The Neuronal Communication System

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I. INTRODUCTION

Man's pursuit of science is driven by the desire to define and characterize the natural world. Often, our developments are circular in nature: we invent science to explain a natural phenomenon, and our new understanding inspires new science. Neuroscience and the quest to understand the basis of brain function is a great example of this sort of symbiotic scientific development. In the early 1900s, pioneering neuroscientists began to speculate about the underlying function of the brain. The basic building block of brain function was discovered to be the neuron - a unique cell type with seemingly very special functionality. Through microscopic investigation, it was shown that these neurons organized into *neural networks*, presumably to implement higher brain function. The first task, however, was to determine how the individual neuron worked and communicated with other neurons. Nearly one hundred years later, we are still learning new things about the rich function of a single neuron's computational abilities. Viewed in light of communication systems theory and practice, we can potentially learn new things about neuronal function or perhaps apply it to develop new methods in communications.

II. BACKGROUND

Beginning with Hodgkin & Huxley in the 1930s, it was theorized and then shown that the basis for neuronal communication was electrical in nature. Since then, electrical engineers have been major contributors to neuroscience. An entire field of electrical engineering, called ”neural networks,” has developed out of this interdisciplinary field. Engineers mimic the ability of the brain to learn through simplistic models of neurons and networks of them. Signal processing is one area which has benefited greatly from these developments.

As shown in Figure 1, a single neuron is comprised of three main sections - a dendritic tree, a soma (cell body), and an axon. The axon generally functions as the ”output” and the dendritic tree takes ”inputs” from other neuron's axonal outputs. At the interface, the axon terminates in a *synapse*. The space between the synapse and the dendrite is called the *synaptic cleft*. Nearly all of the signaling in the human brain takes places via electrochemical transfer. The axon synapse releases chemicals, called *neurotransmitter*, which migrate across the synaptic cleft and have either an excitatory or inhibitory effect on the dendrite. In the excitatory case, the dendrite generates an electrical current by altering properties of the cell membrane. The size of the electrical pulse falls off as a function of the distance to the cell body. In the inhibitory case, the dendrite alters the properties of the cell membrane to have a shunting effect and suppress any currents generated nearby. One neuron may have thousands of synaptic inputs!

One of the first models proposed as the function of a neuron is called the *integrate-and-fire* neuron. At the base of the axon, all of the dendritic currents are summed up. The weight of each dendritic current is a function of the distance it traveled through the dendritic tree to reach the axon. If the resulting voltage exceeds a given threshold, the axon ”fires” an *action potential*, generating an electrical pulse which propagates down to its synapse(s), thereby generating inputs to other neurons [1]. Most of the ”neural networks” in engineering use these simplistic neuron models.

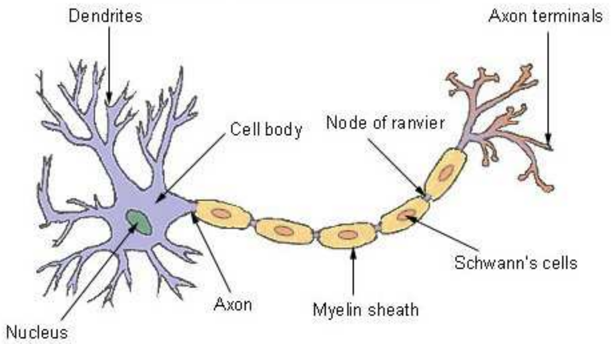

Fig. 1. The Neuron

For mathematical evaluation of this kind of neuronal system, the dendritic tree can be treated as a set of ”passive cables”, and treated much like a standard lumped-element transmission line in microwave engineering. The dendritic cable has capacitance and resistance per unit length, and this model effectively predicts how a signal propagates down the cable. Excitatory synapses inject signals onto this transmission line by allowing ionic currents to flow across the membrane, and inhibitory synapses modify the transmission line such that the signal is attenuated. Recent research has shown that the function of the dendritic tree is much richer than that. There are non-linear active elements as well, whereby signal amplification can occur. It is believed that significant amounts of computation take place in the dendritic tree itself. The physical arborization of the tree, along with the location of each input synapse determine significant computational abilities.

