Real-Time EEG Connectivity Analysis for Brain-Computer Interfaces and Neurofeedback

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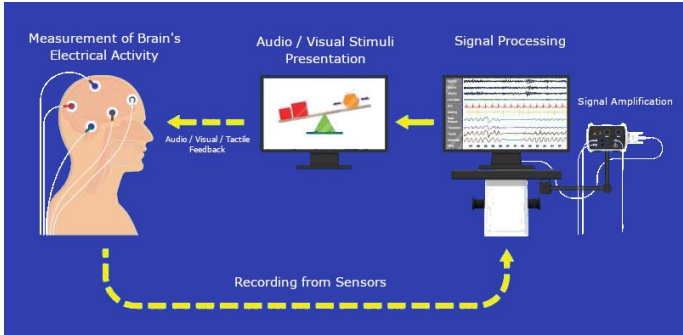
Introduction

- EEG analysis is a fundamental non-intrusive neuroscientific tool
- Functional Connectivity describe the statistics between sensors
- Directed functional connectivity describes influence
- Real time connectivity can be used for neurofeedback



Background - What is PDC?

- Partial Directed Coherence (PDC) is a functional connectivity method

- Frequency domain measurement

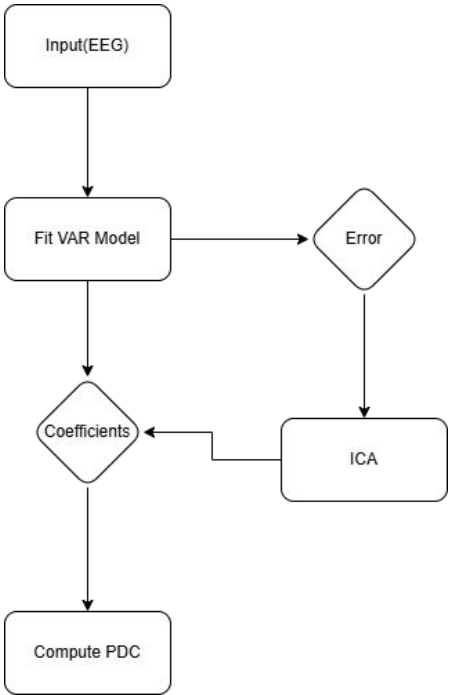
- Answer the question “Does activity in region A drive activity in region B at a particular frequency” ?

Background - What is MVARICA ?

- Multivariate Autoregressive Independent Component Analysis (MVARICA)
- Multivariate Autoregressive (MVAR) modeling capture directional interactions
- ICA, separate statistically independent sources from the noise to improve the model

Jahanian-Najafabadi & Bagh, 2023, 2024a, b, c, 2025a, b, Bagh & Jahanian-Najafabadi, 2024

Background - MVARICA - Steps



Background - MVARICA - Hyperparameters

- Model Order (a.k.a. lag):
  The number of past points the MVAR uses to predict the next data point

- Delta ridge penalty:
  Regularization parameter meant to stabilize the coefficient of the MVAR model

Dataset

- Data from the Child Mind Institute (Healthy Brain Network)
- Datasets are from children and adolescents (age 5-21)
- It is resting state EEG (eyes closed and open)
- 265 datasets (avg. 320 seconds)
- Data is processed following the pipeline in previous work [Jahanian-Najafabadi & Bagh, 2023, 2024a, b, c, 2025a, b, Bagh & Jahanian-Najafabadi, 2024]

Offline System

- Implemented using scot package

- Optimizes model order using Akaike Information Criterion (AIC) score

- Delta ridge penalty is optimized using bisection search

Proposed Method

Method - Step 1

MVAR fitting:

- QR factorization (X is factorized into an orthogonal matrix Q and upper triangle matrix R)
- Incremental QR factorization using Given rotation (i.e. use the overlap instead of computing from scratch)
- Add forgetting factor (with full refactorization after n steps)
- Use GPU for hardware acceleration

Method - Step 2

- Offline MVARICA uses ICA (specifically Fast-ICA)

- Online MVARICA uses Picard-O (Preconditioned ICA for Real Data - under an Orthogonal constraint)

