Distributed large scale simulation of synchronous slow-wave / asynchronous awake-like cortical activity

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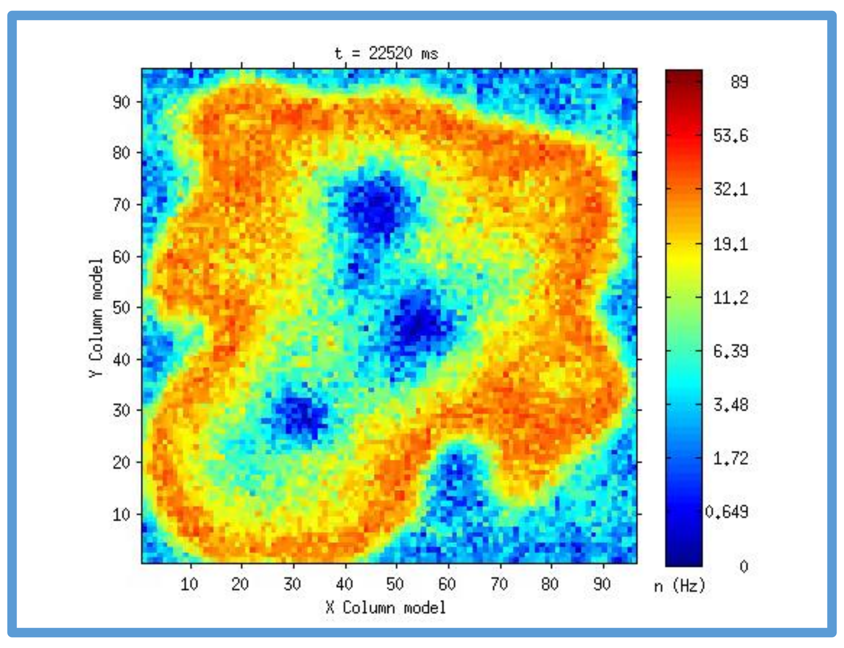
WaveScalES models in NEST

Single-area non-laminar model for Slow Waves and Asynchronous State simulations

Spiking networks of point-like neurons organized in 2-dimensional spatial grids of local modules (grid step dx = 400 µm), including 1250 neurons per module, interconnected with a probability kernel depending on the distance. In this case, $p_{conn} \sim \exp(-r/\lambda)$, λ = 240 µm.

GRID	NEURONS	SYNAPSES
48x48	2.9 M	4.4 G
24x24	0.7 M	1.1 G



NEST implementation:

- Grid of cortical modules described with NEST topology
- Neuron model is a variant of LIF neuron with spike frequency adaptation modeled with NESTML
- Layered structure for the description of excitatory and inhibitory sub-populations
- Connectivity implemented with exponential distribution kernel with masks for excitatory and inhibitory neurons
- Synaptic weights following a normal distribution
- Synaptic delays described with exponential distribution not depending from the distance (custom). To be improved.
- External spikes generated as a Poissonian train of synaptic inputs
  - 400 Poissonian generators for each neuron are required by the WaveScalES model

Neuron model

Leaky Integrate-and-Fire neuron with Spike-Frequency Adaptation modelled as an activity dependent after-hyperpolarization current described by the fatigue variable w.

$$\begin{cases} \tau_v \frac{dV}{dt} = -(V - El) - gww + I \\ \tau_c \frac{dw}{dt} = -w \end{cases}$$

$$if\ V > Vpeak \rightarrow \begin{cases} V = Vreset \\ w = w + \alpha \end{cases}$$

- V: membrane potential
- w: adaption variable due to Ca^+ currents
- I: incoming currents
- V_{peak}: is the voltage threshold
- V_{reset}: reset membrane potential
- E_l: resting potential
- τ_v: decay time constant of v
- τ_c: decay time constant of c
- α: post-spike Ca^+ concentration increment

