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Stochastic resonance in small-world neuronal networks with hybrid electrical–chemical synapses

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ABSTRACT

The dependence of stochastic resonance in small-world neuronal networks with hybrid electrical–chemical synapses on the probability of chemical synapse and the rewiring probability is investigated. A subthreshold periodic signal is imposed on one single neuron within the neuronal network as a pacemaker. It is shown that, irrespective of the probability of chemical synapse, there exists a moderate intensity of external noise optimizing the response of neuronal networks to the pacemaker. Moreover, the effect of pacemaker driven stochastic resonance of the system depends largely on the probability of chemical synapse. A high probability of chemical synapse will need lower noise intensity to evoke the phenomenon of stochastic resonance in the networked neuronal systems. In addition, for fixed noise intensity, there is an optimal chemical synapse probability, which can promote the propagation of the localized subthreshold pacemaker across neural networks. And the optimal chemical synapses probability turns even larger as the coupling strength decreases. Furthermore, the small-world topology has a significant impact on the stochastic resonance in hybrid neuronal networks. It is found that increasing the rewiring probability can always enhance the stochastic resonance until it approaches the random network limit.
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1. Introduction

Noise is inevitable and plays a vital role in nonlinear dynamical systems. One typical representative of noise effects is stochastic resonance (SR), which occurs when the response of a nonlinear dynamical system to a weak periodic signal is optimized by a moderate intensity of random fluctuations [1–3]. Due to its wide applications, stochastic resonance has been extensively investigated in many different fields, particularly in neural systems [4–10]. Experimental and theoretical researches have shown that the ability of sensory neurons to process weak input signals can be significantly enhanced by adding noise to the system [11–14]. Additionally, it is demonstrated that the signal propagation in coupled neural systems is largely improved by external noise via stochastic resonance [15–17]. Therefore, it is important to study stochastic resonance for understanding the signal transmission and information propagation in neuronal networks.

Recently, stochastic resonance in complex neuronal networks has attracted more and more attentions [18–22]. The small-world network, a typical complex network topology proposed by Watts and Strogtz, can capture main characteristics of many real-world networks [23]. By now, a series of empirical studies have shown the existence of small-world architecture in many structural and functional brain networks of humans and animals [24–27]. Compared with regular networks and random networks, the small-world architecture exhibits a relative short length path but along with a high clustering coefficient [23]. With these properties, the small-world topology has many dynamical advantages, such as enhancing the signal propagation speed, computational power, and synchronizability of neural systems [19,28,29]. In recent years, stochastic resonance in small-world neuronal networks

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has been extensively studied [30–32]. It has been reported that the effect of coherence and stochastic resonance in neural networks with small-world topology depends largely on the fraction of rewired links [33,34]. Moreover, Perc has studied the stochastic resonance on excitable small-world neuronal networks via a pacemaker, and found that the small-world topology is able to enhance the stochastic resonance only for intermediate coupling strengths [30].

In neural systems, neurons connect to others via two different types of synapses, the electrical and chemical ones [35]. The coupling of electrical synapse works through gap junctions, and its strength depends linearly on the difference between membrane potentials [36]. While for the chemical synapse, coupling acts through neurotransmitters, which is generated from pre-synaptic to post-synaptic neuron. The chemical coupling occurs only when the pre-synaptic neuron generates an action potential and its strength decays exponentially afterward [37,38]. Both types of synapses are found in biological neural systems [39,40]. In the study of three coupled neurons with common Gaussian white noise, it is conveyed that chemical coupling is more efficient than electrical coupling for the local signal input [16]. Furthermore, as empirical studies have shown that electrical and chemical synapses can coexist in a network [41], the dynamics of neuronal networks with hybrid electrical-chemical synapses has been broadly studied recently. For example, stochastic and vibration resonance in neuron populations with hybrid synapses have been investigated [42,43]. On the other hand, synchronization, as an emerging phenomenon of a population of dynamically interacting units, has also been widely studied in hybrid neuronal networks [44,45]. For instance, Yu et al. have studied delay-induced synchronization transitions in small-world neuronal networks with hybrid electrical and chemical synapses, and found that these two types of synapses can perform complementary synchronization roles [46]. Therefore, it is necessary to explore the role of each type of synapses in the signal detection and propagation based on a hybrid synaptic neuronal network via stochastic resonance.