- Use GPU for hardware acceleration

Method - Hyperparameters - Model Order

Recursive AIC (RAIC):

```
Mean_t, std_t = mean(x), std(x)
Rolling_mean = abs (Mean_t - Mean_t_last_step)
rolling_std = abs (std_t - std_t_last_step)
mean_history <- Rolling_mean
std_history <- rolling_std
eps_mean = percentile (mean_history, change_percentile)
eps_std = percentile (std_history, change_percentile)
is_nonstationary = (Rolling_mean > eps_mean) or (rolling_std > eps_std)
If is_nonstationary:
    Search_window = 5
Else:
    Search_window = 1
For p in (current_model_order- Search_window, current_model_order+Search_window):
     Fit MVAR model and compute AIC
     If fitting fails, assign infinite AIC
Select model order with lowest AIC
Update current model order
```

Method - Hyperparameters - Delta

- Use Adam Optimizer

- Metric is Mean Absolute Error (MAE) of the predicted signal from MVAR coefficient compared to the original data

- Gradient is computed based on the change in the MAE scores

Research Questions

Q1 - How good is the online system ?

i.e. How does it compare to standard offline system

Q2 - How well does it optimize hyperparameters ?

i.e. Does it converge ? What is the error ? How does it compare to standard offline system

Q3 - How fast is it ?

i.e. How does the latency change under different stress conditions.

Results

Picard-O

Parameters

- Used umixing matrix from the previous iteration for warm start
- Maximum iteration is 10
- Tolerance is 1e-4
- Used relative error, defined as
  norm(reconstructed_residual - residual) / norm(residual)
- Average relative error through the experimentation was 2.40E-15

Q1 - How good is the online system ?

Q1 - How good is the online system ?

Metrics:

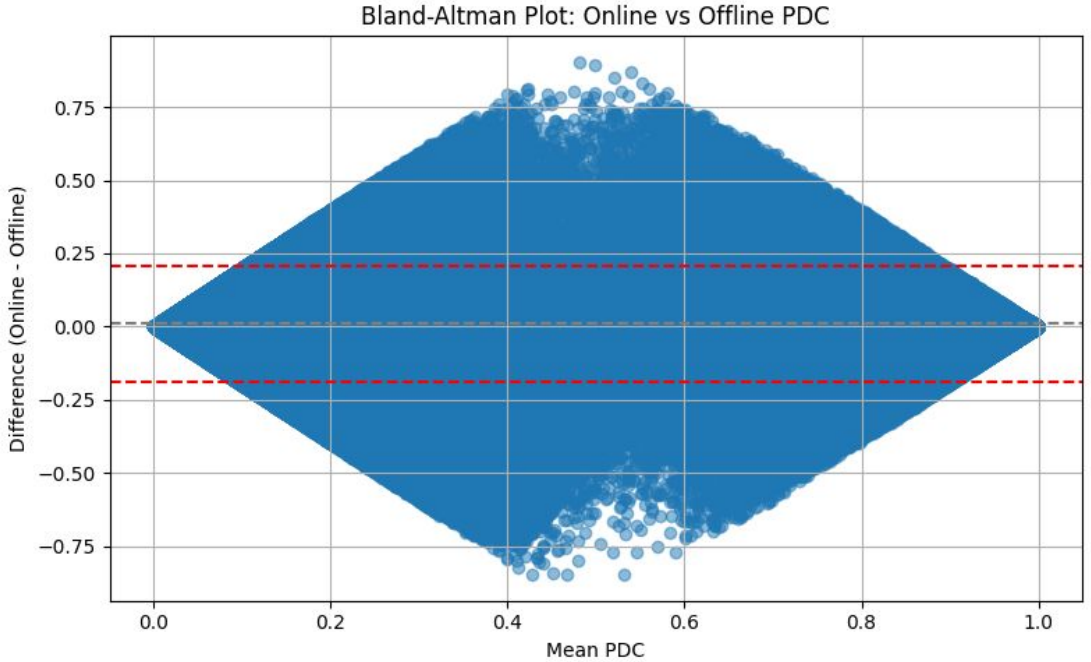
- Bland Altman Plot: measures agreement and systematic Bias
- Mean Absolute Error (MAE): between output PDC of offline and online systems
- Correlation: between output PDC of offline and online systems

