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Together, the two hemispheres of the mouse cortex contain, roughly, 16×10^6 neurons, and $8,000$ synapses per neuron [1]. Modeling and simulation at this scale (and beyond) is an emerging area of scientific exploration that will likely lead to a host of new computational and neuro-scientific insights. To facilitate *near real-time* study of network dynamics, we have recently developed a massively parallel cortical simulator simulator [2] that incorporates relatively simpler phenomenological models of spiking neurons [3], spike-timing dependent plasticity [4], and axonal conductance delays. In this paper, we explore the challenges involved in scaling, stabilizing, and synchronizing such large-scale models.

Scaling

We created a basic connection template with $32,768$ "groups" each of which have 500 neurons. Each group sends axons to 100 randomly selected groups and each neuron from the projecting group makes a total of $c = 80$ synapses with the neurons of the receptive group. The resultant network consisted of a total of $16,384,000$ neurons and $8,000$ synapses per neuron comparable to a mouse. Roughly, 80% of the groups were excitatory and the remaining were inhibitory. For excitatory groups we used axonal delays uniformly ranging from $1-20$ ms, and for inhibitory groups we used a fixed 1ms axonal delay. This network structure is not intended to capture detailed anatomy of the mouse brain, but is a step towards understanding dynamics of large scale models.

Using a BlueGene/L supercomputer with $8,192$ processors (2 times the size in [2]), with 4 TB of main memory (4 times the size in [2]), we were able to load the entire network and all the associated auxiliary data structures. In a stable, sustained firing mode (see below), using a stimulus pattern that delivered super-threshold excitation to every neuron at 4Hz, using 1ms simulation time steps, we were able to simulate 5s of model time in 168s of real-time at a mean firing rate of 4.95Hz. Effectively, when normalized to a 1Hz mean firing rate, we were able to run a 1s of model time in approximately 7s of real-time. Interestingly, with everything else kept the same, but without using spike-timing dependent plasticity, we were able to run 5s of model time in 75s of real-time. When normalized to a 1Hz mean firing rate, this amounts to 1s of model time in approximately 3s of real-time.

To further push the boundaries of scaling, by using $c = 160$ above, we created a network with $16,384,000$ neurons and $16,000$ synapses per neuron (alternatively, we could have created a network with $32,768,000$ neurons and $8,000$ synapses per neuron). We were able to run this model on a larger BlueGene/L supercomputer with $16,384$ processors and 8 TB of main memory. Specifically, in a stable, sustained firing mode, when using a 5Hz stimulation, we were able to achieve 5s of model time in 265s of real-time at a mean firing rate of 5Hz. When normalized to a 1Hz mean firing rate, this amounts to 1s of model time in approximately 11s of real-time.

Stability and Synchronization

Stabilizing cortical simulations is enormously difficult: "For a large network of excitatory and inhibitory

