An Izhikevich simple model version of the hippocampus micro-circuit from the Tort et al (2007) model

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Abstract

We replicate a hippocampal micro-circuit module from the model of Tort et al (2007), using Izhikevich simple neuron models in place of the complex single- and multi-compartment neurons models of the original version. We use the existing pyramidal and fast-spiking neuron models and our new oriens/alveus interneuron model in a micro-circuit that shows self-organisation into both theta and gamma-band activity. Our main result is that our massive reduction of their model appears to have same dynamic properties, yet runs many orders of magnitude faster.

1 Introduction

Recent models of hippocampus CA1/CA3 networks have shown how both theta and gamma frequencies of oscillation can emerge together, and in coherent cell assemblies, from the interactions of a particular microcircuit (Rotstein et al., 2005; Tort et al., 2007). These models show great promise as the basis for understanding a wide range of experimental data obtained from the hippocampus. Unfortunately, these models use multiple micro-circuits comprised of multiple-compartment pyramidal neuron models and complex single-compartment models of fast-spiking (FS) and oriens lacunosum-moleculare (OL-M) inter-neurons, and so are costly to run. Thus, we would like to greatly simplify these models, so that we can properly explore the properties of the networks.

We have already introduced a simple model version of the OL-M interneuron (O-cells). Here, we combine this model with existing simple model versions of pyramidal neurons (E-cells) and fast-spiking inter-neurons (FS-cells) (Izhikevich, 2006) to replicate the structure of a single module from the Tort et al. (2007) model, as they showed that a single module was sufficient to generate simultaneous theta and gamma band oscillations. In one module, the E-cells project to both O-cells and FS-cells, the FS-cells project to all cells (including themselves), and the O-cells project to both FS-cells and E-cells. Connectivity is all-to-all. Following Tort et al. (2007), we use 1 E-cell, 15 FS-cells, and 15 O-cells in the module.

We use the same synapse types (AMPA and GABAa), a simpler single-exponential synapse model (i.e. a step-decay model rather than a double-exponential), and do not (yet) model the ordering of synapses on the E-cell dendritic tree. Otherwise, all appropriate synaptic and injection current parameters are based on those from (Tort et al., 2007). We simulate local-field potential (LFP) recording by summing over all synaptic currents from all cells on each time-step. All differential equations were solved using the forward Euler method with a time-step of 0.25 ms. Full methods will follow in a future report.

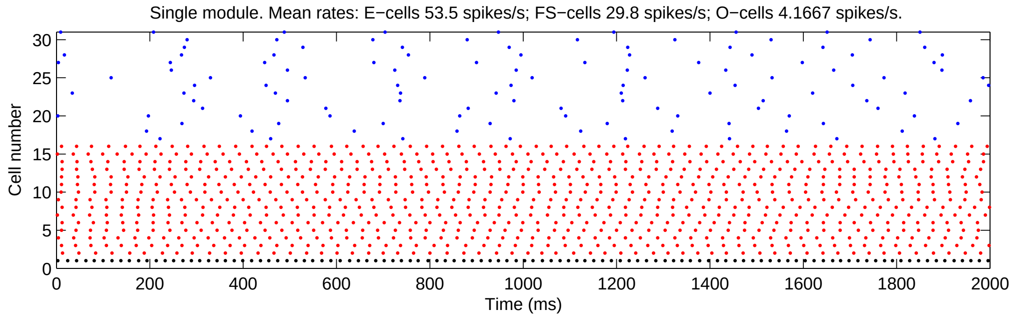

Figure 1: With all synapses turned off, the reduced Tort module shows the correct mean firing rates for each neuron type: E-cells (black) $\sim$ 50 spikes/s; FS-cells (red) $\sim$ 25 spikes/s; O-cells (blue) $\sim$ 3.5 spikes/s.

2 Results

Despite the simplification of the synapse model, and the massive simplification of the neuron models, we are able to replicate the main properties of a single module from the Tort et al. (2007) model.

- When all synapses are disconnected, the three cell types fire at the same approximate mean rates as the Tort model (Figure 1).
- Connecting the synapses causes the formation of cell assemblies that follow the same form as the Tort model, with O-cells firing in a θ rhythm, and FS-cell and E-cell firing time-locked within the theta-cycle (Figure 2).
- Once formed, these cell-assemblies remain stable (Figure 3).
- The spike trains of the E-cell and FS-cell classes have peak power in the γ-band, and the O-cell spike trains have peak power in the θ-band (Figure 4; note that Tort et al. (2007) did not perform this analysis explicitly).
- The simulated LFP for the whole module has clear peaks at both θ and γ-band frequencies (Figure 5).