Q1 - How good is the

Mean: 0.009

Positive 95% percentile: 0.206

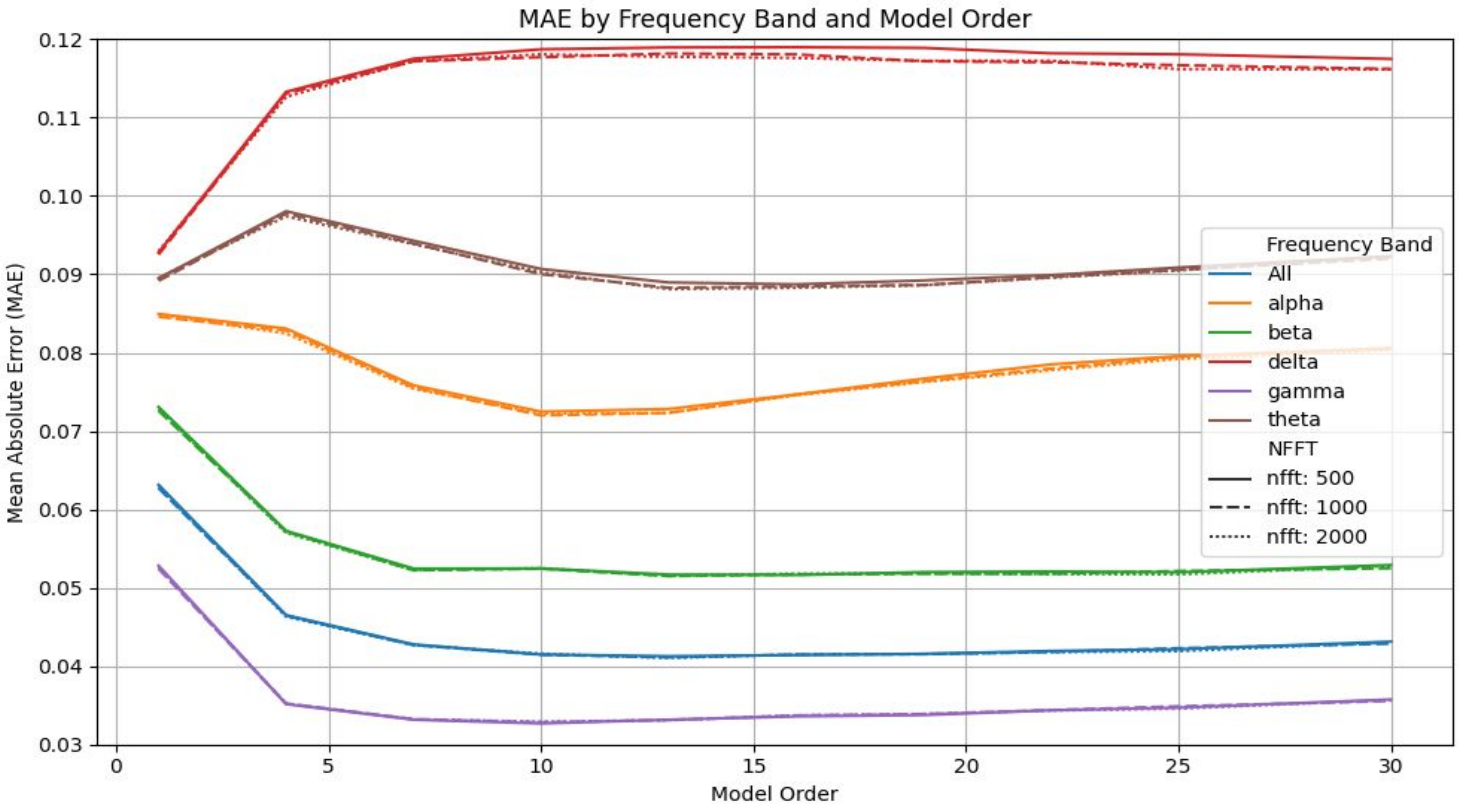
Negative 95% percentile: -0.188



Q1 - How good is the online system ?

