Analysis and Control of Collective Dynamics in Brain Networks of Oscillators

Tommaso Menara*
Giacomo Baggio∇
Danielle S. Bassett†
Fabio Pasqualetti*

∗ Mechanical Engineering
UC Riverside

† Bioengineering
UPenn

∇ Information Engineering
UNIPD

Synchronization in the Brain

Synchronization phenomena are ubiquitous in neural systems

in health...

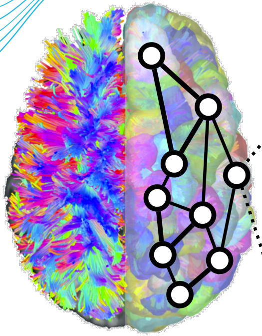
- information processing
- memory storage/retrieval
- motor coordination
- circadian rhythms

...and disease

- dementias (Parkinson's)
- cognitive decline
- epilepsy and seizures
- neurological damage

Characterization and control of synchronization are of paramount importance... **how to do it?**

Brain Networks of Oscillators



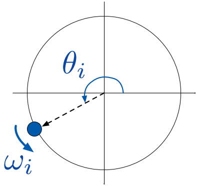
connectivity parcellation

brain network

- ▷ nodes ← brain regions
- ▷ edges ← axonal bundles

Kuramoto Oscillator

$$\dot{\theta}_i(t) = \omega_i + \sum_{j \neq i} a_{ij} \sin(\theta_j(t) - \theta_i(t))$$



▷ θ_i: phase ▷ ω_i: natural frequency

▷ a_{ij}: coupling strength

[Cabral *et al.*, NeuroImage 2011]

each Kuramoto oscillator in the brain network represents a neural population (brain region)

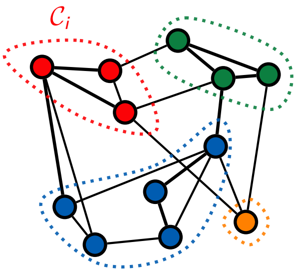
↓

phase trajectories represent neural activity

↓

synchronization analysis of coupled oscillators!

Cluster Synchronization



for a network partition $\mathcal{P} = \{\mathcal{C}_1, \ldots, \mathcal{C}_m\}$:
phases of the oscillators belonging to
the same cluster $\mathcal{C}_i$ evolve synchronized

Cluster Synchronization Manifold

$$\mathcal{S}_{\mathcal{P}} = \{\theta \mid \theta_i = \theta_j \text{ for all } i, j \in \mathcal{C}_k, k = 1, \ldots, m\}$$

$$\dot{\theta}_i = \omega_i + \sum_{j \neq i} a_{ij} \sin(\theta_j - \theta_i)$$

invariance of $\mathcal{S}_{\mathrm{P}}$ iff:

(a) $\omega_i = \omega_j$ in the same cluster

(b) balanced inter-cluster couplings:

$$\sum_{k \in \mathcal{C}_\ell} a_{ik} - a_{jk} = 0 \text{ for every } i, j \in \mathcal{C}_z$$

and $z, \ell \in \{1, \ldots, m\}$, with $z \neq \ell$

stability of $\mathcal{S}_{\mathrm{P}}$ if:
intra-cluster couplings $\gg$ inter-cluster couplings

stability of $\mathcal{S}_{\mathrm{P}}$ if:
heterogeneous natural frequencies across clusters

[Menara *et al.*, IEEE TCNS 2020]

Control of Cluster Synchronization

damage or neurological disorders cause *abnormal* cluster synchronization

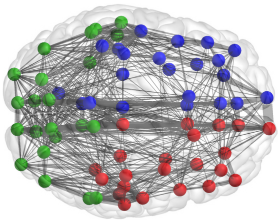
↓

design of sparse optimal corrections to structure (a_{ij}) and frequencies (ω_i)

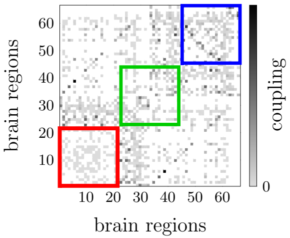
↓

desirable cluster synchronization

[Menara *et al.*, IEEE CDC 2019]



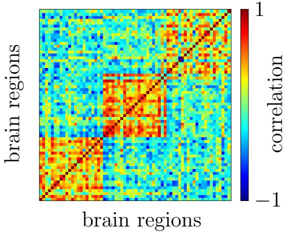
$A = [a_{ij}]$



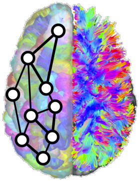
$A + \Delta,\ \omega + \mu$

minimally invasive structural and frequency corrections

desired cluster synch. (correlation of oscillatory neural activity time series)



Conclusion and References



In this work:

- **Synchronization** phenomena are ubiquitous in the brain
- **Characterization** of cluster synchronization in brain networks of oscillators
- **Control** of cluster synchronization with localized minimally invasive interventions

References:

[J. Cabral *et al.*, NeuroImage 2011], [T. Menara *et al.*, ACC 2019], [T. Menara *et al.*, IEEE CDC 2019], [T. Menara *et al.*, IEEE TCNS 2020]

www.tommasomenara.com | tomenara@engr.ucr.edu