Phase Locking States of Bidirectionally Coupled Spiking Neural Networks

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Macroscopic oscillations of different brain regions show phase relations that are persistent across time [5]. Termed as communication through coherence, such *phase locking* is believed to be implicated in a number of cognitive functions [7]. This suggests that there are mechanisms taking place at the cellular level that influence the network's dynamic and structure macroscopic firing patterns. The question is then to identify the biological properties of neurons that permit such motifs to arise. Unfortunately, there is not yet a method for studying macroscopic phase locking, and one of the central issues we face in mathematical neuroscience is to bring about a clear understanding of the synaptic mechanisms responsible for its emergence.

To address this issue, we use a semi-analytic modeling approach. We investigate the dynamical emergence of phase locking within two bidirectionally delayed-coupled spiking networks. While not explicitly a model of any specific brain areas, the design essentially captures many communicating cortical and sub-cortical regions where macroscopic locking takes place. The circuits are made up of excitatory and inhibitory cells coupled in an all-to-all fashion. Each cell is described by a well-established conductance-based model – the quadratic integrate-and-fire – which is known to replicate the dynamical features of neural voltage [6]. Taking advantage of a mean-field approach combined with an exact reduction method [3,8], we break down the description of each spiking network into a low dimensional nonlinear system. Bifurcation analysis of the reduced system enables us to reveal how synaptic interactions and inhibitory feedback permit the emergence of macroscopic rhythms. The adjoint method is then applied, and a semi-analytical expression of the macroscopic infinitesimal phase resetting-curve is derived [2,4].

From there, we study the dynamical emergence of macroscopic phase locking of two bidirectionally delayed-coupled spiking networks within the framework of weakly coupled oscillators [1,9]. The fundamental assumption at the core of this theoretical setting is that synaptic projections from one circuit to another are sufficiently weak. The weak coupling condition allows us to abbreviate the bidirectionally coupled circuits description into a phase equation [1,9]. This simplification significantly reduces the complexity of the interacting macroscopic oscillations, making them mathematically tractable, while at the same time capturing crucial principles of phase locking. An analysis of the phase equation sheds new lights on the synaptic mechanism enabling circuits to bound together, and it uncovers the determinant part played by delay and coupling strength upon the dynamical rise of a variety synchronization modes. For instance, we show that the delay is a necessary condition to get a symmetry breaking, i.e. a non-symmetric phase shift between the macroscopic oscillations. We also find that this effect can easily be controlled by the synaptic weights of the pyramidal neurons.

References

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