CONDUCTANCE VERSUS CURRENT-BASED INTEGRATE-AND-FIRE NEURONS: IS THERE QUALITATIVELY NEW BEHAVIOUR?

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ABSTRACT

The framework of Hodgkin-Huxley conductance-based models provides an excellent description of the electrical behaviour of neurons. However, their non-linear voltage-dependent membrane currents are hard to handle analytically and it has been difficult to gain insight into the quantitative behaviour of ensembles of such neurons. A much-simplified model neuron, the integrate-and-fire (IF) neuron captures many of the broad features that biological neurons share and has become a standard component of models of large recurrent-networks.

A cortical neuron in an active network receives a massive synaptic bombardment. This input is commonly approximated as a fluctuating *current*. Synaptic drive is, however, better modelled by a fluctuating *conductance*. Recently, the effect this conductance change has on the response of neurons has been brought to the attention of theorists and experimentalists [1, 2]. It was demonstrated that synaptic bombardment *in vivo* can lead to four-fold conductance increases, as compared to the quiescent case. Such an increase can have dramatic effects on the integrative properties of the neuron - effects that are neglected in current-based models. Here we examine the impact of this conductance change analytically and make a comparison with the case of current-based model synapses.

The model we consider comprises a passive leak with reversal potential E_L and passive time constant τ_L. The excitatory and inhibitory synaptic conductances are modelled as Poissonian trains of delta pulses ($\mathcal{P}_e$ and $\mathcal{P}_i$ respectively):

$$\frac{dV}{dt} = -\frac{1}{\tau_L}(V - E_L) - a_e(V - E_e)\mathcal{P}_e - a_i(V - E_i)\mathcal{P}_i.$$

Reversal potentials for both the excitatory (E_e) and inhibitory (E_i) synapses are included (see [3] for a treatment of this system with purely excitatory inputs) and a_e, a_i set the scale for post-synaptic potential amplitudes. This model is equivalent to that recently introduced in [2] in the limit that the correlations in the induced conductances are short - the model neglects correlations that are known to be important at higher frequencies [4]. Nevertheless, it does allow for a fair comparison with the current-based IF neuron, and most importantly, it captures the principal features of dynamic conductance changes, varying time constant and voltage-dependent post-synaptic potential amplitudes.

In the limit of small post-synaptic potentials we obtain solutions for both the membrane potential distribution and the firing rate. Of particular interest are the different modes in which the neuron can be induced to fire; (i) through an increase of the mean voltage, (ii) or through increased voltage fluctuations.

(i) Increase of the mean voltage: In the current-based IF neuron the depolarization of the membrane is implemented by the increase of the total current. In the conductance-based case this can be achieved through both increasing the excitatory presynaptic rate or decreasing the inhibitory rate. We show that a balanced case (in which both mechanisms act to preserve the steady conductance) is identical in behaviour to pure current injection: the average membrane potential changes

linearly with increasing drive. However, if this balance does not exist, for example by only increasing the presynaptic excitatory rate, the corresponding increase in conductance leads to a sub-linear depolarization with the drive.

(ii) Increase of the voltage variance: It was recently suggested that changes in the variance of the presynaptic input allows for a rapid coding scheme [5]. Using the current-based models they demonstrated that a population of neurons responds faster to a change in the level of fluctuations than to an increase in the direct drive. We find that a similar signalling mode exists for the conductance-based case when there is an increase of synchrony in the presynpatic population. However, an additional mode is also present in which a balanced increase in the excitatory and inhibitory drives can in some cases cause a *decrease* in the membrane potential fluctuations - again due to the competing conductance increase. This is reminiscent of the decrease in firing rate with increasing noise seen in simulations of Hodgkin-Huxley type neurons [6].

As mentioned above, there are special modes of behaviour for which the conductance and current-based IF neurons respond identically. However, it can be asked if the *general* response of the conductance-based case can be approximated in the existing framework of the current-based IF model, through parameter changes. Analytically we demonstrate that, as long as the conductance effect is taken into account by a dynamically changing membrane time constant, it is acceptable to neglect the voltage-dependence of the post-synaptic potentials. This approximation is compared with the Gaussian approximation [7] that has previously been used to examine the spike-train statistics of such models. We close with an examination of the implications of our results for the properties of networks built of IF neurons with conductance-based synapses.

Keywords: integrate-and-fire models, conductance changes, fluctuations.

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