Announcing the Final Examination of Alan Paris for the degree of Doctor of Philosophy

Time & Location: November 1, 2016 at 1:00 PM in Partnership 3 116
Title: BIOPHYSICAL SOURCES OF 1/F-TYPE NOISES IN NEUROLOGICAL SYSTEMS

High levels of random noise are a defining characteristic of neurological signals at all levels, from individual neurons up to electroencephalograms (EEG). These random signals degrade the performance of many methods of neuroengineering and medical neuroscience. Understanding this noise also is essential for applications such as real-time brain-computer interfaces (BCIs), which must make accurate control decisions from very short data epochs. The major type of neurological noise is of the so-called 1/f-type, whose origins and statistical nature has remained unexplained for decades. This research provides the first simple explanation of 1/f-type neurological noise based on biophysical fundamentals. In addition, noise models derived from this theory provide validated algorithm performance improvements over alternatives.

Specifically, this research defines a new class of formal latent-variable stochastic processes called hidden quantum models (HQMs) which clarify the theoretical foundations of ion channel signal processing. HQMs are based on quantum state processes which formalize time-dependent observation. They allow the quantum-based calculation of channel conductance autocovariance functions, essential for frequency-domain signal processing. HQMs based on a particular type of observation protocol called independent activated measurements are shown to be distributionally equivalent to hidden Markov models yet without an underlying physical Markov process. Since the formal Markov processes are non-physical, the theory of activated measurement allows merging energy-based Eyring rate theories of ion channel behavior with the more common phenomenological Markov kinetic schemes to form energy-modulated quantum channels. These unique biophysical concepts developed to understand the mechanisms of ion channel kinetics have the potential of revolutionizing our understanding of neurological computation.

To apply this theory, the simplest quantum channel model consistent with neuronal membrane voltage-clamp experiments is used to derive the activation eigenenergies for the Hodgkin-Huxley K+ and Na+ ion channels. It is shown that maximizing entropy under constrained activation energy yields noise spectral densities approximating \( S(f) = 1/f \), thus offering a biophysical explanation for this ubiquitous noise component. These new channel-based noise processes are called generalized van der Ziel–McWhorter (GVZM) power spectral densities (PSDs). This is the only known EEG noise model that has a small, fixed number of parameters, matches recorded EEG PSDs with high accuracy from 0 Hz to over 30 Hz without infinities, and has approximately 1/f behavior in the mid-frequencies.

In addition to the theoretical derivation of the noise statistics from ion channel stochastic processes, the GVZM model is validated in two ways. First, a class of mixed autoregressive models is presented which simulate brain background noise and whose periodograms are proven to be asymptotic to the GVZM PSD. Second, it is shown that pairwise comparisons of GVZM-based algorithms, using real EEG data from a publicly-available data set, exhibit statistically significant accuracy improvement over two well-known and widely-used steady-state visual evoked potential (SSVEP) estimators.

Major: Modeling and Simulation

Educational Career:
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