We also noted that the results were robust to changes in the size of the time-step (within one order of magnitude), and to increasing the number of FS- and O-cells (only tested for equal numbers).

3 Conclusion

The reduced model version of the hippocampus micro-circuit module replicates all reported dynamic properties of a single module from the Tort et al. (2007) model. This is achieved despite reducing the number of equations in the overall model by an order of magnitude, simplifying the synapse model, and using the simplest possible numerical solution method. The result is that the reduced model runs in reasonable computational time on a desktop PC (on a 1.3GHz Centrino, Matlab version with a 0.1ms time-step it takes $\sim$ 3s per 1s of simulated time); at the current size, it would run faster than real-time if transferred to C/C++. Thus this reduced version can be scaled up to many hundreds or thousands of neurons and still remain computationally feasible. The next task is to link together multiple modules to replicate the full Tort et al. (2007): given that the single module of their model contained the principle dynamic properties of interest, we anticipate that this will be successful.

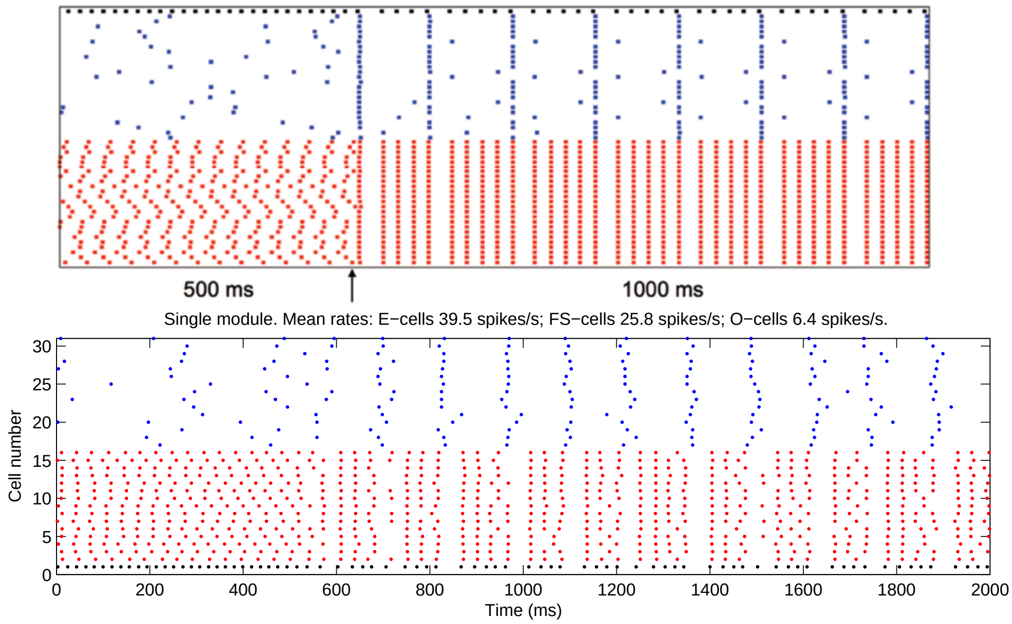

Figure 2: Spontaneous organisation into coherent cell assemblies. Top: a single module from the Tort model showing that coherent assemblies of cell-types emerged after synapses were turned on at 500ms (arrow); taken from Tort et al (2007), SI Fig6D. Bottom: the reduced model shows the same spontaneous formation, with approximately the same firing patterns in all cell classes. The synchronous assembly takes longer to emerge in the reduced model, and the synchrony between cells is less severe — the synchrony increases with smaller time-steps.

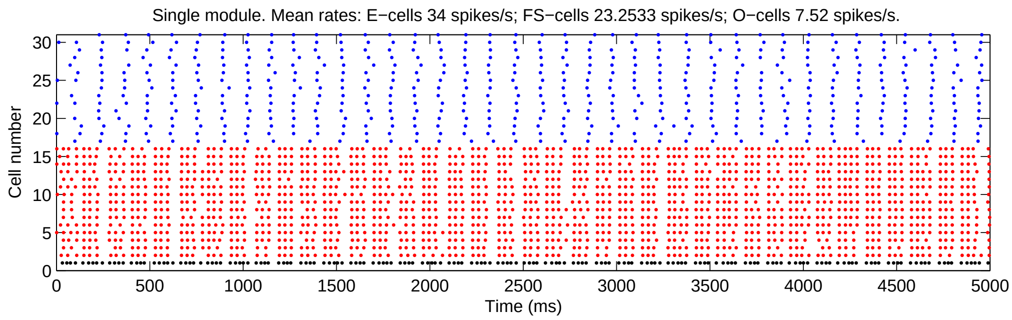

Figure 3: With synapses turned on from the start, the reduced model shows stable cell-assemblies throughout.

