Effects of the topology and delayed connections in the synchronization properties of a neuronal network

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Motivation:

Synchronous rhythms are fundamental mechanisms for temporal coordination of neural activity.

These temporal correlations are associated with cognitive and behavioral functions (Wang 2010).

Abnormal and abrupt synchronized activity of neurons might play a key role in brain diseases as schizophrenia or epilepsy (Uhlhaas 2010).

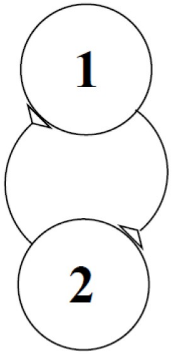
delayed connections?
Many sources of delay in the brain: finite propagation speed, chemical reactions, latency times in neural connections, etc.

different topologies?
It is a fundamental ingredient in defining the collective properties of the system dynamics.

Thesis overview:

2 Neurons motif
- Temporal dynamics of the synapse
- Types of synapses

(Chapter 2)



Neuronal Networks
- Topology
- Axonal Delay

(Chapter 3)

Conclusions

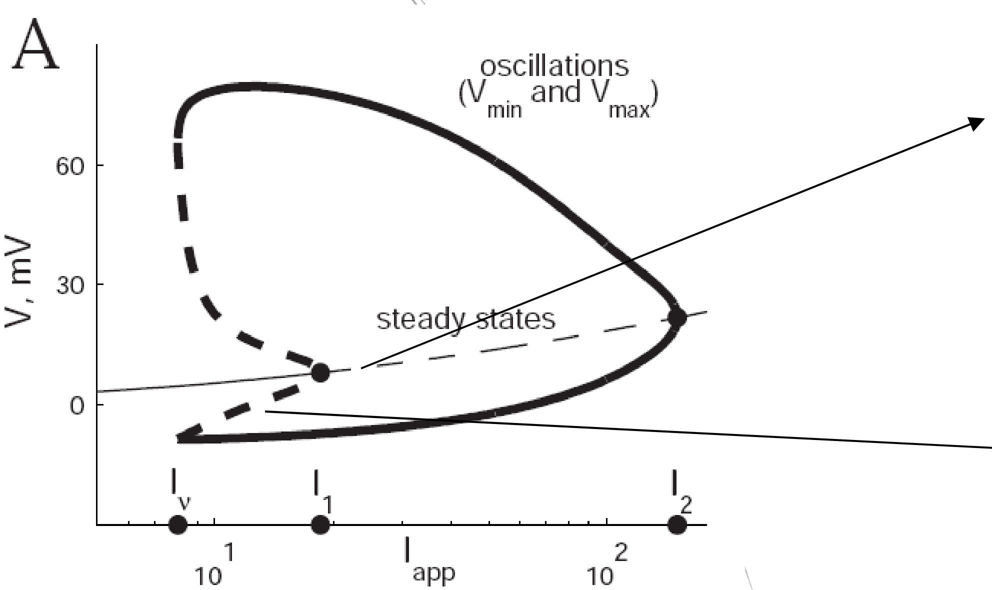
(Chapter 4)

The HH neuron model

$$C_m \dot{V} = I - g_{Na} m^3 h (V - V_{Na}) - g_K n^4 (V - V_K) - g_L (V - V_L)$$

Biophysical model of a neuron (meaningful parameters)

4 dimensional system: *V* (membrane potential)
m ,*h* and *n* (ion gates variables)