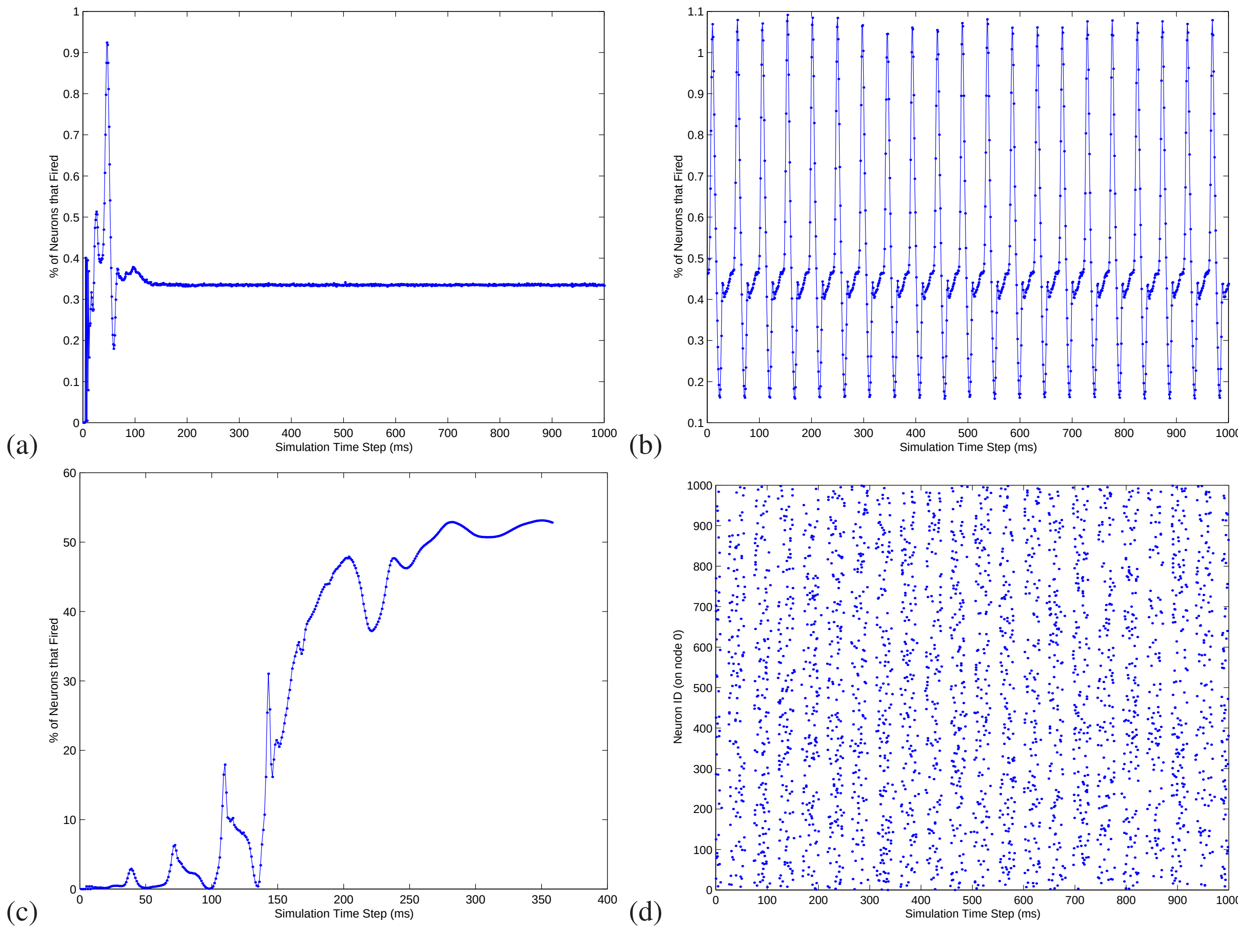

Figure 1: Dynamics of a network with $16,384,000$ neurons and $16,000$ synapses per neuron. Panels (a), (b), and (c) display percetage of neurons that fired at each simulation time step. Panels (a), (b), and (c) exhibit, respectively, damped, sustained, and avalanche behaviors. Panel (d) shows the raster of $1,000$ neurons (out of $16,384,000$ neurons) corresponding to stable mode in panel (b).

neurons with small EPSPs it is very difficult, if not impossible, to attain steady ongoing activity at low firing rates." [5] It is very easy to drive a network into avalanche mode or into an uninteresting quiescent state, but is difficult to maintain it in a stable periodic, quasi-periodic, or chaotic states [6].

A neuron decides to fire on the basis of co-incident activity at its synapses and the synaptic efficacies. We found that the allowed *maximum synaptic efficacy* (which upper bounds the growth of excitatory synaptic efficacies under spike-timing dependent plasticity) and the *probability of the super-threshold stimulus* together greatly affected the behavior of our networks described above. During the course of this study, we used several models with varying number of synapses from 1 synapse per neuron to $16,000$ synapses per neuron. We observed that finding a range of maximum synaptic efficacies corresponding to stable models is harder to achieve for higher number of synapses per neuron if the stimulus probability is kept low. Further, there appears to be a threshold stimulus probability below which – when maximum synaptic efficacy is varied – models make a sharp transition from damped mode to avalanche mode. For the network with $16,000$ synapses per neuron, the three modes, namely, damped, sustained, and avalanche, are captured in Figure 1. We found similar behavior also for the smaller, mouse-scale network with $8,000$ synapses per neuron.

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