Local phase synchronization and clustering for delayed phase coupled oscillators in k-nearest-neighbors network

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Numerous experiments using different recording techniques have revealed that the human brain displays clustered correlation patterns in its spontaneous activities. Understanding the mechanism of cluster synchronization phenomena is crucial, as it may provide insights into underlying brain functions and brain diseases. Among a variety of network parameters that affect the correlation between brain areas' activity, the role of delay has been the subject of extensive research in recent years. It is common knowledge that time delays in signal transmission in neuronal systems primarily depend on inter-areal distance, the presence or absence of myelination, as well as synaptic and dendritic processes.

In this study, we investigated clustering and local phase synchronization in a system of a generalized Kuramoto model on a ring network, where each phase oscillator is coupled to number of its nearest neighbors. We assumed that the interactions take place through a finite time delay that is dependent on the distance of the nodes on the ring and we hypothesized that such distance-dependent delays in neuronal systems may contribute to the emergence of clustered correlation patterns in brain activities. We determined the dynamical behavior of this model for different numbers of oscillators, connected neighbors, and different values for delays.

We found that correlation patterns between pairs of oscillators are generally dependent on the time delay. The phase difference between each oscillator and its neighbors depends on the value of the interaction delay. The main finding was that in presence of multiple connections with different delays, the competition between different connections leads to breaking translational symmetry of the network and emergence of clusters of synchronized oscillators.

Our key finding reveals that time delays, and in particular, distant dependent delays play a significant role in shaping correlation patterns and phase synchronization in neuronal networks. This understanding could have implications for controlling synchronization in neuronal networks, neuromodulation, and brain stimulation.

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