Identifying Dynamics in Neural Networks

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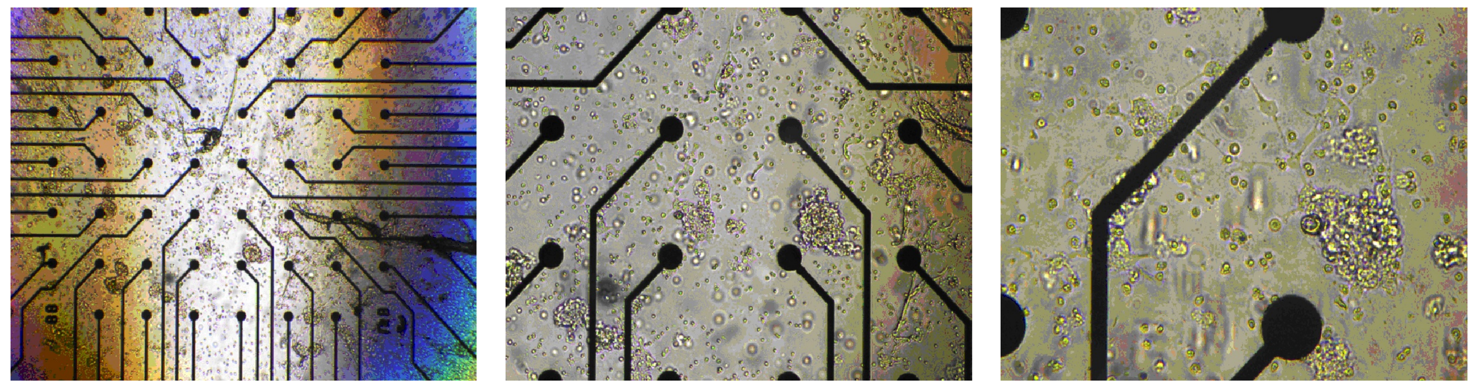
Introduction

We have developed new methods for identifying dynamics and quantifying complexity in biological neural networks. By combining these methods with online stimulation we hope to study network behavior on different spatiotemporal scales. We are currently validating our methods on a computation model.

Microelectrode Array (MEA)

Our study of in vitro neural networks is done on microelectrode arrays (MEAs), cultured with either rat cortical or spinal cord neurons. MEAs consist of electrodes which are able to record the spiking behavior of nearby plated neurons by measuring or stimulating voltage in the extracellular environment that occurs when a neuron spikes.



Mathematical Model

To validate our analysis on a known system we implemented the Izhikevich model [1]. The Izhikevich model combines computational efficiency with the ability to reproduce biologically accurate behavior. Each neuron is modeled as a two dimensional ODE (v_i, u_i) which exhibits spiking.

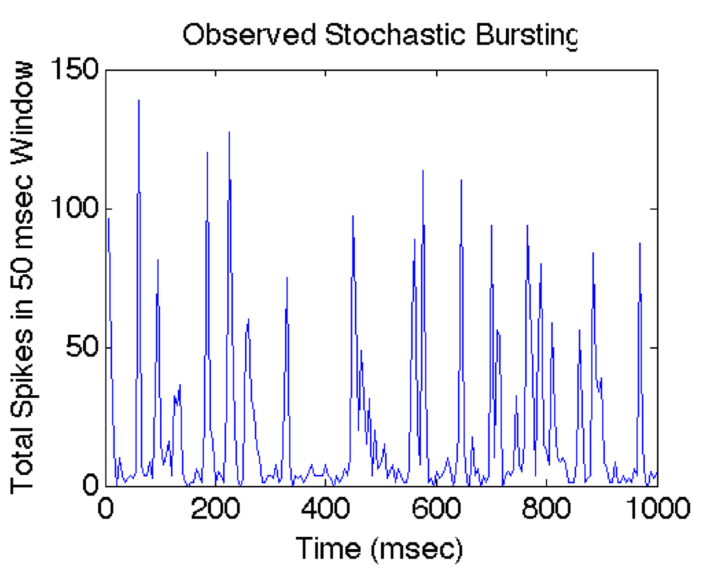
$$\dot{v}_i = \frac{1}{25}(v_i^2 + 125v_i) - u_i + I_i \qquad I_i = \omega_i + \beta + \sum_{j=1}^{n} S(i,j) * 1(v_j > v_{\text{threshold}})$$