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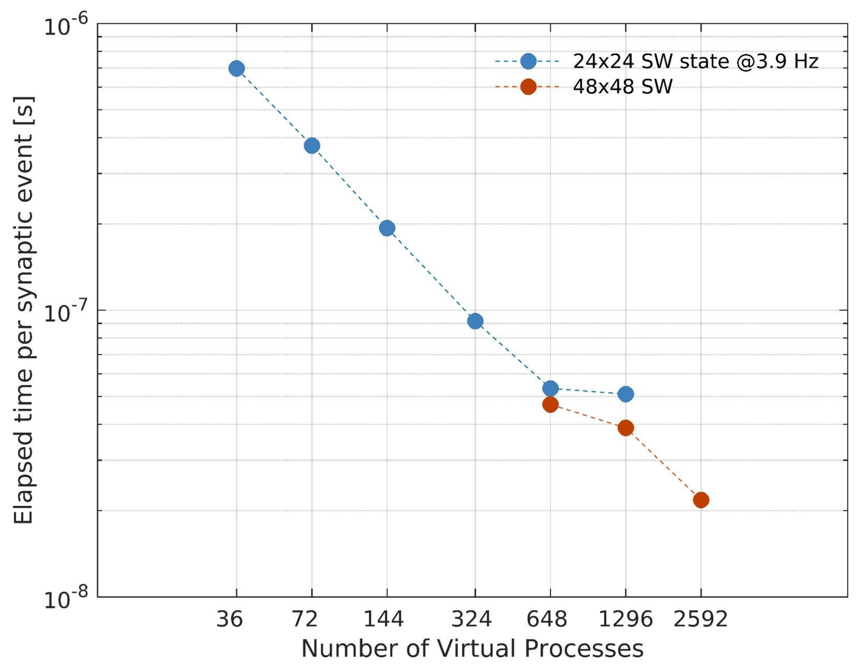
Scaling

Slow Waves simulations of the WaveScalES model have been run on the NEST simulator (v 2.12.0), for two problem sizes (24x24 and 48x48 grids of cortical columns), spanned on a set of virtual processes ranging from 36 to 2592 (one VP per core) on the Marconi A1 cluster at CINECA.

NEST version 2.12.0



Simulation cost per synaptic event

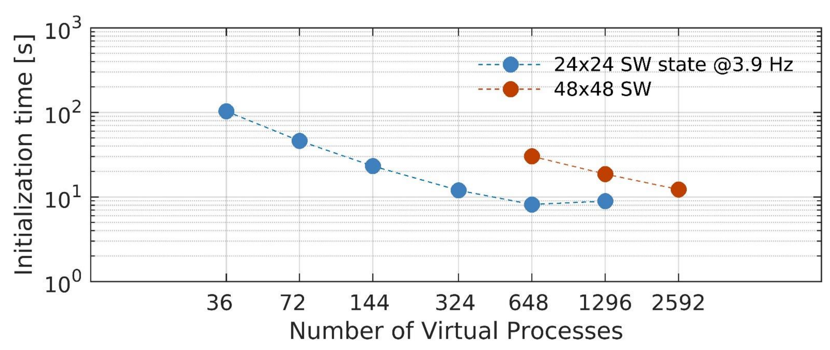
Elapsed time per simulated second normalized to the number of synapses and firing rate:

$$\frac{elapsed\ time}{num\ of\ syn * firing\ rate}$$

Execution platform

Marconi A1 (Broadwell) cluster at CINECA, 1.512 nodes, each one being a 36-core unit made of two Intel Xeon Haswell E5-2697 v4 18-core processors clocked at 2.30GHz

The Marconi platform is provided by CINECA in the frameworks of HBP SGA1 collaboration. We acknowledge G. Fiameni and R. Zanella for the support received.

