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Connectivity–informed solution for spatio–temporal M/EEG source reconstruction

Ivana **Kojčić**[1], Théodore **Papadopoulo**[1], Rachid **Deriche**[1] and Samuel **Deslauriers-Gauthier**[1]

Athena project–team, Inria, Université Côte d'Azur, Sophia Antipolis, France

Contact: ivana.kojcic@inria.fr

http://team.athena.inria.fr

Abstract: Recovering brain activity from M/EEG measurements is an ill–posed problem and prior constraints need to be introduced in order to obtain unique solution [1]. The majority of the methods use spatial and/or temporal constraints, without taking account of long–range connectivity. In this work, we propose a new connectivity–informed spatio–temporal approach to constrain the inverse problem using supplementary information coming from diffusion MRI. We present results based on simulated brain activity obtained with realistic subject anatomy from Human Connectome Project [4] dataset.

1. The forward problem

The relationship between source amplitudes and M/EEG measurements is expressed by the following linear model:

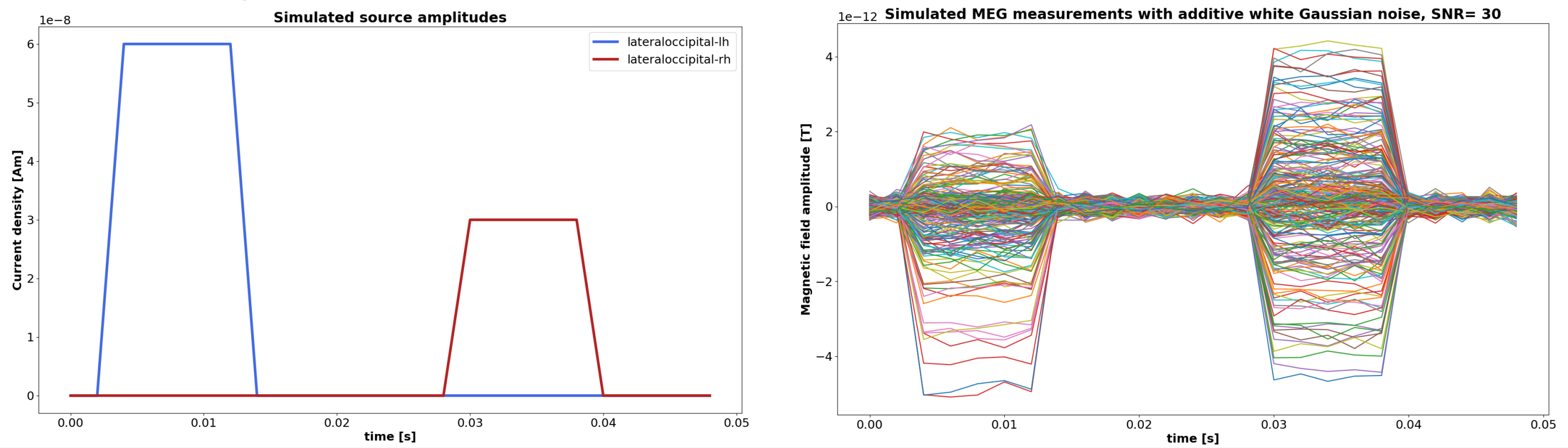
$$\boxed{M = GJ + \epsilon}$$ where

- $M \in \mathbb{R}^{N\times T}$ matrix of M/EEG signals measured at **N sensors** at **T time instants**
- $G \in \mathbb{R}^{N\times S}$ forward operator (leadfield matrix), where each column corresponds to forward field of one of **S sources**
- $J \in \mathbb{R}^{S\times T}$ unknown matrix of S source amplitudes (current distribution) along time
- ϵ additive white Gaussian noise

- The source space of size S is parcellated into **K cortical regions** according to Desikan–Killiany atlas [5], where K=68 (S>>K).
- **Brain** is modelled as a simple undirected **graph** with **K nodes**.

3. Simulation of cortical activity

- Simulations were preformed using MNE-Python software [3] based on realistic subject anatomy from HCP dataset.
- **1 cortical region = 1 source** of activity (assumed to be constant over that region).
- Cortical activations were simulated for 2 connected brain areas in the primary visual area (left & right lateral occipital region), with a corresponding Δ and decrease in amplitude.