Metric	Score
MAE	0.070
RMSE	0.101
Pearson Correlation	0.910 (P-Value <0.001)
Spearman Correlation	0.421 (P-Value <0.001)

Q


MAE by Frequency Band and Model Order
Mean Absolute Error (MAE)
Model Order
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0
5
10
15
20
25
30
Frequency Band
All
alpha
beta
delta
gamma
theta
NFFT
nfft: 500
nfft: 1000
nfft: 2000

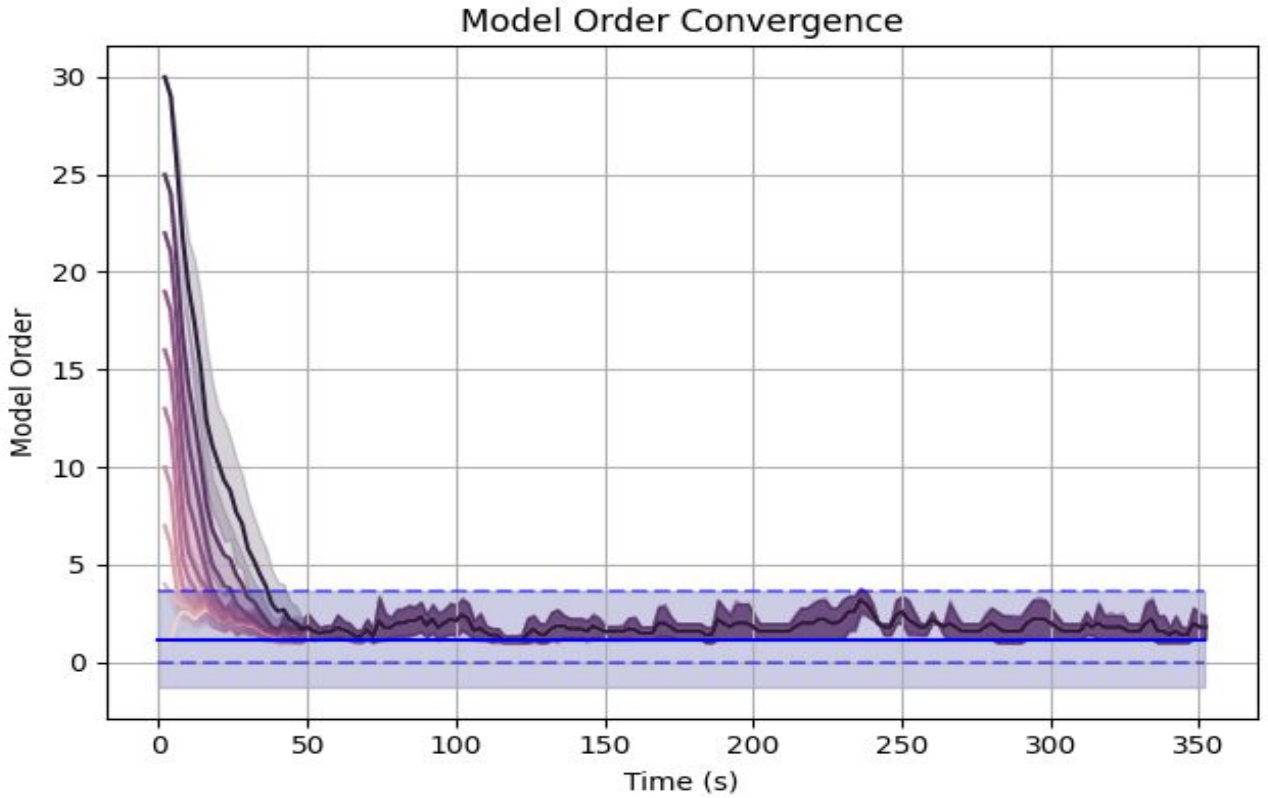
Q2 - How well does it optimize hyperparameters ?