In this work, we will study the phenomenon of stochastic resonance in small-world neuronal networks coupled via hybrid electrical-chemical synapses. All neurons are subjected to the external noise, while only one neuron is stimulated as a pacemaker. We will explore the dependence of stochastic resonance of the system on the probability of chemical synapse as well as the network structure. The remainder of this paper is organized as follows: In Section 2, the mathematical model of the considered neuronal network is introduced. Main results are presented in Section 3, in which the stochastic resonance in small-world neuronal networks with hybrid synapses is discussed. Finally, a brief conclusion is drawn in Section 4.

2. Mathematical model and setup

The two dimensional Rulkov map [47] is employed to describe the neuronal dynamics. Due to its low dimension and simplicity, the model can be operated at low computational costs, but also capture the main dynamical features of neuron in complex networks. According to [46], the temporal evolution of each unit can be described by the following set of discrete equations:

$$x_i(n+1) = \frac{\alpha}{1+x_i^2(n)} + y_i(n) + I_i^{syn}(n) + \sigma\xi_i(n) \tag{1}$$

$$y_i(n+1) = y_i(n) - \beta x_i(n) - \gamma \tag{2}$$

where $x_i(n)$ is the fast dynamical variable representing the neuron membrane potential, and $y_i(n)$ is the slow variable denoting the slow gating process, which is due to the small values of parameters $\beta = \gamma = 0.001$. n is the discrete time index. The parameter α is crucial for the dynamics of a neuron: for $\alpha < 2.0$, all neurons are excitable; whereas $\alpha > 2.0$, these neurons can exhibit spikes or bursts. Thus, we choose $\alpha = 1.95$ so that all neurons are excitable. Each neuron is initiated from fixed point $(x^* = -1, y^* = -1 - (\alpha/2) = -1.995)$. $\xi_i(n)$ is Gaussian noise with zero mean and intensity σ. The synaptic current $I_i^{syn}(n)$ comprises two parts: the electrical and chemical ones, i.e., $I_i^{syn}(n) = I_{i,e}^{syn}(n) + I_{i,c}^{syn}(n)$.

In the case of electrical coupling,

$$I_{i,e}^{syn}(n) = g_e \sum_{j=1, j\neq i}^{N} C_e(i,j)(x_j(n) - x_i(n)), \tag{3}$$

where g_e stands for the electrical coupling strength. C_e is the electrical connectivity matrix: if neuron i couples to neuron j via an electrical synapse, then $C_e(i, j) = C_e(j, i) = 1$, otherwise $C_e(i, j) = C_e(j, i) = 0$, and $C_e(i, i) = 0$.

While for the chemical case,

$$I_{i,c}^{syn}(n) = g_c(x_i(n) - v) \sum_{j=1, j\neq i}^{N} C_c(i,j)\Gamma(x_j(n)), \tag{4}$$

where g_c is the chemical coupling strength. $v = 1.5$ guarantees all the chemical synapses considered in this paper are excitatory. C_c is the chemical coupling matrix: if neuron i is coupled to neuron j through a chemical synapse, then $C_c(i, j) = 1$, otherwise $C_c(i, j) = 0$, and $C_c(i, i) = 0$. Additionally, the chemical synaptic coupling function is defined as follow

$$\Gamma(x_j(n)) = 1/(1 + \exp\{-\lambda[x_j(n) - \Theta_s]\}), \tag{5}$$

where the parameter $\lambda = 30$ represents the constant rate for the onset of excitation. $\Theta_s = -1$ is regarded as the threshold. The pre-synaptic neuron is able to affect the post-synaptic one once the membrane potential of presynaptic one exceeds the threshold.

Based on Watts-Strogatz procedure [23], the small-world network, comprising $N = 200$ neurons, is initiated as a regular ring with $K = 6$ nearest neighbors. Then each edge in the network is rewired with the probability p. If $p = 0$, the network is regular, while that is completely random for $p = 1$. In the intermediate situation ($0 < p < 1$), the small-world network is obtained, as exemplified in Fig. 1. Generally, when $p > 0.3$, the topology is considered as a random one. Furthermore, from purely electrical synapses by changing electrical synapses to chemical ones with the probability f, a hybrid synaptic neuronal network is established.

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