DPSNN-STDP for WaveScalES

Large scale simulations of the cortical activity investigating slow waves, plasticity, sleep and memory consolidation

Elena Pastorelli

The APE parallel/distributed computing lab - INFN Roma

Brain Research:
Scientific and Translational

Novel experimental techniques permit a quantitative exploration of the Brain Architecture

Understanding the brain, at **different levels of abstraction**. Since ever, one of the greatest intellectual ambitions. A quantitative approach is emerging.

Europe, brain disorders and trauma cost: 798 billion € /year

Increasing, due to the progressive population aging

Possible therapies from better understanding

Computational Neuroscience: an Emerging Quantitative Discipline

Novel Brain **Experimental** Techniques, multi-modal High Spatial and Temporal Definition

Simulations on Massive Parallel Computers, Robots, Neuromorphic platforms

Computational Neuroscience

Theoretical Models: Long-Range and Short Range Connectome (architecture of connections), Dynamic laws for Neuron Membrane Potential and Currents and Synaptic Plasticity (learning), Consciousness Theories

The Human Brain Project - Intro

- Planned European fund. 500M Euro, Oct 2013 – 2023
  - Original Consortium: 112 research institutes
  - Ramp up phase: Oct 2013 – March 2016

- Spring 2015 (also in response to criticism during first-years ramp-up phase):
  - Competitive call for new scientific proposals/partners (evaluation by external reviewers)
    - INFN leads the WaveScalES proposal, 4 proposals selected among 57 submitted
  - HBP Commitment: before 2018 define transformation into legal entity
    - National Stakeholders board – will be proportional to national investments
    - National /Regional Partnering Projects
    - Scientific Board (presently, 13 + 10 members)
  - Periodic (bi-annual) plan revision, new competitive calls, additional partners

- First HBP operational phase, April 2016-March 2018
  - WaveScalES starts April 2016
  - 1 MEuro/year, if good results, until 2023

Slow Waves and Perturbations

- During deep-sleep and anaesthesia the cortex moves in a low-complexity mode:
  - Collective oscillations, ~ @ 0.1 – 4 Hz, between two states:
    - Down state: neurons nearly silent (firing @ few Hz)
    - Up state: neurons active (firing @ tens of Hz) for a few hundreds ms, then inhibition switch the system to the down-state
  - Local oscillation phase -> slow-waves moving on the cortical surface (planar, spirals, …)
- Perturbative approach:
  - Localized spatio-temporal impulse
  - Measure the impulse response
  - Quantification of consciousness potential and damages in disease/trauma, forecast of emergence from coma

WaveScalES in HBP - Summary

- Experimental WaveScalES partners (will) measure brain Slow Waves during deep-sleep and anaesthesia, and during the transition to consciousness, including:
  - non invasive techniques on human: high-def. electro-encephalographic response to trans-cranial magnetic stimulations
  - electro-physiological response to in-vitro/in-vivo opto-pharmacologic stimulation of murine models
- INFN in WaveScalES – mainly in collab. with ISS Roma
  - large scale parallel/distributed simulation of Slow Waves and perturbation responses

WaveScalES
partners / topics / key persons

1. INFN, Istituto Nazionale di Fisica Nucleare, APE **Parallel/Distributed Computing** Lab, Roma, Italy
2. Consorci Institut d´Investigacions Biomèdiques August Pi i Sunyer, Barcelona, Spain – **Murine electro-physiology**
3. Università degli Studi di Milano, Italy – **Measures in humans**
4. Fundació Institut de Bioenginyeria de Catalunya, Spain – **Optopharmacological Perturbations**
5. Istituto Superiore di Sanità, Italy – **Theoretical Models**

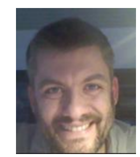
Pier Stanislao Paolucci

Piero Vicini


Maria Victoria Sanchez-Vives

Julia Weinert


Marcello Massimini

Mario Rosanova


Pau Gorostiza

Miquel Bosch


Maurizio Mattia

Paolo Del Giudice


INFN slow-wave simulation platform

Distributed simulation of SWA and its changes on large scale models of single and multiple areas composing a cortico-thalamic system.