Q2 - How well does it optimize hyperparameters ?

Metrics:

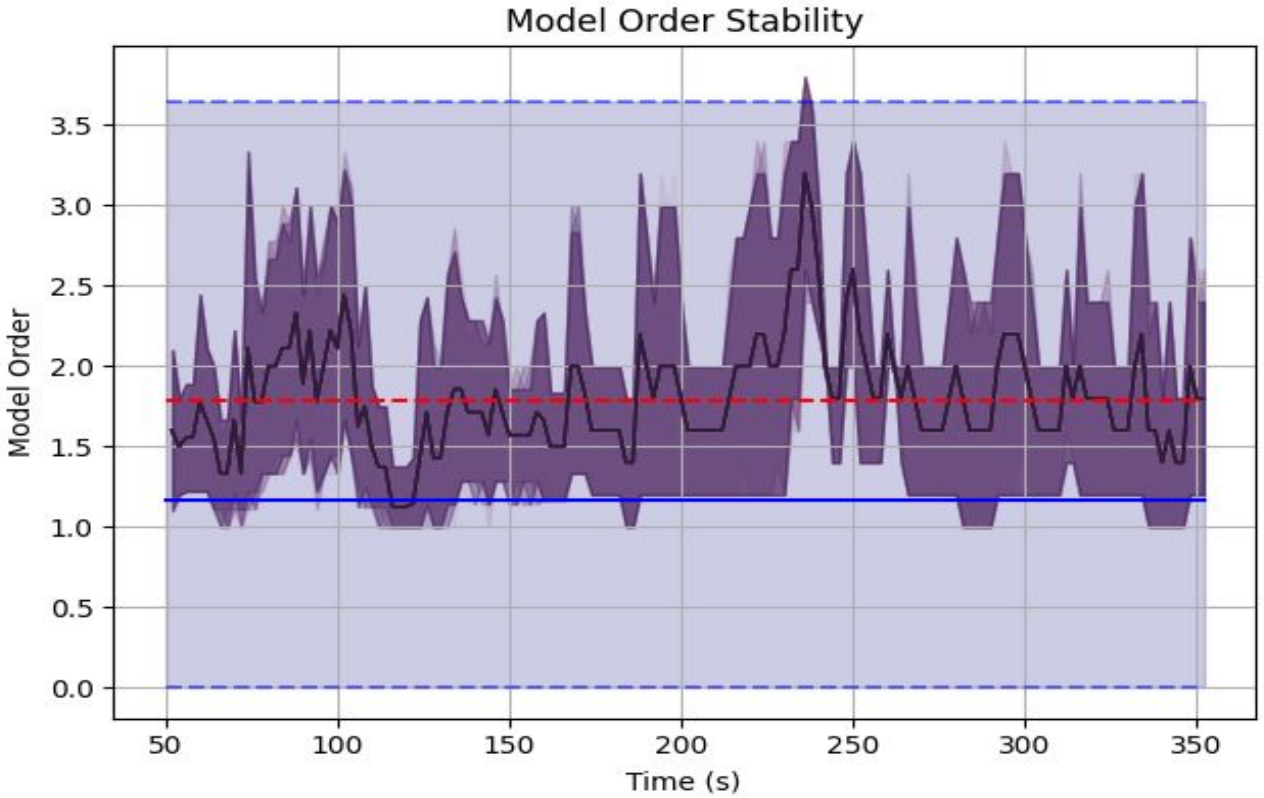
- Convergence
- Stability
- Accuracy

Q2 -

