Poz, Po4, Po8, O1, Oz, O2, Iz

Table 4.1.2. Communities using Louvain for graph of PDC EC 30% density

Community ID	Number of nodes	Channels
0	26	Fc5, Fc3, Fc1, Fcz, C5, C1, Cz, Cp5, Cp3, Cpz, Fp1, Fpz, Af7, Af3, Afz, Af4, Af8, F7, F5, F3, F1, Fz, T7, T9, Tp7, O1
1	16	Fc2, Fc4, Fc6, C2, C4, C6, Fp2, F2, F4, F6, F8, Ft8, T8, T10, P6, Po8
2	22	C3, Cp1, Cp2, Cp4, Cp6, Ft7, Tp8, P7, P5, P3, P1, Pz, P2, P4, P8, Po7, Po3, Poz, Po4, Oz, O2, Iz

DTF

Table 4.1.3. Communities using Louvain eyes-open for graph of DTF EO 30% density

Community ID	Number of nodes	Channels
0	10	Fc5, Fcz, Fc4, Fc6, Cz, Cpz, Afz, F2, F4, T9
1	18	Fc3, Fc1, Fp1, Fpz, Fp2, Af7, Af3, Af4, Af8, F7, F3, F6, F8, Ft8, Pz, O1, O2, Iz
2	18	Fc2, C1, C2, C4, C6, Cp2, F1, Fz, Tp8, P1, P2, P4, P8, Po7, Poz, Po4, Po8, Oz
3	18	C5, C3, Cp5, Cp3, Cp1, Cp4, Cp6, F5, Ft7, T7, T8, T10, Tp7, P7, P5, P3, P6, Po3

Table 4.1.4. Communities using Louvain eyes-open for graph of DTF EC 30% density

Community ID	Number of nodes	Channels
0	22	Fc5, Fc3, Fc1, C1, C2, Cp5, Cp3, Cp1, Cpz, Fp1, Af7, Af3, Afz, F7, F1, Fz, Ft7, T7, P3, P1, Po3, Poz
1	22	Fcz, Fc2, Fc4, Fc6, Cz, C4, C6, Fpz, Fp2, Af4, Af8, F3, F4, F6, F8, Ft8, T10, Pz, P6, Po7, Po8, O1
2	20	C5, C3, Cp2, Cp4, Cp6, F5, F2, T8, T9, Tp7, Tp8, P7, P5, P2, P4, P8, Po4, Oz, O2, Iz

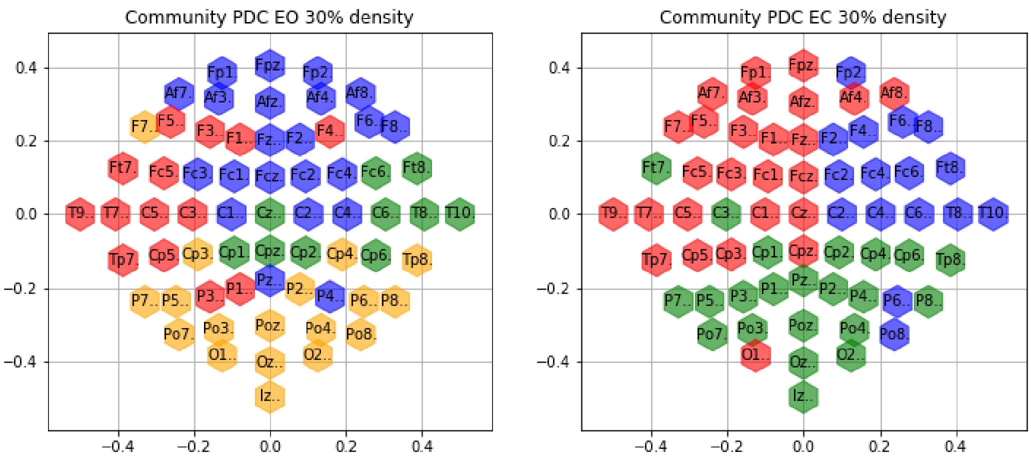

Figure 4.2.1. Graphical representation of the community structure for PDC

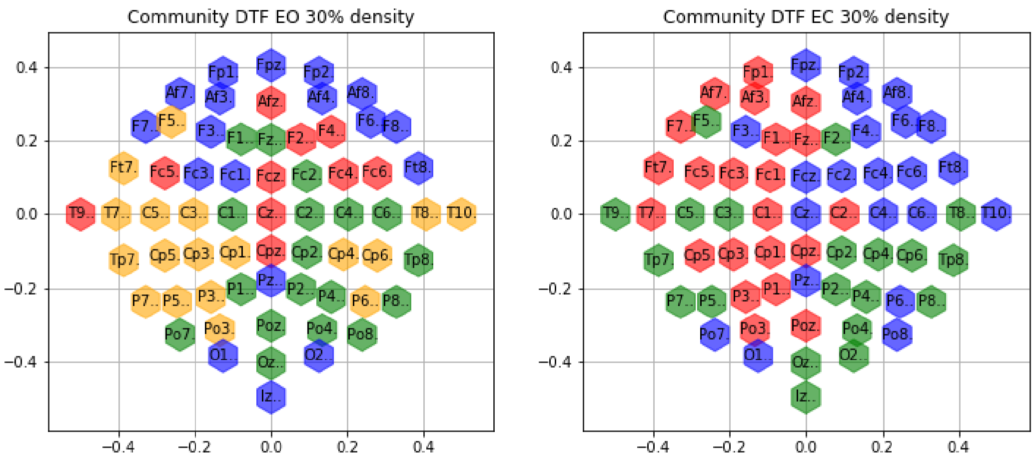

Figure 4.2.2. Graphical representation of the community structure for DTF