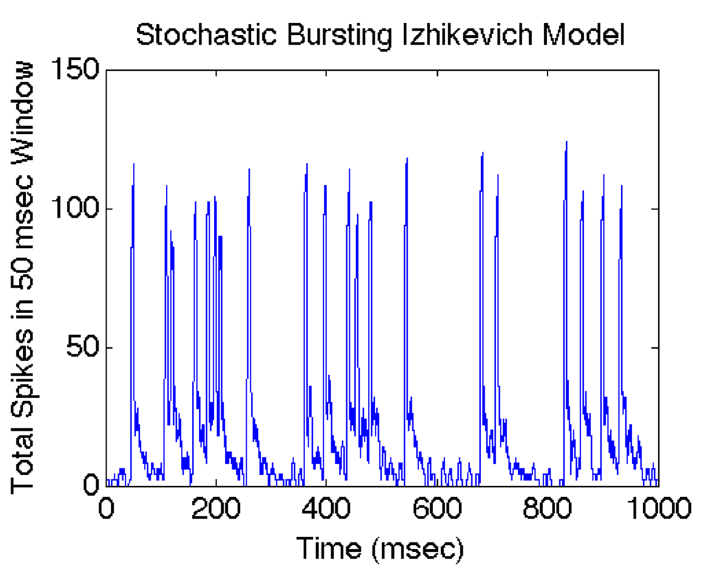
$$\dot{u}_i = a(bv_i - u_i) \qquad \beta(t) = \sum_{k=1}^{\infty} \alpha_k \phi(t - \tau_k)$$

The n neurons are connected by an n x n matrix S which represents connectivity strengths. The network is made stochastic by the term ω_i which represents a Gaussian random process. We have added β as an optional bursting effect.

Stochastic Network Bursting

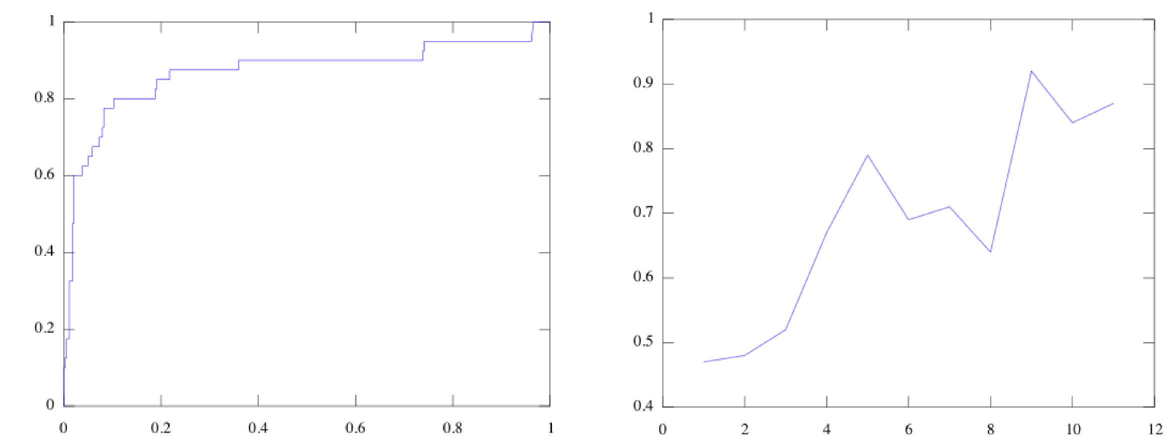
Real neural networks can exhibit stochastic bursting, which presents a challenge to statistical techniques that use correlations to determine network connections. To replicate this we added the β term to the Izhikevich model (see above) where ϕ is a compactly supported burst shape and α_k and τ_k are random. Below we compare bursts in a real network (left) and in our model (right).





Determining Network Connections

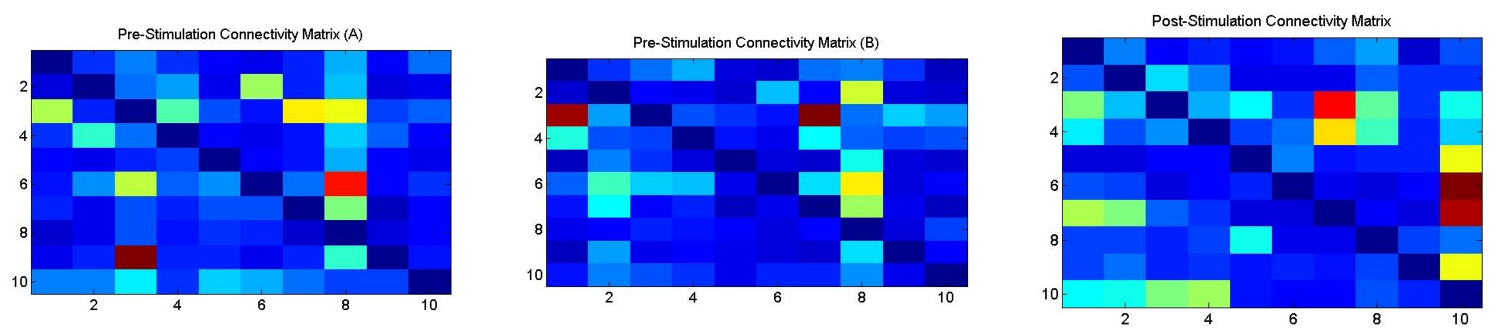
To determine if neuron A influences neuron B we consider a randomly chosen spike of B and find the distribution of time-to-previous-A and time-to-next-A. These distributions are compared with the Kolmogorov-Smirnov test, which determines whether the distributions are different at a given confidence level.



