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Spatiotemporal patterns and chaotic burst synchronization in a small-world neuronal network

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Abstract

The spatiotemporal patterns and chaotic burst synchronization of a small-world neuronal network are studied in this paper. The synchronization parameter, similarity parameter and order parameter are introduced to investigate the dynamics behaviour of the neurons. Chaotic burst synchronization and nearly complete synchronization can be observed if the link probability and the coupling strength are large enough. It is found that with increasing link probability and the coupling strength chaotic bursts become appreciably synchronous in space and coherent in time, and the maximal spatiotemporal order appears at some particular values of the probability and the coupling strength, respectively. The larger the size of the network, the smaller the probability and the coupling strength are needed for the network to achieve burst synchronization. Moreover, the bursting activity and the spatiotemporal patterns are robust to small noise.

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Keywords: Small-world neural network; Burst synchronization; Spatiotemporal pattern; Complex propagation

1. Introduction

Brain is a complex network that can extract and integrate various information perfectly from external and internal stimuli. It has been proven that the mammals' structural network of regional cerebral cortex demonstrates properties of complex networks from the experiments on animals and others [1–3]. A single neuron in the vertebrate cortex may connect to more than ten thousands postsynaptic neurons via synapses in the forming of complex neural networks [4]. Therefore, it is necessary to employ networks to investigate the complex spatiotemporal behaviour of neural systems observed in the brain cortex.

In recent years, much attention has been paid to dynamical processes in complex networks [5–8]. Small-world networks [9,10] and scale-free networks [11] have been studied extensively because their properties seem to be

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a quantifiable characteristic of many real-world structures, such as social, electronic communication or biological networks [12–16]. There is a small-world brain network [17]. The brain is a complex network on multiple spatial and time scales. It supports both segregated and distributed information processing. Network architecture is regarded as a key substrate for sensorimotor and cognitive processing, which may be localized discretely in specialized regions or represented by coherent oscillations in large-scale distributed systems. Small-world topology comprises both high clustering (compatible with segregated or modular processing) and short path length (compatible with distributed or integrated processing). Eguiluz et al. have used functional magnetic resonance imaging (fMRI) to extract functional networks connecting correlated human brain sites [18]. Analysis of the resulting networks in different tasks shows that the distribution of functional connections and the probability of finding a link versus distance are both scale-free. Moreover, it displays the typical properties of small-world networks because of the small characteristic path length and the large clustering coefficient. Synchronization of small-world networks depends not only on their structure but also on the type of couplings [19]. It is found that small-world networks of nonidentical Hodgkin–Huxley (HH) coupled by excitatory synapses can give rise to a fast system response with coherent oscillations [20].

Increasing the randomness of the network topology leads to an enhancement of the temporal coherence and spatial synchronization of the phenomenon. Spatial synchronization increases as characteristic path length shortens and firing frequency increases as clustering coefficient decreases [21]. The spatial synchronization and coherence in a complex network of the chaotic modified Hodgkin–Huxley (MHH) thermo-sensitive neurons have also been studied by Gong et al. [16]. They found that the synchronization and coherence which are absent in regular networks can be greatly enhanced by random shortcuts between the neurons. He et al. investigated pattern formation of spiral waves in an inhomogeneous excitable medium with small-world connections [22]. It is found that a well behaved spiral wave can be formed against the destructive role of the inhomogeneous medium with small-world connections which can not survive in the given inhomogeneous medium with completely local regular connections or completely random connections. In addition, Lü et al. introduce a new concept of synchronizability matrix to characterize the maximum synchronizability of small-world dynamical networks. Several new concepts, such as sensitive edge and robust edge, are proposed for analyzing the robustness and fragility of synchronization of a network [23].

In neural systems, different neurons connected to another group of neurons will receive a common input signal, which often approaches a Gaussian distribution as a result of integration of many independent synaptic currents [24]. A group of neurons can respond collectively to a common synaptic current due to synchronization. Noise can induce phase synchronization and complete synchronization [25]. Clinically, the connection between burst and synchronization is extremely important, since synchronization in large neural populations is widely viewed as a hallmark of seizures. Taking account of two schemes for encoding information (that is, rate coding and temporal coding), two types of rhythm synchronization of coupled neurons – spike and burst synchronizations – are studied in Ref. [26]. It is shown that the temporal encoding scheme, which is closely related to both the spike and burst synchronizations, is more comprehensive than the rate coding scheme. It is also found that the spike synchronization is equivalent to the phase synchronization and the burst synchronization occurs prior to spike synchronization for coupled neurons. It is well known that bursts of spikes, as opposed to single spikes, are considered to enhance the reliability of communications between neurons by facilitating transmitter release. For example, mammalian neurons fire bursts to increase the reliability of synaptic transmission [27]. In order to understand neural information processing in the brain, it is necessary to explore how burst synchronization appears or disappears in a neuronal network.

Here we study the burst synchronization in a small-world network of a chaotic HR neuron model with electrical coupling in a noisy environment. We mainly focus on how the topological probability, defined as the fraction of random shortcuts, the coupling strength and the noise intensity affect the spatiotemporal evolution of small-world neuronal networks. With increasing number of shortcuts from zero, we observe chaotic burst synchronization and nearly complete synchronization in the small-world network. Similar results can be obtained if the coupling strength is large enough. However, the burst synchronization cannot be enhanced when the noise is increasing.

Accordingly, the rest of this paper is organized as follows. In Section 2, we introduce a small-world network of chaotic HR(Hindmarsh–Rose) neurons with noise. In Section 3, the appearance of chaotic burst synchronization and nearly complete synchronization in this small-world network is investigated. The effects of the probability, coupling strength and noise strength on the small-world network are discussed, respectively. Finally, the conclusion is made in Section 4.