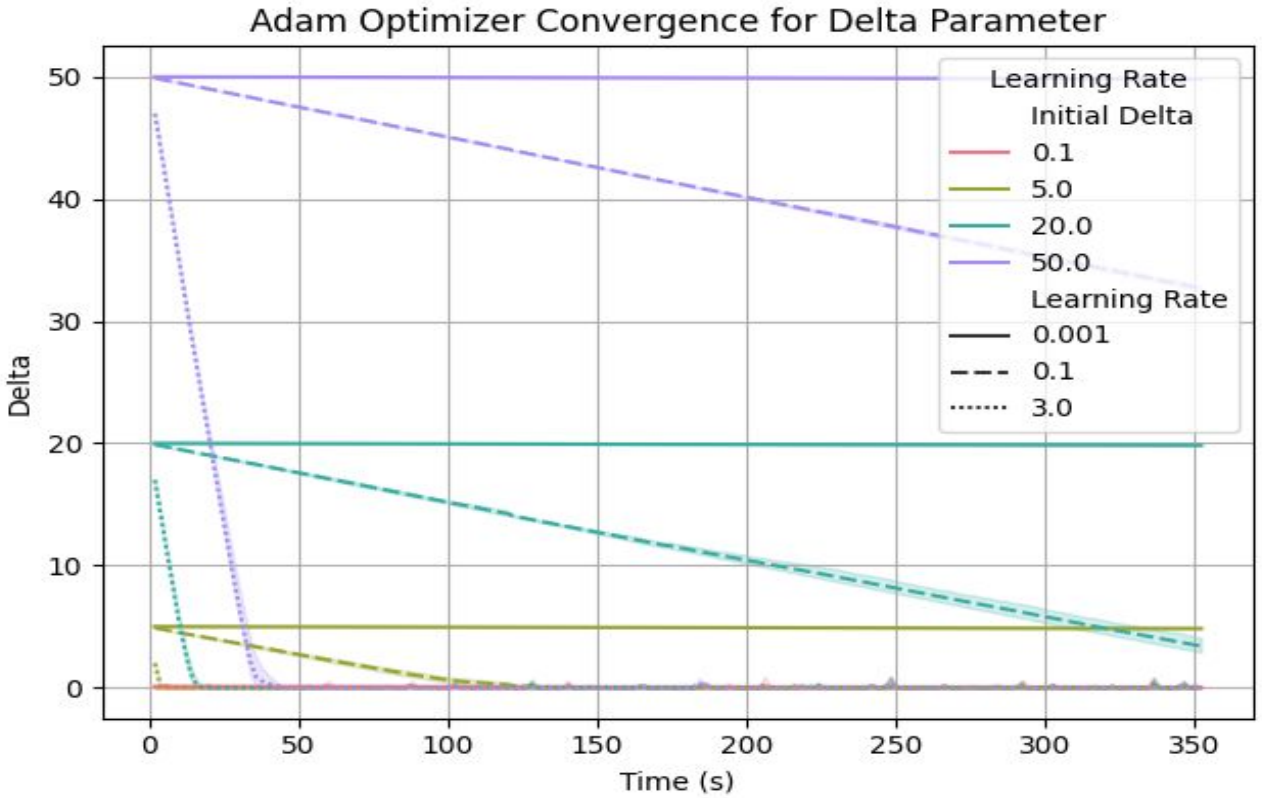

Model Order Convergence
Model Order
Time (s)
0
5
10
15
20
25
30
0
50
100
150
200
250
300
350

?

Q2 - ?