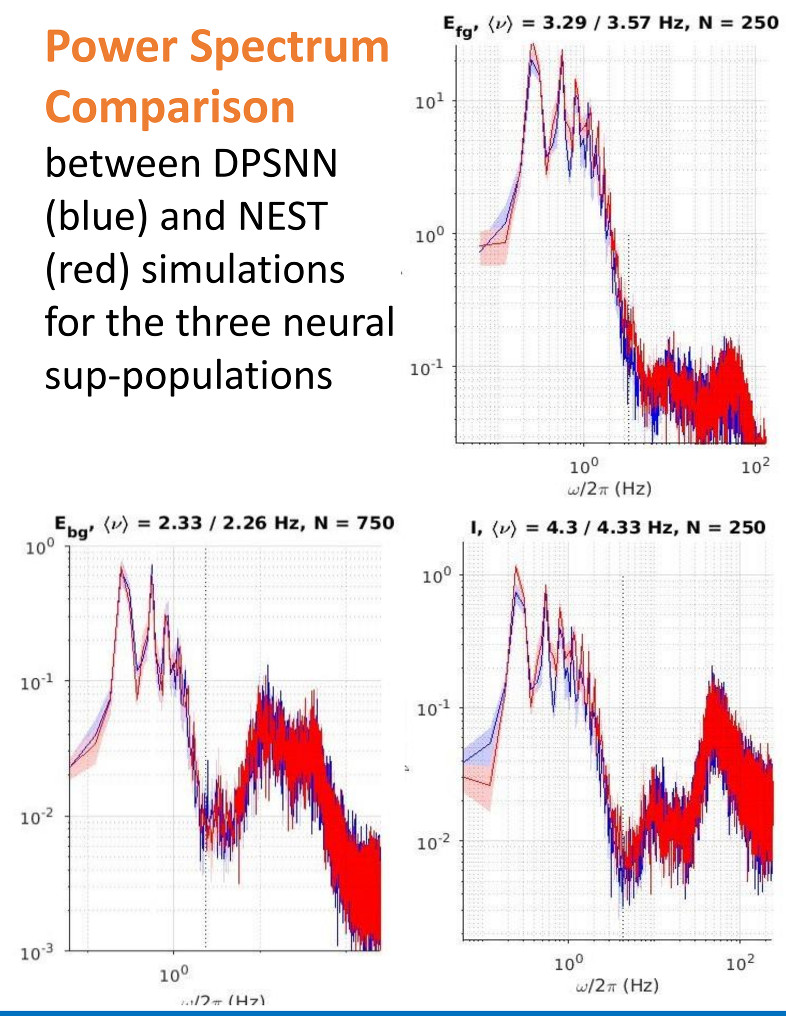


Initialization time

The initialization time, in seconds, is the time required to complete the building of the whole neural network. The plot reports the initialization time scaling with the number of virtual processes, for two different network sizes, 24 by 24 and 48 by 48 grids, presenting an exponential connectivity with an average of 1120 synapsis per neuron.

Power Spectrum Comparison

between DPSNN (blue) and NEST (red) simulations for the three neural sup-populations



Memory usage

The cost of the WaveScalES NEST model is between 67 and 80 byte per equivalent synapse, where the total number of equivalent synapses is calculated considering both the recurrent synapses of the system and the external synapses, simulated using 400 Poissonian trains per neuron.

Model validation on NEST

The model has been validated against DPSNN simulation engine. Power spectrum comparisons reports a good alignment between DPSNN (blue) and NEST (red) simulations for all the sub-populations of a network expressing Slow Waves.

DPSNN and NEST cooperation framework

DPSNN

Distributed **P**lastic **S**piking **N**eural **N**etwork simulation engine for large-scale spiking simulations distributed over thousands of MPI processes, including columnar, areal and inter-areal connectivity models.