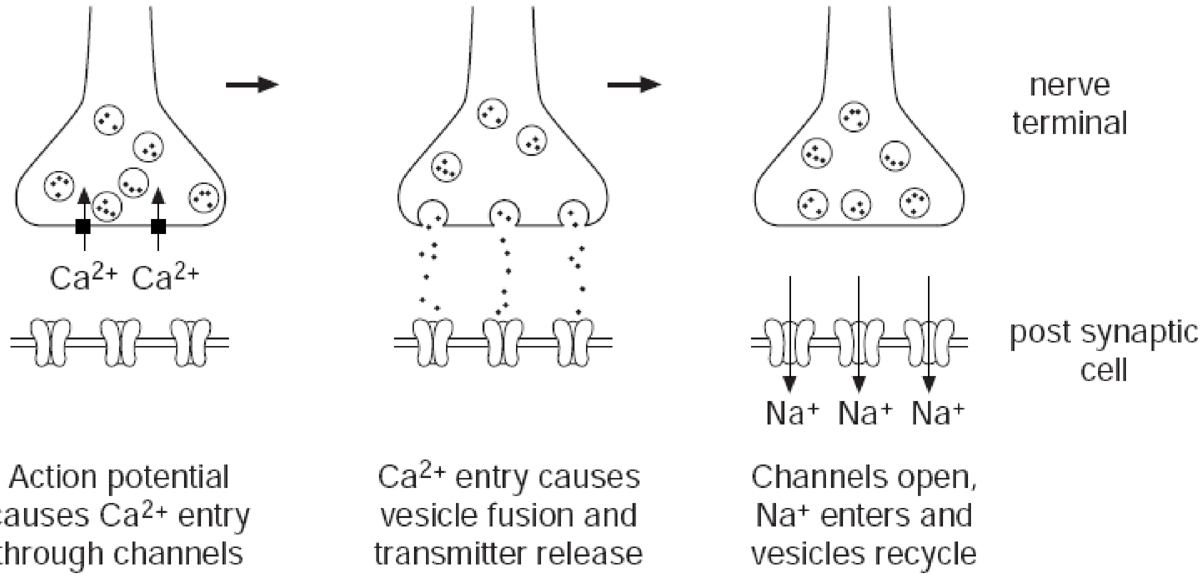
Resting to spiking:
Hopf bifurcation

Bistability:
stable limit cycle-fixed point

Bifurcation diagram of the HH, *V* vs applied I (Rinzel 1980)

Intercellular Communications

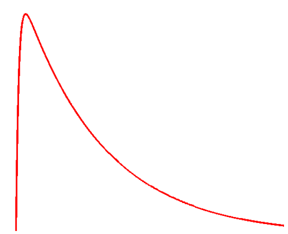
Chemical Synapses



Temporal dynamics

Type of synapses: excitatory-inhibitory

$$I_{syn} = g_{syn}(t)(V(t) - E_{syn})$$



Synchronization Indexes

Oscillators' phases

$$\phi = 2\pi \frac{t - \tau_k}{\tau_{k+1} - \tau_k}, \tau_k \leq t \leq \tau_{k+1}$$

Local Indicator

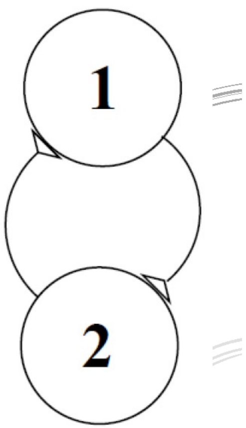
$$s_i(t) = \frac{1}{n_i} \sum_{j \in \nu(i)} \sin^2 \left(\frac{\phi_i(t) - \phi_j(t)}{2} \right)$$

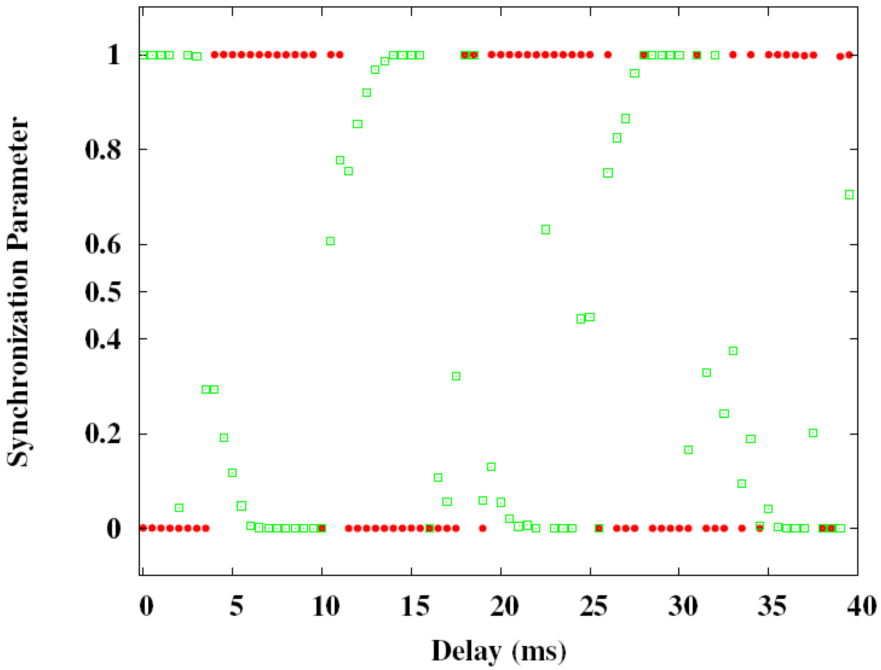
$$S^{loc} = \lim_{T \to \infty} \frac{1}{T} \int_0^T \left(\frac{1}{N} \sum_{i=1}^{N} s_i(t) \right) dt$$