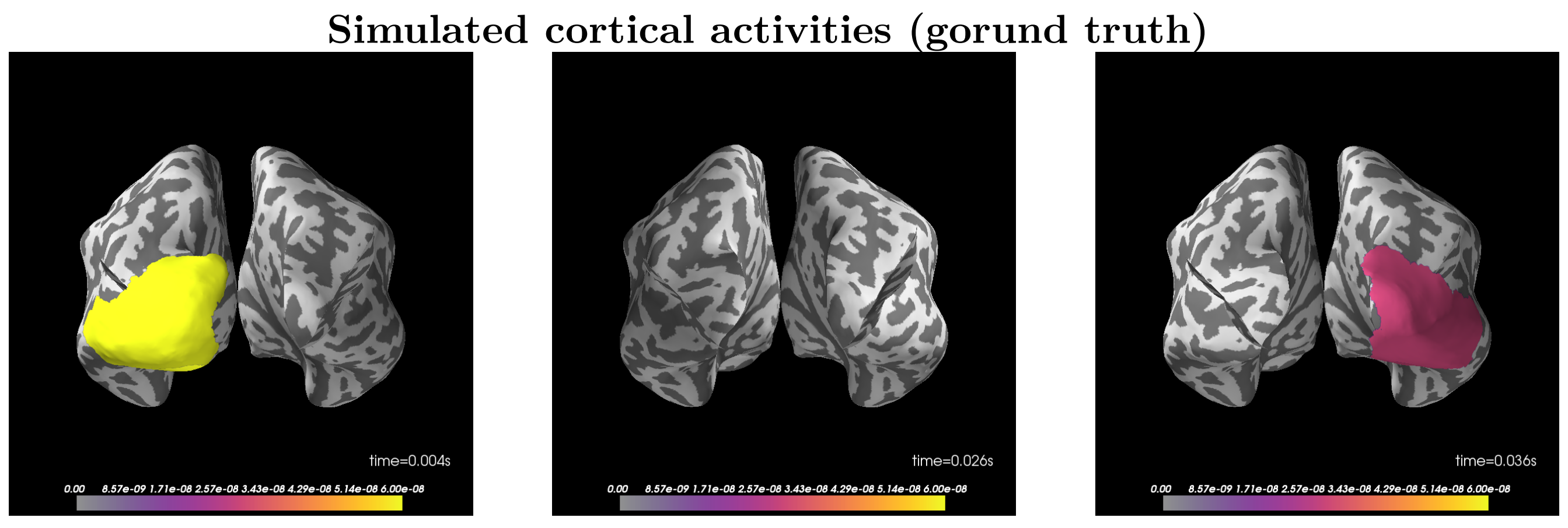


4. Results

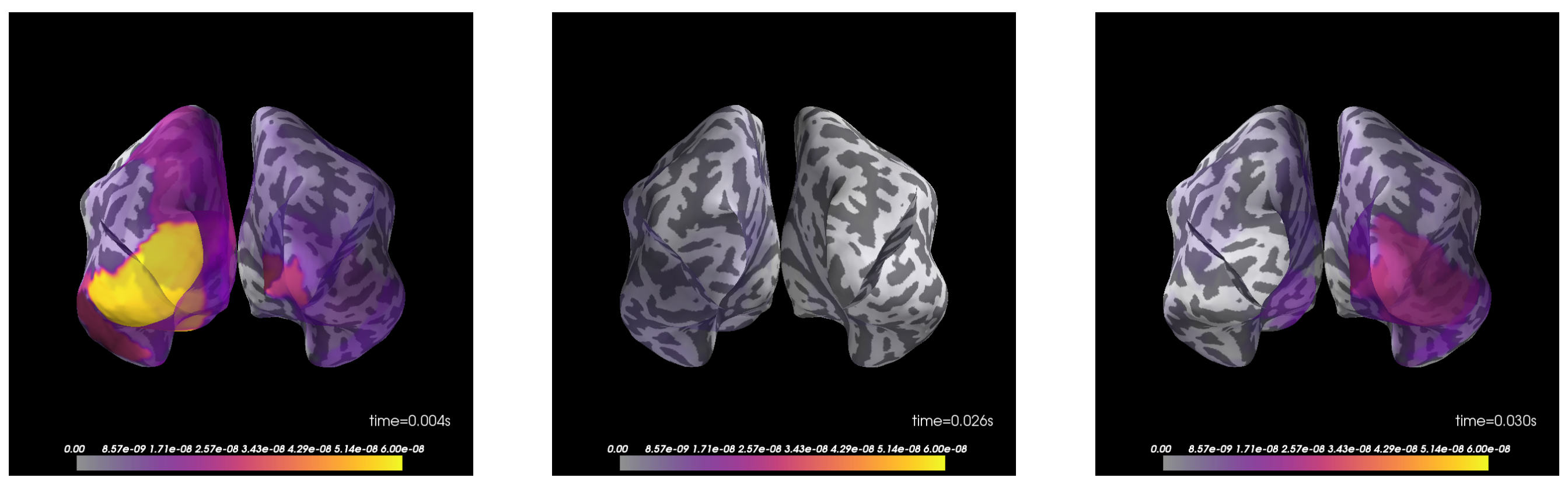
- Results of reconstruction of cortical activity from simulated MEG measurements are presented and compared to original LORETA method.