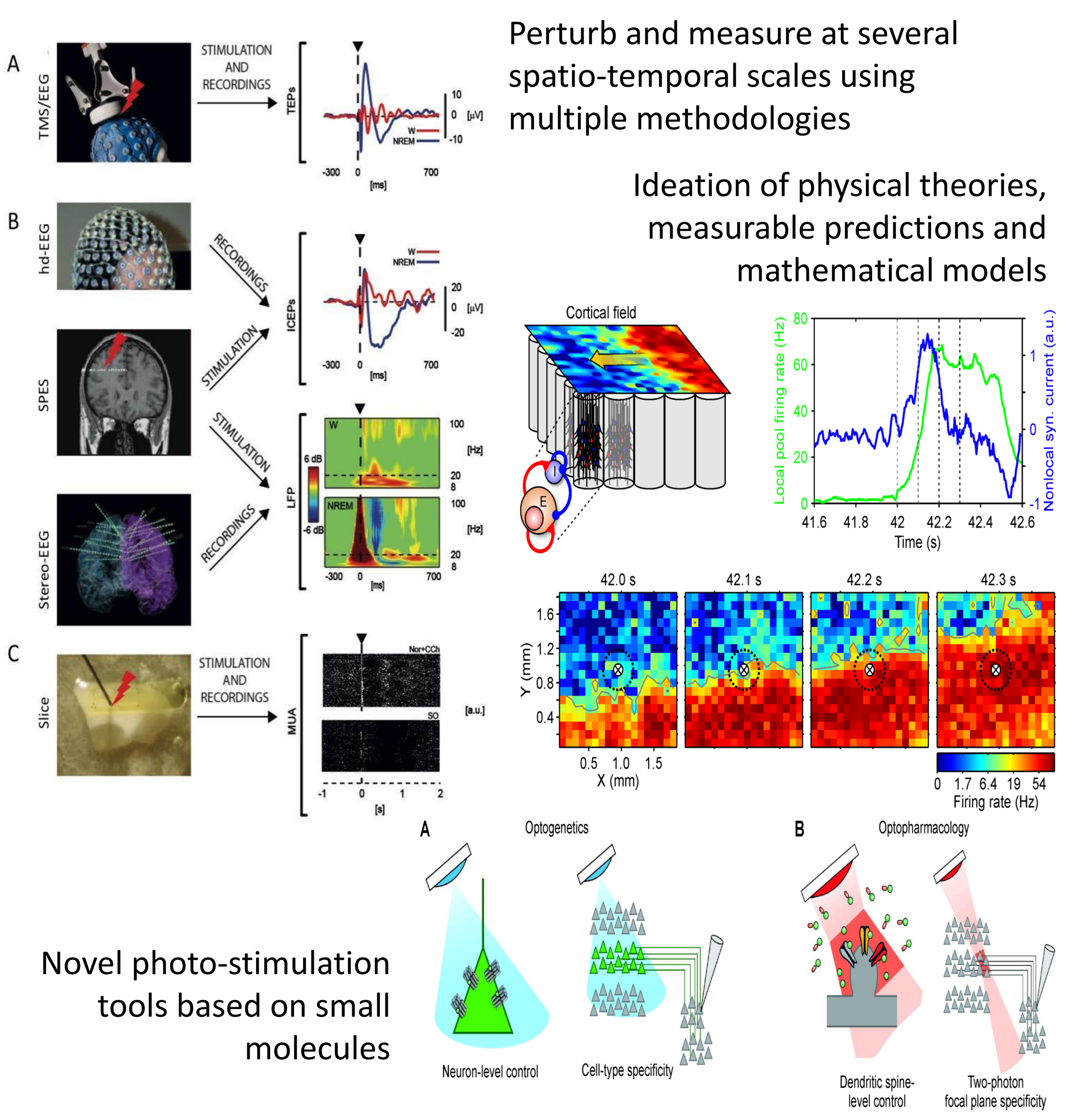
Porting to NEST

All WaveScalES simulation models are ported from DPSNN to NEST, to be offered to the research community in the framework of HBP platforms.