Main investigations:

- ❑ Usage of a layered grid of columns for each area
- ❑ Inter-areal connection models
- ❑ Distribution of a spiking neural network over several thousands of MPI processes

Starting point:

DPSNN-STDP → Distributed Polychronous Spiking Neural Net with synaptic Spiking-Time Dependent Plasticity

Development of Distributed Plastic Spiking Neural Net Simulator in INFN

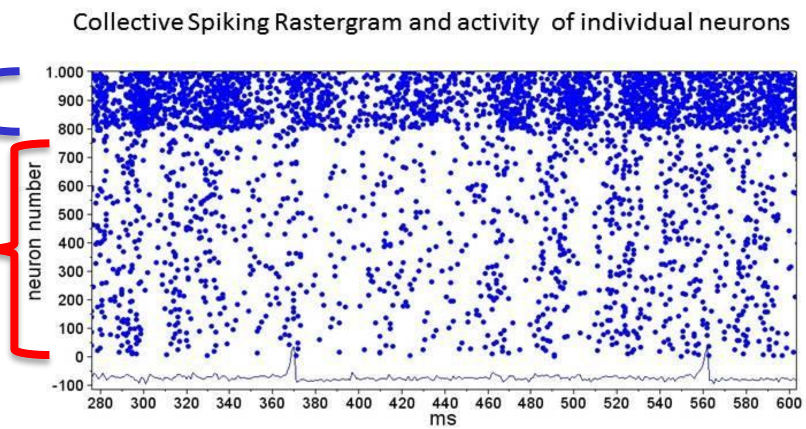
- INFN coordinated **EURETILE(2010 - 2015)** FP7 project
  - Investigation of future generations of distributed/parallel computers
  - Focus on software/hardware scalability on many core systems
  - **Start of DPSNN code development** as a source of requirements and architectural inspiration for extreme parallel computing
- INFN third party of ISS Roma in **CORTICONIC (2013 – 2016)** FP7 project
  - Identify computational principles of the cerebral cortex
  - First comparison with in-vivo/in-vitro experimental results
  - **DPSNN improved** for CORTICONIC simulations (support of more realistic biological models) **importing models from ISS Perseo** scalar simulator
- DPSNN simulator **key benchmark** in **EXANEST (2016-2018)** FET Project (INFN, Piero Vicini)

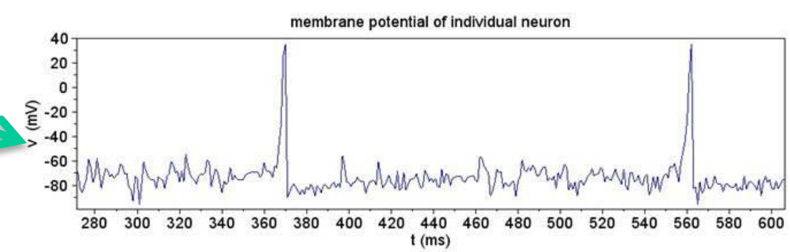
The DPSNN-STDP simulator

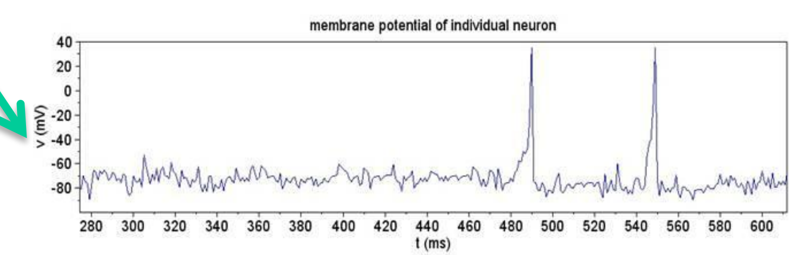
- **Distributed**: designed for execution on distributed/parallel computing systems:
  - ~ 11 elapsed sec/Hz to simulate one second of activity of 20G synapses and 11M neurons on a 64 server cluster (Galileo - Intel Haswell 2 x Intel Xeon 2630 v3@2.4GHz, 8 cores each), network complexity comparable with ~1 cm^2 of rat cortical tissue area
- **Spiking Neural Net**: present implementation:
  - Cortical Field: a bi-dimensional grid of Cortical Modules with local and first, second, third … neighboring modules connections
  - Cortical Modules composed of point neurons. Implemented models:
    - Izhikevich neuron
    - Leaky-Integrate-and-Fire neuron with spike frequency adaptation
- **STDP**: synaptic long term potentiation/depression based on relative timing of synaptic activation and post-synaptic neural spiking
- **Polychronous**: investigation of the computational properties created by hierarchies of individual synaptic delays