III. PURPOSE

For many years, tools from communications and information theory have been utilized to explain neuronal behavior. In [2], the authors model the axonal channel, and determine that minimum diameter for an axon is tightly correlated with the amount of noise generated. They show that models predict any channel thinner than $0.1\mu m$ is dominated by noise and essentially useless. This accurately supports what is found in nature. Nearly every axon which has been measured is larger in diameter than $0.1\mu m$, but not by much. It is interesting to note that evolution has pushed these diameters towards their limit of usefulness. They literally operate at the limit of SINR.

In [3], the authors examine the capacity and energy cost of information transmission in the blowfly visual system. They compare the biological system with a silicon implementation meant to mimic its functionality. They find that for the most part, the biological system performs better at a lower energy cost.

There are countless papers written on neural networks and their application to a variety of engineering problems. Coding theory has been utilized to explain the variety of axonal action potentials and their meaning and importance. I propose to continue developing this link and examine at the dendritic tree as a communication system. I will attempt to develop models for this neuronal communication system, and see what kinds of lessons can be learned from or applied to the system.

IV. METHODOLOGY

It is not difficult to visualize the dendritic tree as a multi-branch communication channel. Each excitatory synapse functions as a transmitter with varying power, and each inhibitory synapse effectively reduces the channel gain. Additionally, regions which perform signal amplification can be viewed as simplistic analog relays inserted into the channels.

In fact, recent research indicates that the parallelism goes even deeper than that. Excitatory synapses exhibit spatial correlation, just like closely placed transmitters in a multi-antenna system. When these synapses are too close together, the signal strength is reduced. With proper spacing, multiple synapses can implement directional selectivity, along the lines of beamforming in a multiple-antenna system. If the synapses fire in the correct order, enough signal is generated to reach the axon and cause an output action potential. If they don’t, no output is generated [4].

In auditory neurons, coincidence detection is implemented in the dendritic tree. Based upon the angle of sound reaching two ears, different neurons fire. It is believed that this functionality is implemented through sets of neurons with varying dendritic lengths from the synapses. Synchronous firing of the input synapses from the ears determines which angle the sound is coming from. This spatial correlation computation can exhibit accuracy better than 20 microseconds! [5].

There is another concept called back-propagating action potentials. When the axon fires, it generates a signal which propagates both down the axon and back up through the dendritic tree. Researchers have found that this back-propagation influences synaptic plasticity (i.e. the ability for the inputs to learn when their input has caused an output). This could be compared with a communication handshaking mechanism which has the ability to learn!

There are many potential avenues of research. I plan to begin by modeling the dendritic tree as a multiple-transmitter, single-receiver system and see what kinds of interesting relationships arise. I will begin by modeling a prescribed set of synaptic terminals along a single length of dendritic cable. I will research existing models of passive dendritic cable (transmission lines, essentially) and then insert that proven model into my multi-transmitter single-receiver model.

The derived matrix model ought to exhibit characteristics (things like spatial correlation between inputs) through close examination of that matrix. For instance, if we take the SVD of this input-output matrix, we should see that certain spatial or temporal relationships are stronger than others. Next, I will take on the concept of active dendrites, where certain sites act as relays. This bears significant resemblance to the relay channel, and we should be able to derive additional important relationships when the dendritic tree contains these relaying-capable regions.

From this research, it is possible that we may gain some new insight into how dendrites compute, or show that we can use tools from communication theory to aid in understanding the function of the neuron. It is also possible that we may gain some new and interesting insights into developments for communication systems, and perhaps steal ideas from neuronal functionality to gain some new kind of communications ability that we had not envisioned before.

Additionally, I will explore the concept of physical limitations on axonal diameter due to noise, and see if an expression for the capacity of the channel can be derived which matches this proposed limit. Another related concept is discussed in [6], where the amount of noise (i.e. other synapses firing) actually scales the properties of the cable such that it is ”harder” for information to reach other portions of the dendritic tree or the axon. If we view these other synapses as interference, it is as if we are using up some maximum communication capacity of the system, and as more synapses fire the remaining available capacity is reduced. This again is suggestive of a relationship between the neuron as a communication system and principles of information theory.

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