Global Indicator

$$S^{glob} = \lim_{T \to \infty} \frac{1}{T} \int_0^T \left(\frac{1}{N} \sum_{i=1}^{N} s'_i(t) \right) dt$$

2 HH reciprocally connected





excitatory

inhibitory

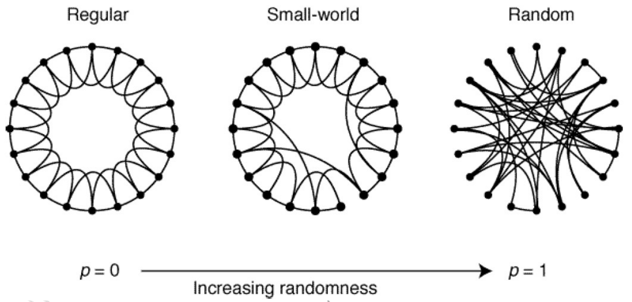
Natural period:
14.65 ms

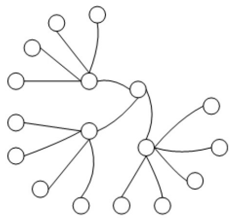
S=0
in-phase
S=1
anti-phase

Figure 1: Synchronization index of two fast coupled HH neurons as a function of the delay in the connections, for fast excitatory (red dots) and fast inhibitory (green dots) synapses. In this case the rise time is 0.1 ms and the decay time is 3 ms. A resonant effect is observed, switching between the in-phase to anti-phase solutions.

Our networks:

- 10^3 HH neurons.
- Reciprocal delayed chemical connections (4 in average) .
- Network topologies: Regular, Small World, Random, Scale Free and all to all.





- Delay: Homogeneous

  Heterogeneous (gamma distribution)
  - Fixed variance
  - Variance proportional to the mean delay

- Heterogeneous currents (distribution of natural frequencies)

- Homogeneous delays:

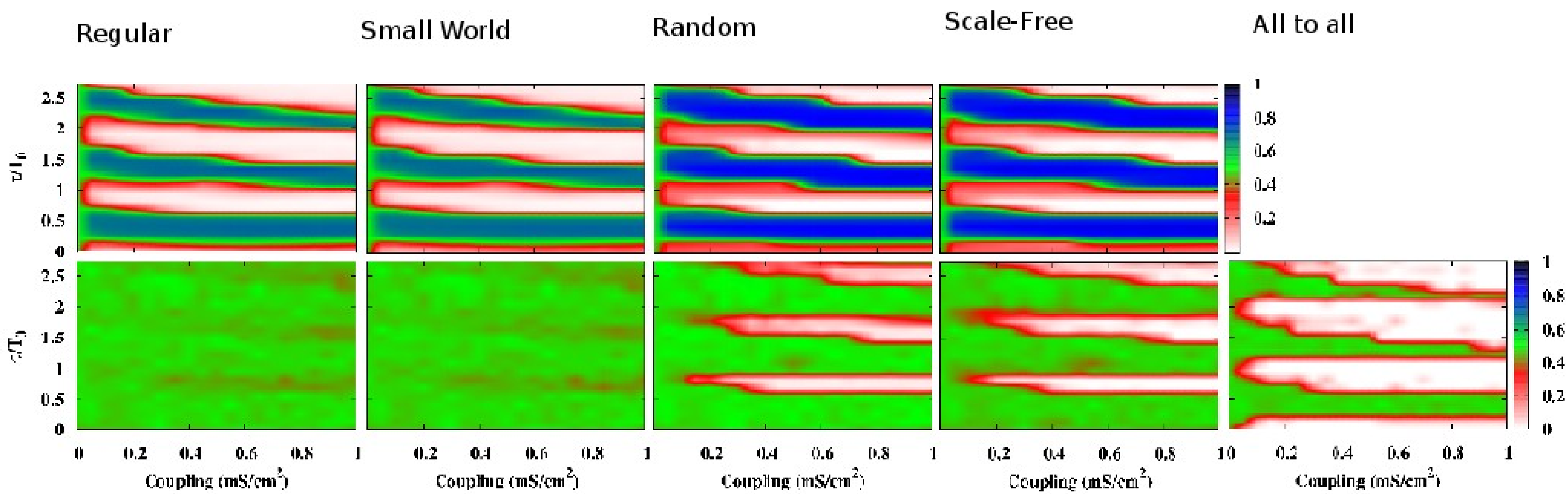


Figure 2: Local and global synchronization indexes for the different network topologies as a function of both the coupling strength and the delay in the connections. An index value of zero represents an in-phase state, whereas a value of one represent an anti-phase state.