We applied our method to the Izhikevich model and attempted to determine the S matrix. Above left we see a receiver operating characteristic (ROC) curve. The area under the ROC curve is a measure of the accuracy of our method, this is plotted as a function of simulation time in minutes above right.

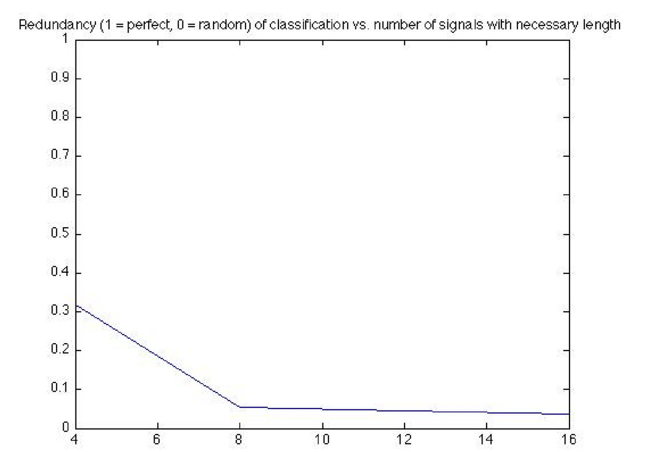
In Vitro Electrical Stimulation

In an attempt to see if we could change the dynamics of a neural network, we implemented a period of electrical stimulation and examined the connections pre-stimulation and post-stimulation via the Kolmogrov-Smirnov test to see if there was a difference in predicted connections. The pre-stimulation period was broken into two periods of approximately equivalent spike counts so that we could take note of the network's state. This was not done post-stimulation due to the restricted amount of data.



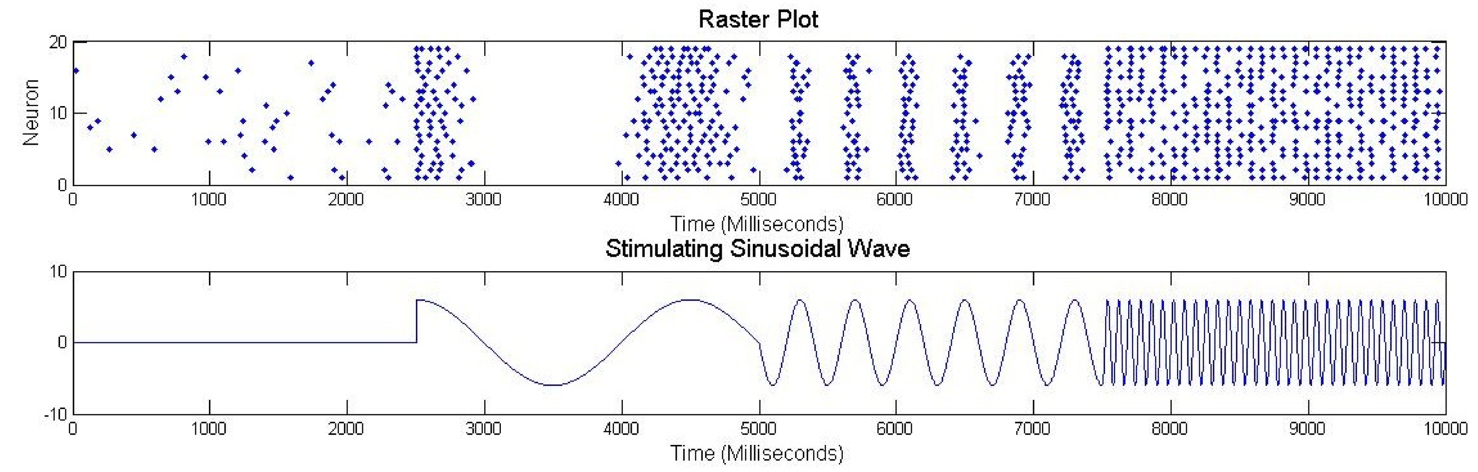
Determining Network Information Capacity

Following [3] we used Support Vector Machines (SVM) with Radial Basis Functions to identify an input signal using only the network output. The input signals were randomly chosen binary patterns of a fixed length and were input into a single neuron. After training the SVM we attempt to classify a sequence of input signals. The resulting sequence of classified signals is considered to be a message received through a noisy channel. To quantify the capacity of the network we plot the amount of information preserved by the network versus the signal length.