Small scale example of neural net simulation

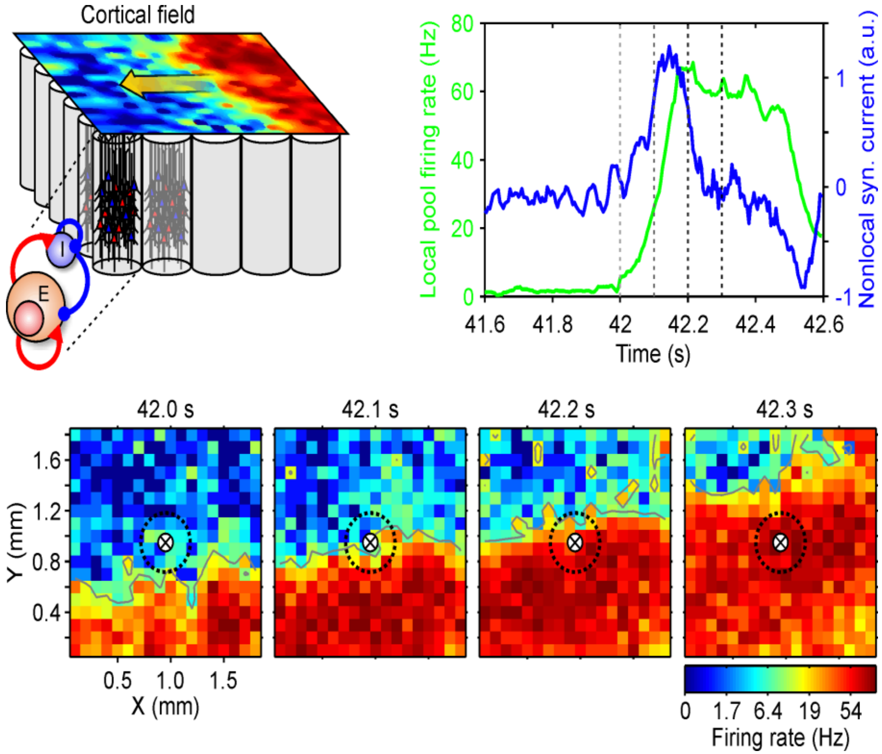
- 200 inhibitory neurons
- 800 excitatory neurons
- Time resolution: 1ms
  - (horizontal axis)
- Each dot in the rastergram represents an individual spike
- The evolution of the membrane potential of individual neurons is simulated
- The evolution of individual synaptic strength is computed (not shown in the picture)
- individual synaptic delays are taken into account
- Individual connections and neural types can be programmed







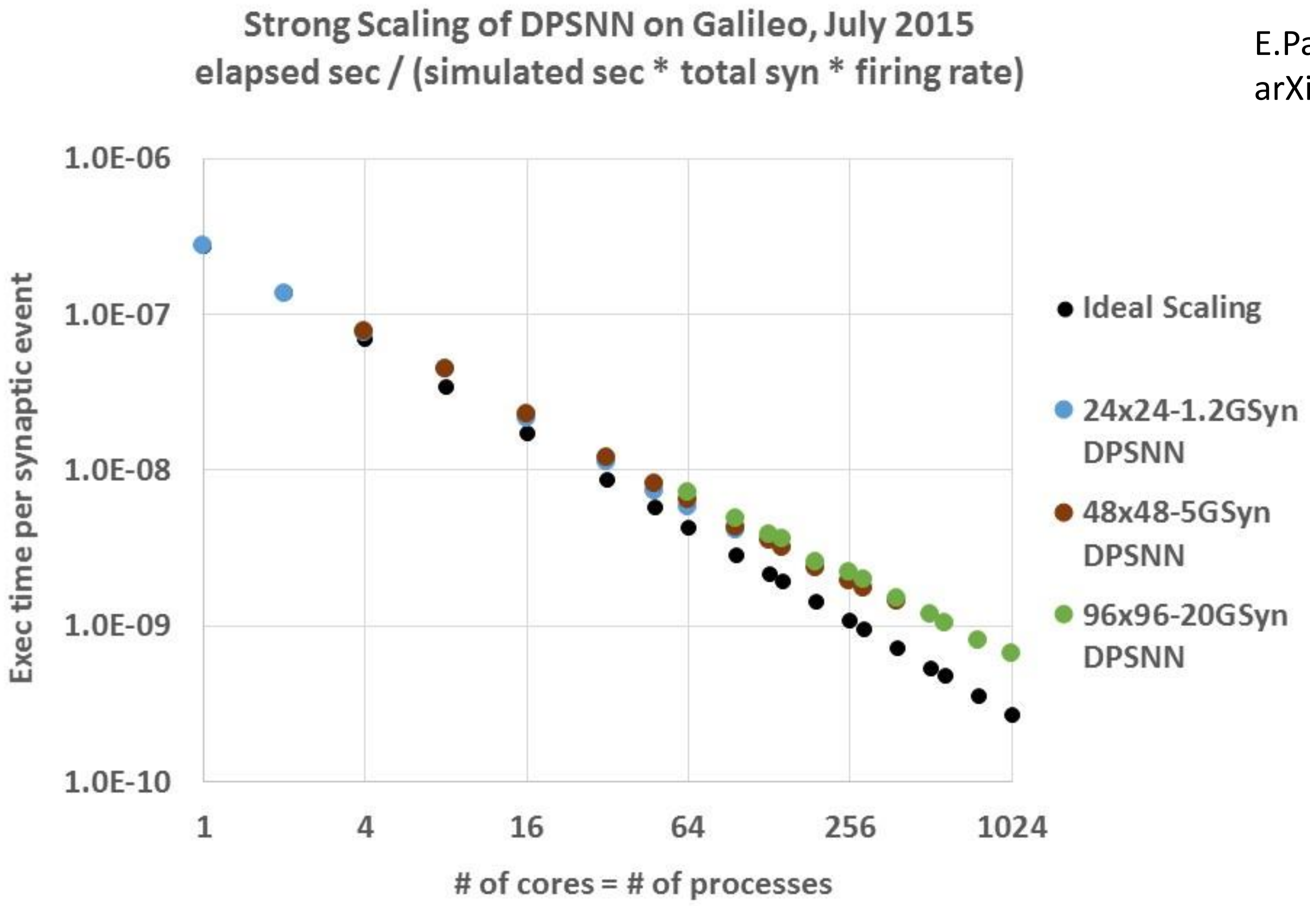
Example of simulation produced by INFN simulator DPSNN