- Heterogeneous delays:

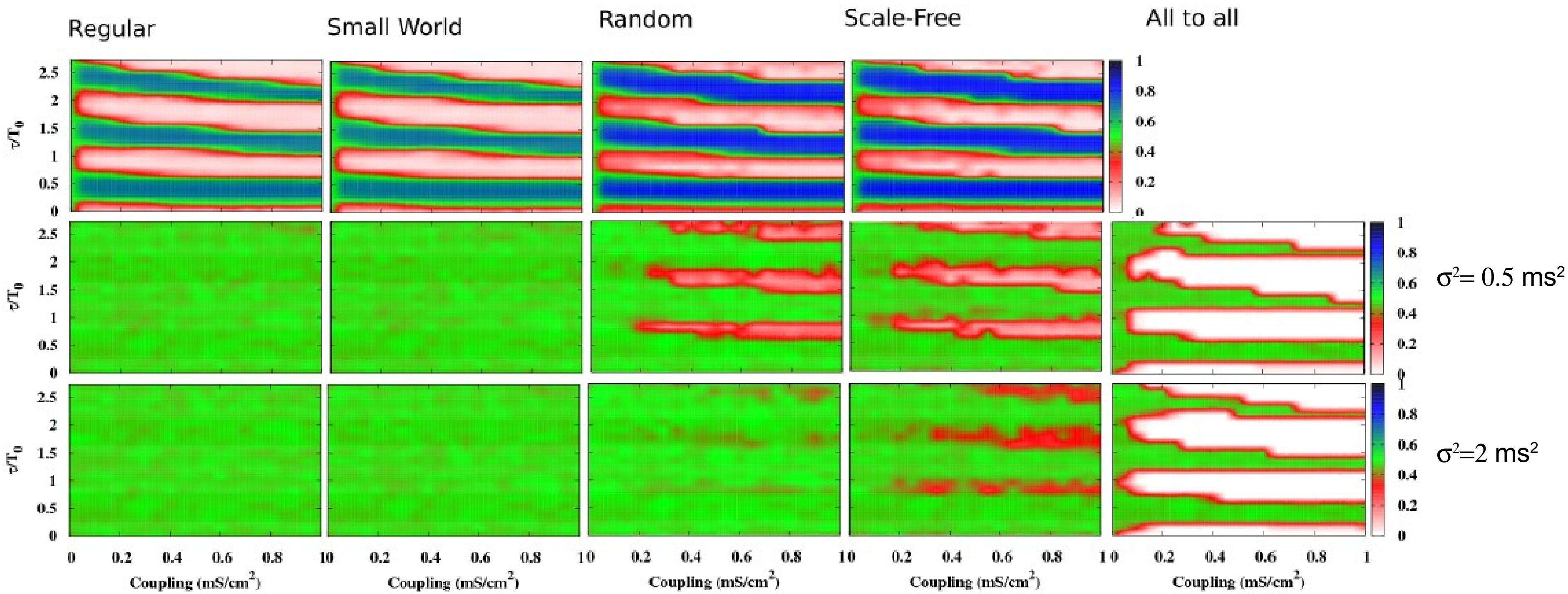


Figure 3: Local and global synchronization indexes for different network topologies as a function of both the coupling strength and the mean delay in the connections. Delays were generated according to a gamma distribution. The mean value is varied between 0.2 to 40 ms, and the variance is kept constant at 0.5 ms^2 in the middle panel and 2 ms^2 in the bottom one.