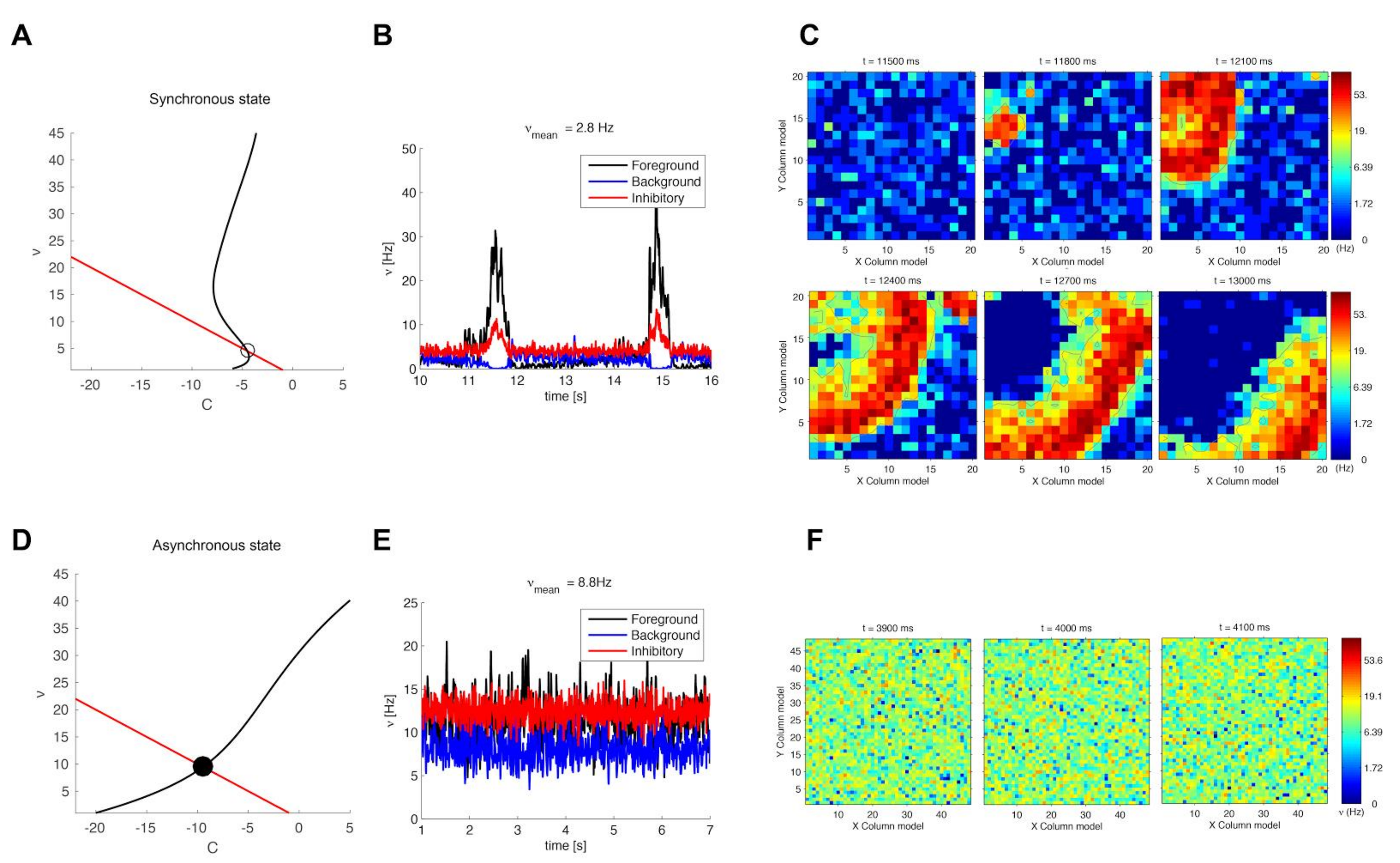
Use-case: the WaveScalES experiment in HBP

The WaveScalES experiment

Measurement, perturbation, theoretical modelling and simulation of cortical Slow Waves in deep-sleep / anaesthesia and during transition to consciousness. Modelling of memory consolidation during deep-sleep.



Simulation aims: 1) Reproduction of Slow Waves Activity (SWA) and Asynchronous Awake (AW) states. 2) Match with experimental data acquired by the WaveScalES team



Dynamical representation of SW and AW states. Panels A and D: nullcline representation in the phase space for, respectively, the unstable fixed point that induces oscillatory dynamics (A) and the stable fixed point at high level of activity representing the asynchronous awake state (D). Panels B and E: firing rate time course of a sample module made up of foreground, background and inhibitory sub-populations (respectively in black, blue and red) for sleep state (B) and asynchronous state (E). Panels C and F: time consecutive sketches of the activity distribution in space, showing wavefront propagation of a wave in sleep state (C) and showing the activity during an awake state (F).

Mean field theory, describing the dynamical activity of single modules, is used to set the asynchronous or bistable working regime of the network

$$\begin{cases} \frac{d\nu_i}{dt} = \frac{\phi_i(\vec{\nu}, \vec{c}) - \nu_i}{\tau} \\ \frac{dc_i}{dt} = -\frac{c_i}{\tau_c} + g_i \nu_i \end{cases}$$

WaveScalES teams and key-persons

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