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Event-driven simulation of neural population synchronization facilitated by electrical coupling

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Abstract

Most neural communication and processing tasks are driven by spikes. This has enabled the application of the event-driven simulation schemes. However the simulation of spiking neural networks based on complex models that cannot be simplified to analytical expressions (requiring numerical calculation) is very time consuming. Here we describe briefly an event-driven simulation scheme that uses pre-calculated table-based neuron characterizations to avoid numerical calculations during a network simulation, allowing the simulation of large-scale neural systems. More concretely we explain how electrical coupling can be simulated efficiently within this computation scheme, reproducing synchronization processes observed in detailed simulations of neural populations.

Keywords: Event-driven; Spiking neuron; Neural synchronization; Electrical coupling

1. Introduction

One of the abilities of biological neural systems is their parallel information processing. The study of the dynamics of the cells that form these massively parallel computation systems is still an open issue (D'Angelo et al., 2001; Koch, 1999). Most of the computations that take place in these systems are spike driven: a spike that arrives to a target cell affects its state, producing a transient behaviour. Besides, in some models, the neural state evolution can be predicted. This has motivated the development of event-driven simulation schemes (Delorme and Thorpe, 2003; Mattia and Guidice, 2000; Reutimann et al., 2003). Some approaches simulate simple neural models in which the new neural state can be calculated after an input spike with a simple expression (Delorme and Thorpe, 2003). Other approaches use iterative calculation during the simulation to obtain the future neuron state of more complex models (Makino, 2003). Some authors use lookup tables to support concrete features such as stochastic dynamics (Reutimann et al., 2003). In our approach, the complete neural dynamics are compiled into lookup tables to enable the efficient simulation of detailed neural models which traditionally required time-

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driven approaches. Therefore during the event-driven simulation, only table accesses are needed in order to calculate the neuron state evolution.

The short-term dynamics defined by complex differential equations which require numerical calculation are computationally costly to simulate. We have developed an event-driven computation scheme that uses pre-calculated short-term dynamics which are stored on cell characterization tables, enabling the simulation of models of different degree of complexity (limited by the size of the tables required to store the model). In this way, an event-driven computation scheme in which the cells states are only updated at the arrival of spikes represents a very efficient tool for the simulation of large-scale systems. Network long-term dynamics (for instance learning models) can be simulated on a different time scale. We can adopt an event-driven scheme if the leaning mechanisms to be simulated are driven by spikes.

The two assumptions that are done to develop the event-driven computation scheme based on tables are the following: (a) the effect of a spike on a target neuron state can be predicted (since the simulation time jumps from one event to another, the neuron state must be also updated discontinuously, as indicated in Section 2) and (b) the number of inter-related variables that define the cell model dynamics is not very large (this makes the number of needed table dimensions affordable).

The process of building up cell models and setting up a system scale simulation requires of different stages:

(1) Detailed neuron model simulation.
Detailed simulations of neural models are done with specific tools such as NEURON (Hines and Carnevale, 1997) or GENESIS (Bower and Beeman, 1998). A simplification process leads to simplified models characterized by a reduced number of variables and differential equations.
(2) Table definition.
We define the table structure that will be used by the simulator to calculate the neural state evolution of a synaptic-conductance-based neural model online quickly, for instance synaptic conductance decay $g_{\mathrm{exc}}(\Delta t)$ and $g_{\mathrm{inh}}(\Delta t)$, firing time prediction $t_{\mathrm{f}}(V_{\mathrm{m},t_0}, g_{\mathrm{exc},t_0}, g_{\mathrm{inh},t_0})$ and the membrane potential evolution $V_{\mathrm{m}}(V_{\mathrm{m},t_0}, g_{\mathrm{exc},t_0}, g_{\mathrm{inh,t_0}}, \Delta t)$. All these variables depend on their previous states (at the last time they where updated t_0), the previous state of other variables or the time elapsed Δt since then.
(3) Compilation of the characterization tables.
All the transient dynamics of the cells are simulated off-line. This requires massive numerical computation to sample the cell behaviour accurately when using complex neural models. This massive computation consists roughly on single cell simulations under different conditions. This can be easily parallelized in clusters of computers if a very fast table creation process is required.
(4) Efficient neural system simulation.
We run the event-driven simulation scheme that uses efficiently these tables to avoid online numerical calculations (this is briefly described in the next section).

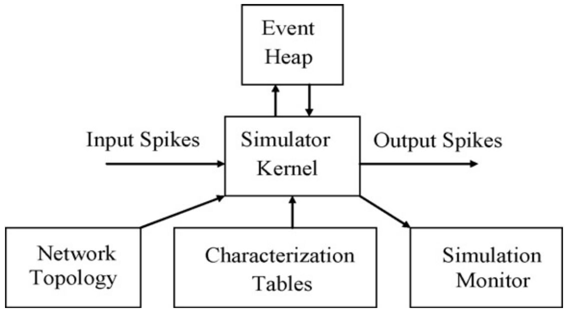

Fig. 1. Block diagram of components of the event-driven simulation scheme.

In the next section we describe briefly the table-based event-driven computation scheme (see Fig. 1). In Section 3 we describe how electrical synapses can be simulated in the presented computational approach. Furthermore, we show some illustrative results of neural population synchronization processes facilitated by electrical coupling. This experiment is motivated by different reasons: (1) validation of the implementation of electrical synapses, (2) the event-driven simulation of neural synchronization processes in highly interconnected large networks with arbitrary delays may become a challenge, because a large number of events are fired in a short time interval (which may lead to saturation of the event reordering data structure), and finally (3) synchronization processes seem to play an important role in the computations occurring within the molecular layer of the cerebellum, and should be integrated in further cerebellar simulations (we plan to study the role of this computational primitive in the sparse coding that is generally assumed to take place within the cerebellar granular layer).

2. Table-based event-driven computation scheme

The characterization of the neural dynamics requires a finite number of cell simulations under different initial conditions during a finite time interval (e.g. 50 ms).