- Heterogeneous currents:
  - Gaussian distribution: I= 9 μA/cm^2 , σ=2.5 μA/cm^2

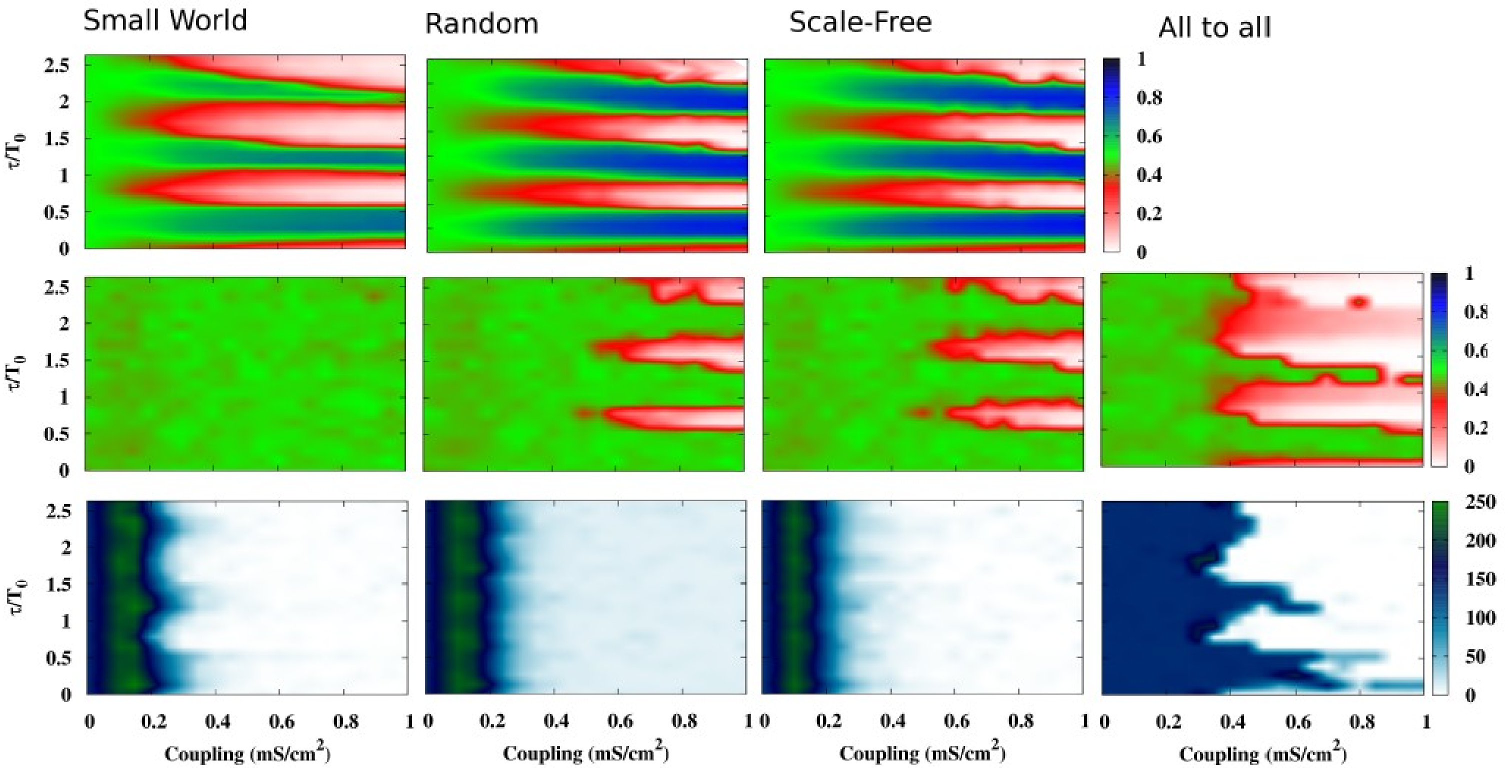


Figure 4: Contour plots of local and global synchronization indexes (top-middle panels) in the coupling-delay phase space for a heterogeneous ensemble of neurons, and for different topologies. Density plots of the number of non-spiking neurons (bottom panel).

Homogeneous delay (excitatory synapses) :

i) at a local scale, that interacting neurons display in-, out- and anti-phase firing,

ii) at a global scale, random connections are required for a coordinated firing,

iii) axonal latencies give rise to a resonant effect with the internal period of the oscillatory neurons.

Heterogeneous delays:

i) global synchronization in a random network is lost when $\sigma^2 \sim 2\ ms^2$.

ii) scale free topology is more robust and maintain globally synchronized regions even for larger variances.

Heterogeneous currents:

I) the effect of the distribution of natural frequencies requires an increase of the coupling strength needed to achieve a global synchronous state.

ii) global synchronized regions are reduced for almost all networks

iii) annihilation of repetitive firing is observed in some neurons in the networks

It is possible to extrapolate this results to neuron models with type II excitability or type II PRC?

Thank you!