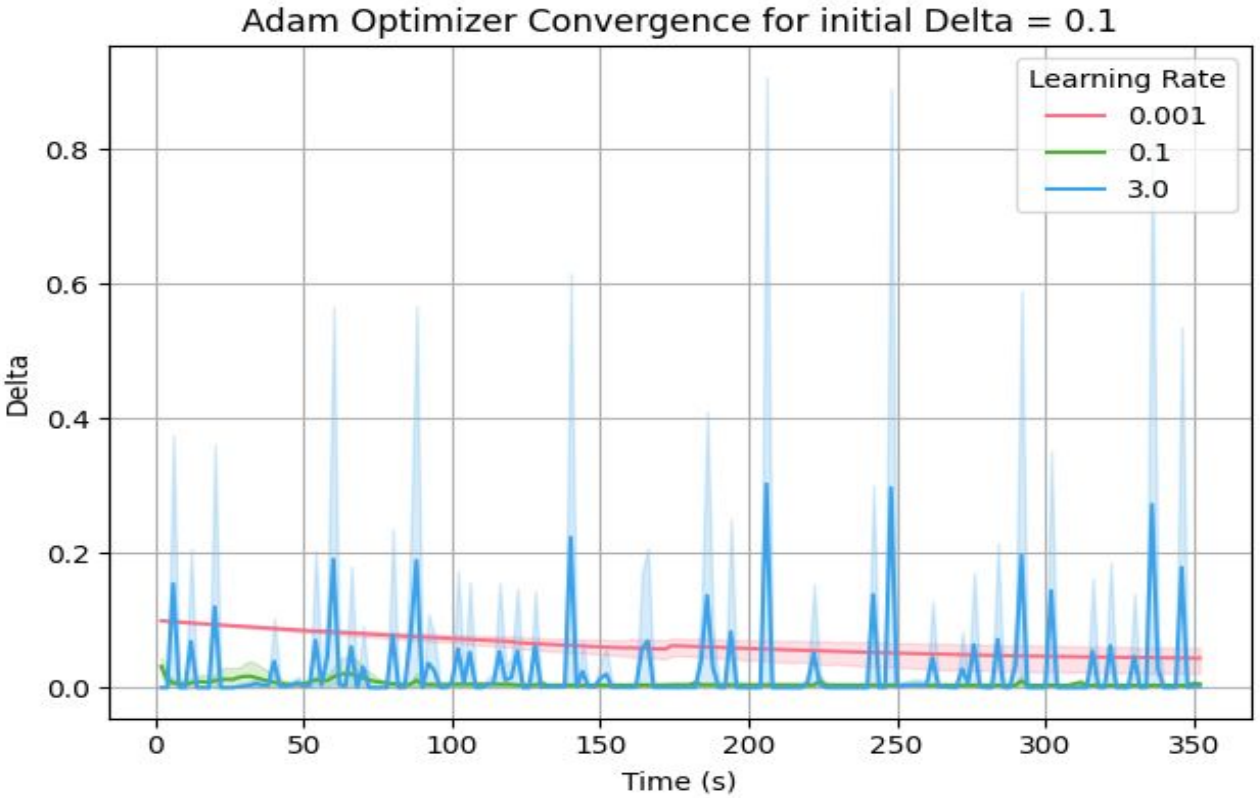

Model Order Stability
Model Order
Time (s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
50
100
150
200
250
300
350

Q2 -


Adam Optimizer Convergence for Delta Parameter
Learning Rate
Initial Delta
0.1
5.0
20.0
50.0
Learning Rate
0.001
0.1
3.0
Delta
Time (s)
0
10
20
30
40
50
0
50
100
150
200
250
300
350

?

Q2 -


Adam Optimizer Convergence for initial Delta = 0.1
Learning Rate
0.001
0.1
3.0
Delta
0.0
0.2
0.4
0.6
0.8
0
50
100
150
200
250
300
350
Time (s)

