Spiking activity propagation in neuronal networks: Reconciling different perspectives on neural coding

Supplementary material

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Network model

Neurons

The neurons in the network were modeled as leaky integrate-and-fire neurons, with the sub-threshold dynamics of the membrane potential $V^i(t)$ in neuron i described by:

$$C\,\frac{d}{dt}V^i(t) + G_{\text{rest}}\left[V^i(t) - V_{\text{rest}}\right] = I^i_{\text{syn}} \tag{1}$$

where I^i_{syn} is the total synaptic input current into neuron i and C, G_{rest} reflect the passive electrical properties of its membrane at rest ($V_{\text{rest}} = -70$ mV) When the membrane potential reached a fixed spike threshold V_{thresh} above rest, a spike was emitted, the membrane potential was reset to its resting value, and synaptic integration was halted for 2 ms, mimicking the refractory period in real neurons.

Network

We simulated a six layer feed-forward network (FFN) with 150 excitatory neurons in each layer. All the neurons were driven by excitatory and inhibitory Poisson type spike trains to obtain an average firing rate of 2 Hz in all the neurons. Neurons from layer 'N' made connections exclusively with neurons in layer 'N+1' with a connection probability ϵ. This connection probability was a free parameter in the model and was systematically varied from 0.1 to 1. Neurons in the last layer did not send out connections.

Synapses

Inter-group synaptic input was modeled by transient conductance changes, using alpha-functions

$$G(t) = \begin{cases} J\,\frac{t}{\tau}\,e^{-\frac{t}{\tau}} & \text{for } t \geq 0 \\ 0 & \text{for } t < 0. \end{cases} \tag{2}$$

Synaptic conductance transients were taken to have a uniform rise time of $\tau = 0.33$ ms. We refer to the peak amplitude 'J/e' of the conductance transient at $t = \tau$ as the 'strength' of the synapse. Generally, excitatory and inhibitory synapses had different strengths J_{e} and J_{i} assigned.

Assuming fixed synaptic couplings, the total excitatory conductance $G^i_{\text{exc}}(t)$ in neuron i was given by

$$G^i_{\text{exc}}(t) = \sum_{j=1}^{K_{\text{exc}}+K_{\text{ext}}} \sum_k g_{\text{exc}}(t - t^j_k - D). \tag{3}$$

The outer sum runs over all excitatory synapses ($K_{\text{exc}} + K_{\text{ext}}$) on this particular neuron, the inner sum runs over the sequence of spikes arriving at a particular synapse. A neuron received K_{exc} exclusively from the neurons in the previous group. K_{exc} was determined by the number of neurons in a group and the inter-group connection probability (ϵ). In all the simulations neurons received $K_{ext} = 1000$ external excitatory inputs which were modeled as uncorrelated Poisson type spike trains. Similarly, the total inhibitory conductance $G^i_{inh}(t)$ in neuron i was given by

$$G^i_{inh}(t) = \sum_{j=1}^{K_{inh}} \sum_k g_{inh}(t - t^j_k - D). \tag{4}$$

In the network studied here, neurons received $K_{inh} = 250$ external inhibitory inputs which were modeled as uncorrelated Poisson type spike trains. Neurons did not receive any inhibition from within the network i.e. from previous group.

A uniform transmission delay of $D = 2$ ms was imposed for all synapses, in all simulations.

Thus, the total synaptic current into neuron i was

$$I^i_{syn}(t) = -G^i_{exc}(t)\left[V^i(t) - V_{exc}\right] - G^i_{inh}(t)\left[V^i(t) - V_{inh}\right], \tag{5}$$

with $V_{exc} = 0$ mV and $V_{inh} = -80$ mV denoting the reversal potentials of the excitatory and the inhibitory synaptic currents, respectively.

Together with inter-group connection probability (ϵ), the synaptic strength J_e was a free parameter and was varied from 0.15 mv to 0.75 mV.

Stimuli

We used two different stimulus classes to study the activity propagation in the FFN. Activity in the FFN was initiated by stimulating all neurons in the first group with a pulse packet (PP), or with asynchronous firing rate.

A Pulse packet is a volley of spikes with a Gaussian shape, characterized by its strength, i.e. the number of spikes in the volley (α here we used $\alpha = 100$), and its temporal dispersion of the spikes, i.e. the standard deviation of the spike timings in the volley (σ here we used $\sigma = 10$ ms).

Asynchronous firing rate was modeled as homogeneous and uncorrelated Poisson type spike trains. Each neuron in the first group of the FFN received 200 homogeneous and uncorrelated Poisson type spike trains for a finite interval of 500 ms with at a given rate (10 spikes/s $\leq$ fr_{stim} $\leq$ 50 spikes/s).

Simulation Tools

All network simulations were written in python (http://www.python.org) using PyNN (http://neuralensemble.org/trac/PyNN) as interface to the simulation environment NEST(http://www.nest-initiative.org). The dynamical equations were integrated at a fixed temporal resolution of 0.1 ms. Simulation management was performed using the python package NeuroTools (http://neuralensemble.org/trac/NeuroTools).