t = 0.004s t = 0.026s t = 0.036s

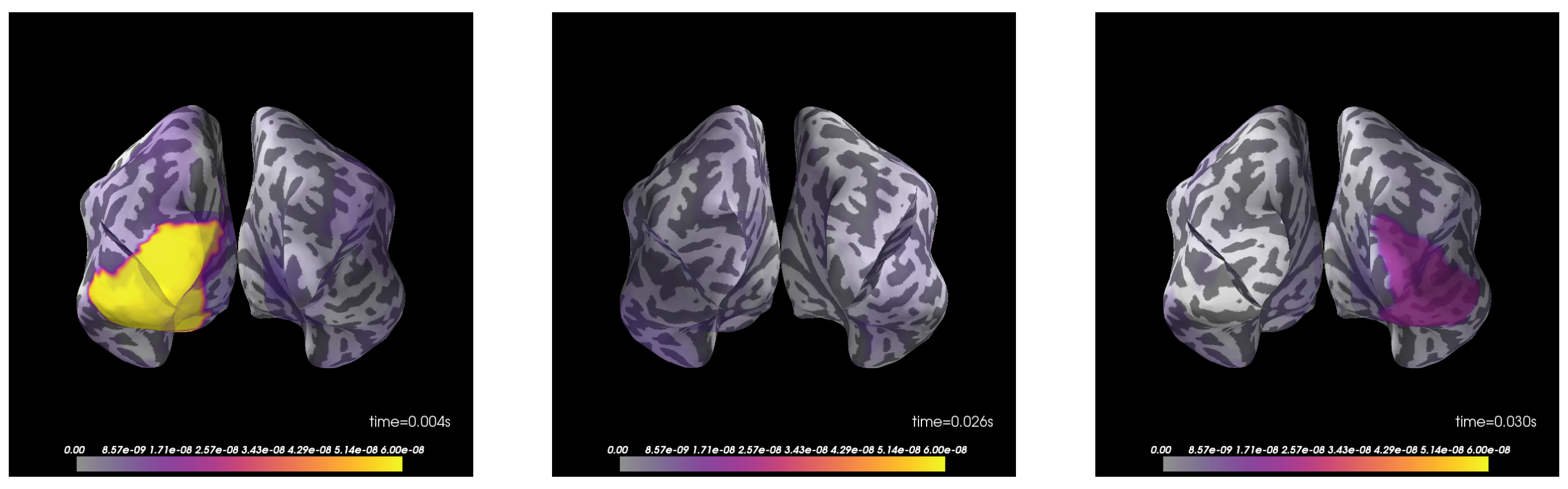
Simulated cortical activities (gorund truth)



Reconstructed sources – original LORETA



Reconstructed sources – connectivity-informed LORETA



2. The inverse problem

Consider the minimization problem: $\hat{J} = \underset{J}{\arg\min}\left\{\|M - GJ\|_2^2 + \lambda\|LJ\|_2^2\right\}$

LORETA

- Low resolution brain electromagnetic tomography (**LORETA**)[2] assumes simultaneous and synchronous activations of neighbouring brain areas.
- Maximally smooth solution – minimial norm of discrete Laplacian of the current distribution.

Our approach

- Include in the regularization supplementary information from diffusion MRI :
  - **anatomical** (long–range) **connections**
  - **transmission delays** Δ between cortical regions

- Recovered source amplitudes are obtained by:

$$\boxed{\hat{J}_L = (G^TG + \lambda L)^{-1}G^TM}$$

$$\boxed{\hat{J}_C = (\widetilde{G}^T\widetilde{G} + \lambda\widetilde{L})^{-1}\widetilde{G}^TM}$$

λ^* – optimal **regularization parameter** chosen for both methods using Generalized Cross–Validation.

- **L** is symmetric normalized **Laplacian matrix** computed on the cortical regions:

$$L^{symm} = I - D^{-1/2}AD^{-1/2}$$

- **D** – degree matrix
- **A** is a symmetric (K × K) **adjacency** (connectivity) **matrix** on the coritcal regions with elements:

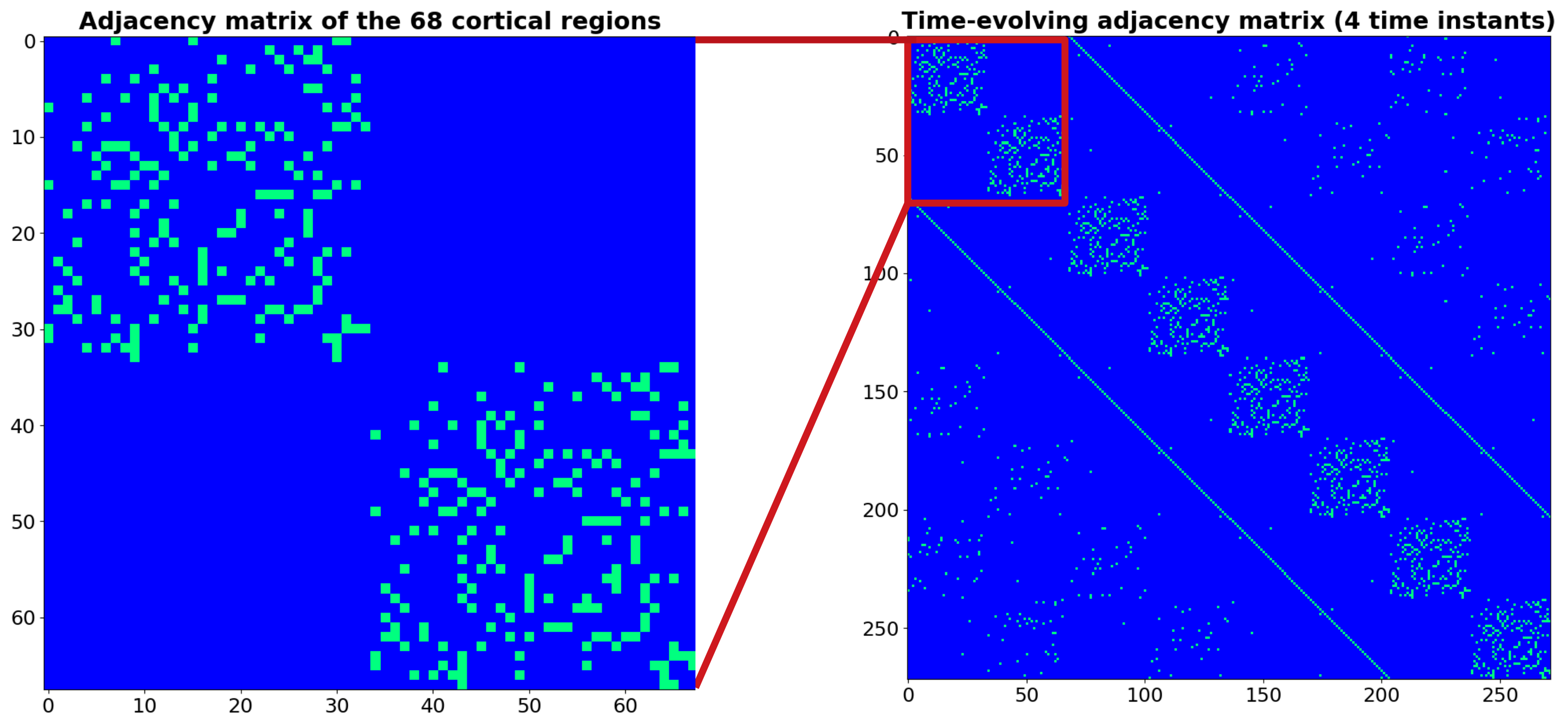
$$a_{ij} = \begin{cases} 1, & \text{if vertices } i \ \& \ j \text{ are connected by an edge} \\ 0, & \text{otherwise} \end{cases}$$

- edges between neighbouring nodes – **short-range** connections (between adjacent brain areas)

- $\widetilde{G}$ is a block–diagonal leadfield matrix of size (N × T) × (K × T)
- $\widetilde{L}$ is a **time–evolving** block–diagonal **Laplacian matrix**
- Spatio–temporal adjacency matrix $\widetilde{A}$ of size (K × T) × (K × T) evolves with time according to long-range connectivity
- Δ = (length of the streamline) / (speed of information signal along fiber tracts)
- edges between neighboring nodes – **short-range & long-range** connections

- Main block-diagonal matrices are the adjacency matrix on the cortex ($A = A_0 = A_{ii}$)

$$\widetilde{A} = \begin{bmatrix} A_0 & A_1 & \dots & A_{T-2} & A_{T-1} \\ A_1 & A_0 & \dots & \dots & A_{T-2} \\ \vdots & \dots & \dots & \dots & \vdots \\ A_{T-2} & \dots & \dots & A_0 & A_1 \\ A_{T-1} & A_{T-2} & \dots & A_1 & A_0 \end{bmatrix}$$



5. Conclusion

- The preliminary results obtained using our spatio–temporal approach were closer to the ground truth in terms of amplitude and focality.
- We tackled the ill–posed problem in both space and time and obtained promising results. However, further simulations need to be performed with multiple subject in order to validate the preliminary results.

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