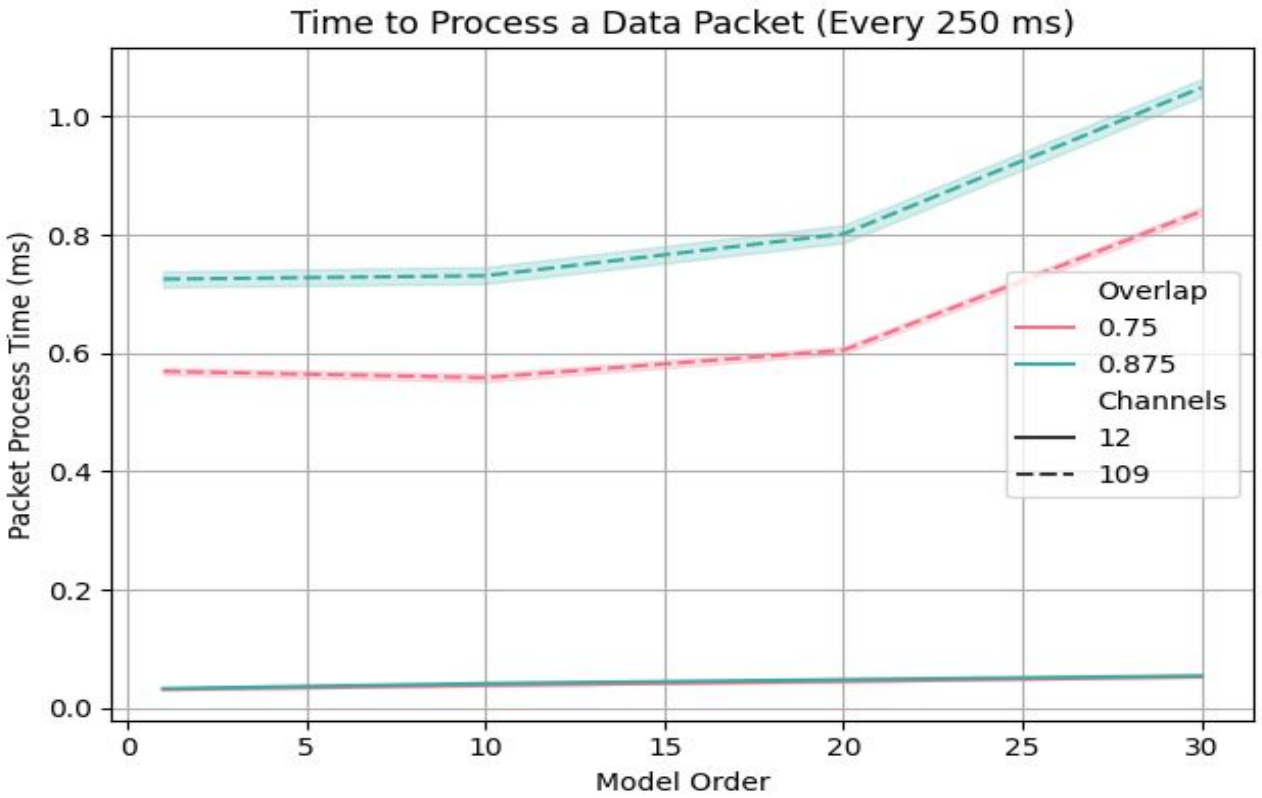
?

Q3 - How fast is it ?

Q3 - How fast is it ?

Channel Nbr.	Duration (second)	MVAR fitting (ms)	Building MVARICA (ms)	PDC (ms)	Data Packet (ms)	Recursive AIC (ms)	Adam (ms)	All Steps (ms)
12	1 (75% overlap)	10.6	30.5	0.7	41.9	25.5	19.1	86.7
12	2 (87.5% overlap)	10.6	32.8	0.7	44.2	25.5	19.1	88.8
109	1 (75% overlap)	92.6	523.4	27.0	643.0	124.8	166.7	934.5
109	2 (87.5% overlap)	99.5	699.4	27.5	826.5	129.5	166.5	1222.5

Q3 -


Time to Process a Data Packet (Every 250 ms)
Packet Process Time (ms)
Model Order
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
25
30
Overlap
0.75
0.875
Channels
12
109

Conclusion

- Proposed a real-time MVARICA model
- Model is accurate with offline system
- Model hyperparameters optimizable in real-time
- Model run in real-time for lower channel numbers (Maybe use PCA ?)

Thanks for Listening

Citations

- Jahanian Najafabadi, Amir, & Bagh, Khaled. (2023). Resting-state EEG Classification of Children and Adolescents Diagnosed with Major Depression Disorder Using Convolutional Neural Network (Preprint, IEEE).
- Jahanian Najafabadi, Amir; & Bagh, Khaled (2024). Resting-state Functional Connectivity for Major Depression Disorder Using Electroencephalography: A Deep Learning Approach
- Bagh, Khaled; Jahanian Najafabadi, Amir (2024a). Graph-Based Analysis of Brain Connectivity in Major Depressive Disorder Using EEG (Preprint, IEEE)
- Jahanian Najafabadi, Amir; Bagh, Khaled, Hommel, Bernhard. (Nature Scientic Report, Under Review). Resting-State EEG Classication of Children and Adolescents Diagnosed with Obsessive Compulsive Disorder Using Convolutional Neural Network and Graph Based Analysis.

Q&A