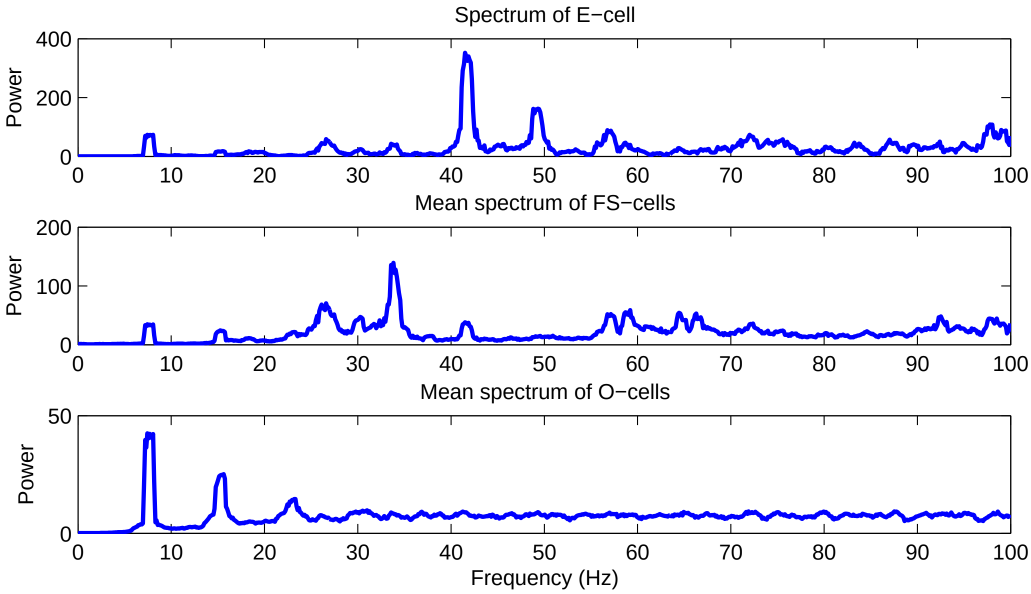

Figure 4: Multi-taper power spectra of the E-cell, FS-cell, and O-cell spike trains (from the data shown in Figure 3). Top: the E-cell shows a clear γ-band peak in its spike train firing. Middle: the mean FS-cell spectrum also shows a clear γ-band peak, but at a lower frequency. Bottom: the mean O-cell spectrum shows a clear θ-band peak.

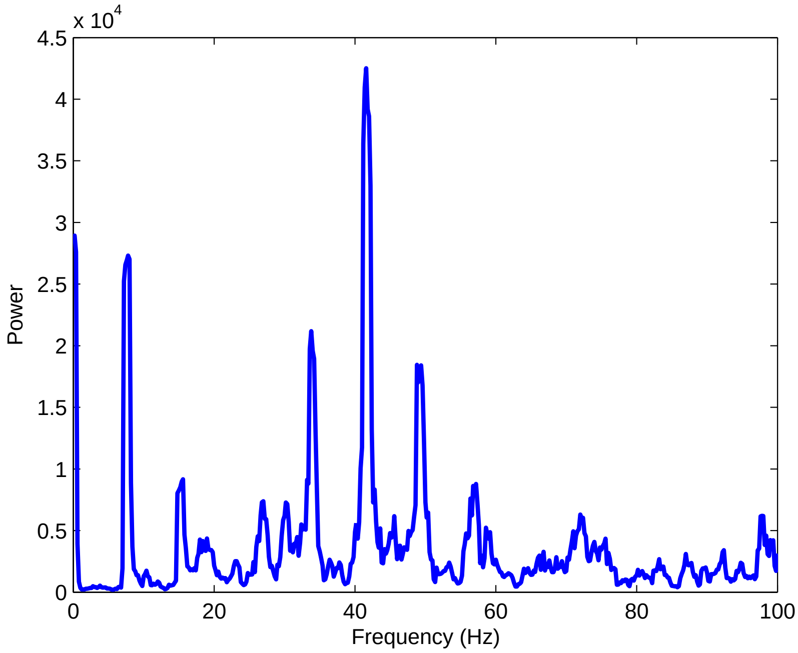

Figure 5: Multi-taper power spectrum of the simulated LFP recording, showing that the whole module's LFP had two peak frequencies corresponding to the spike train properties, one in the θ-band and the other in the γ-band.

References

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