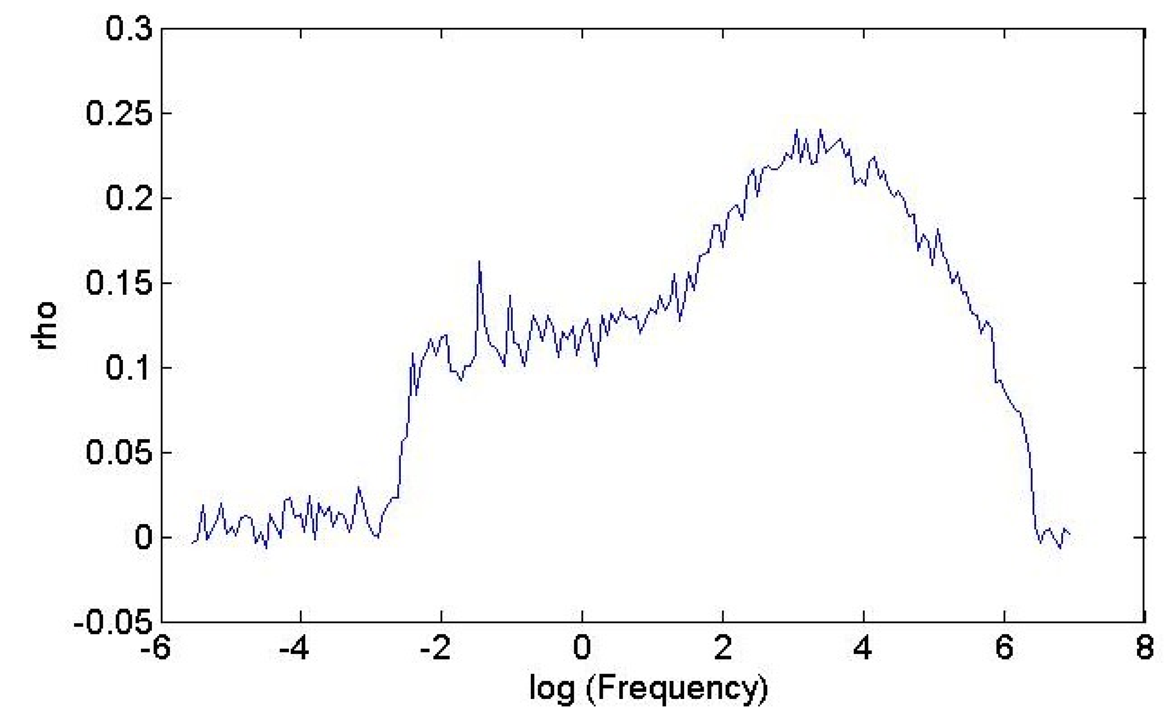


Inducing Network Synchrony

We wanted to investigate network synchronization with an eventual goal of being able to desynchronize a synchronized network. Some literature suggests sinusoidal stimulation at certain frequencies can induce network synchronization. We examine this through the Izhikevich model.



In order to determine quantitatively whether or not there was synchrony in the network, we utilized the Hilbert transform to determine ρ where ρ is a measure of network synchrony. $0 \le \rho \le 1$ where $\rho = 0$ indicates no synchrony and $\rho = 1$ indicates a high level of synchrony.



Future Plans

We would like to continue our investigation of network dynamics in model as well as in vitro. Once we have a broader understanding of these network dynamics, we would like to explore aspects of pattern steering in neural networks.

References

[1] Eugene M. Izhikevich. "Polychronization: Computation With Spikes." Neural Computation (2006) 18:245-282.

[2] S. Feldt, et al. "Functional clustering algorithm for the analysis of dynamic network data." PHYSICAL REVIEW E (2009) 79, 056104.

[3] Einat Kermany, et al. "Tradeoffs and Constraints on Neural Representation in Networks of Cortical Neurons." The Journal of Neuroscience, 14 July 2010, 30(28): 9588-9596.