Simulation of a large field of cortical columns (pixels of the bottom snapshots), each composed of 2500 excitatory and inhibitory leaky IF neurons. Top, firing rate of the central column (green) of the cortical field and the net synaptic input it receives from neighbouring columns (blue): local vs global contribution. Simulations performed within CORTICONIC project (ISS/INFN) with a total of 10^6 cells and 10^9 synapses.

Strong Scaling of DPSNN simulator, measured up to 1024 cores, 20G synapses

E.Pastorelli, et. al (2015)
arXiv:1511.09325



Simulator improvements

- Introduce **inter-areal connection** to scale from single area to multiple area SWA simulation.
- Distribute simulation on **thousands of MPI processes**, clusters of point-like spiking neurons and their incoming (plastic) synapses
- Refine columnar, **layered architecture** used to describe the single area
- Set-up the **tools** needed to observe:
  - Wave propagation
  - Structural complexity indexes
- Synaptic **plasticity**
  - Inclusion of STDP and improved plasticity models
  - Comparison of the effects of different plasticity models

References

About the proposal of measurable observables about consciousness and integration/differentiation and macro/scale connectivity

- Casali et al., (2013) "A Theoretically Based Index of Consciousness Independent of Sensory Processing and Behavior" Science Translational Medicine
- G. Deco, G. Tononi, et al., (2015) "Rethinking segregation and integration: contributions of whole-brain modelling" Nature Reviews Neuroscience

About Consciousness: example of system of axiomes / postulates focusing on a balance of integration and differentiation

- G. Tononi (2015) "Integrated Information Theory" Scholarpedia
- G. Tononi and C. Koch (2015) "Consciousness: here, there and everywhere" Philos. Trans.
- **Supporting mathematical framework**
  - Oizumi M, Albantakis L, Tononi G (2014) From the Phenomenology to the Mechanisms of Consciousness: Integrated Information Theory 3.0. PLoS Comput Biol 10(5): e1003588. doi:10.1371/journal.pcbi.1003588

About meso-scale cortical connectivity models

- Schnepel P, et al. (2015) "Physiology and impact of horizontal connections in rat neocortex" Cerebral Cortex
- T.C. Potjans and M. Diesmann (2014) "The Cell-Type Specific Cortical Microcircuit: Relating Structure and Activity in a Full-Scale Spiking Network Model", Cerebral Cortex

About pioneering large scale modeling experiments of the thalamo-cortical system

- Modha, S. D., & al., (2011) "Cognitive Computing", Communications of the ACM,
- E. M. Izhikevich, G. M. Edelman, (2008) "Large-scale model of mammalian thalamocortical systems" PNAS

About Slow Waves

- Destexhe, A., & Contreras, D. (2011)." The Fine Structure of Slow-Wave Sleep Oscillations: from Single Neurons to Large Networks." Sleep and Anesthesia
- Timofeev, I., & Chauvette, S. (2011). "Thalamocortical Oscillations: Local Control of EEG Slow Waves." Current Topics in Medicinal Chemistry,

About DPSNN, the large scale neural simulator developed by the APE lab of INFN in cooperation with ISS

- P.S. Paolucci, et al., (2015) "Dynamic Many-process Applications on Many-tile Embedded Systems and HPC Clusters: the EURETILE programming environment and execution platforms", Journal of Systems Architecture
- E.Pastorelli, et al. (2015) "Impact of exponential long range and Gaussian short range lateral connectivity on the distributed simulation of neural networks including up to 30 billion synapses " arXiv:1512.05264
- P.S. Paolucci, et al.. (2013) "Distributed simulation of polychronous and plastic spiking neural networks: strong and weak scaling of a representative mini-application benchmark executed on a small-scale commodity cluster". arXiv:1310.8478
- M. Mattia, P. Del Giudice (2000) "Efficient Event-Driven Simulation of Large Networks of Spiking Neurons and Dynamical Synapses. Neural Computation"

Thank you!