Chaos, Solitons and Fractals 108 (2018) 15–24

Contents lists available at ScienceDirect

Chaos, Solitons and Fractals

Nonlinear Science, and Nonequilibrium and Complex Phenomena

journal homepage: www.elsevier.com/locate/chaos

Investigation of dynamical behaviors of neurons driven by memristive synapse

Ge Zhang[a], Chunni Wang[a,*], Faris Alzahrani[b], Fuqiang Wu[a], Xinlei An[c]

[a] Department of Physics, Lanzhou University of Technology, Lanzhou 730050 China
[b] NAAM-Research Group, Faculty of Science, King Abdulaziz University, Jeddah 21589, Saudi Arabia
[c] School of Mathematics and Physics, Lanzhou Jiaotong University, Lanzhou 730070,China

ARTICLE INFO

Article history:
Received 1 November 2017
Revised 11 January 2018
Accepted 11 January 2018

Keywords:
Synapse
Electrical activity
Memristor
Bifurcation

ABSTRACT

Synapse is an important bridge for receiving and encoding signals, and the description for synapse current is critical for further signal processing. This paper investigates the dynamical characteristic in isolated neuron and chain neuronal networks with memristive autapse or synapses, respectively. Autapse plays important role in modulating the electrical activities, and thus the information encoding is enhanced. Within the improved neuron model, memristor is used to map the modulation of synapse current. Within an isolated new neuron model with memory, the modes in electrical activities can be controlled by the synapse current completely. Bifurcation analysis is carried out and mode transition is discussed. Furthermore, the modulation of synapse current on chain network is investigated, and the dependence of wave propagation on intensity of synapse is discussed. The diversity in synapse current can suppress the synchronization approach on the network.

1. Introduction

Accompanied by developing artificial intelligence, more researchers begin to investigate the potential mechanism of signal processing in brain [1–5]. Some neuroscientists discussed the retrieval methods, according to information encoded and transmitted in neural network [6,7], which is helpful to understand the dynamical behavior of the brain and application of artificial intelligence. Up to now, the investigation in brain science and artificial intelligence field has become attractive topics when it accounts for the mechanism about learning, memory, choosing and cognition in neuronal networks. Based on some mathematical and biological neuron models, memory effect and electromagnetic induction are considered [8–11]. It is important to discuss the connection topology between neurons, physical processing and encoding mechanism in electrical activities of neurons. The intelligent algorithm of like brain can help to create and improve the deep learning calculating and theory [12–14], the application technology like brain can design the intelligent controller and equipment [15,16]. Indeed, there is a capacity of storing up many information in single neuron and cooperation between neurons can enhance the ability of signal encoding with respect to detection of action potentials with singe-neuron sensitivity, the sensor composed of quantum defects within a diamond chip, detects mechanism of time-varying magnetic fields generated by action potentials [17]. Therefore, it is challengeable to design more effective neural network for rapid and exact signal processing. The formation of memory and learning mechanism have been discussed and the biological function of synapse can be understood [18]. Santiago et al. [19] claimed that memory stems from and is up to synapses, and it is possible that a large amount of synapse and various intensity of connection is to basic for leaning in brain. Carney et al. [20] summarized the principle of learning and memory in cell, and they confirmed that the varied intensity of synapses is enough to change the structure of neuronal network originally and ability of dealing with information, and short-term memory storage depend on time-length about increasing or decreasing intensity for synapses. In short, the synapse, the same as the neuron itself, plays an important role to understand dynamic characteristic and nature in brain.

The neuron in the nervous system is the basic functional unit for signal processing because the collecting, sorting, storing and transferring information can be accomplished by neurons. In the terms of information transition, synapse is a significant structure that permits a neuron (the presynaptic neuron) to pass an electrical or chemical signal to another neuron (the postsynaptic neuron) [21–25]. On the other hand, autapse (a specific synapse developed from auxiliary loop) can enhance self-adaption of neurons, and

* Corresponding author.
E-mail addresses: wangchunni@lut.cn, wangcn05@163.com (C. Wang).

https://doi.org/10.1016/j.chaos.2018.01.017
0960-0779/

thus appropriate modes in electrical activities can be selected [26–31] when autaptic modulation is triggered. The autapse is classified into two types: electrical, chemical way combined axon with dendrite [32–34]. In experimental way, autapse is found in substantia nigra, and the autaptic modulation on electrical activities is analyzed to confirm the biological function of autapse connection. So, excitability is adjusted to reproduce the electrical activity of neural behavior are detected by emulating theoretical neuron model [35,36] driven by autapse. For the neural basket cell, the autaptic modulation is considered on Hodgkin-Huxley model by applying time-delayed feedback to the soma of the itself, is proposed to detect the dynamical response and potential biological function of autapse connection [37]. Particularly, Qin et al. [38] confirmed that local distribution of autapses and appropriate parameter setting in autapses can induce stable formation of target waves,and break up of target waves can develop spiral waves in the network. Song et al. [39] confirmed the positive contribution of autaptic modulation on synchronization in a forward feedback network. Excitability modulation is important to trigger mode transition in electrical activities. As mentioned by the researchers [8], autaptic modulation and neurons contribute to the collective signal encoding, the astrocytes also have supportive and protective functions to neurons. Seri et al. [40] confirmed that a population of small electron-dense subgranular layer cells can be derived from the astrocytes, and probably behave as a transient precursor in the formation of new neurons. That is to say, astrocytes help to produce new neurons in the adult mammalian hippocampus. Tang et al. [41] constructed a minimal neuron-astrocyte network model by connecting a neurons chain and an astrocytes chain and the results found that calcium wave propagation in astrocytes determines the propagation of seizure-like discharges (SDs) in the connected neurons. Reactive astrocytes are proposed and it may provide a permissive substratum to support axonal regrowth after an injury to the CNS in recently studies [42,43].

Based on the neuron models, some researchers thought that neural circuits [44,45] can also be effective to understand the mechanism for signal processing. For example, the synchronization problems such as exponential stochastic, robust, have been investigated in neural networks with stochastic noise perturbations, mixed delay and uncertain parameters [46,47]. The spiking activities of neurons on 3D Morris-Lecar model is worthy of further investigating. Upadhyay et al. [48] discussed the dynamical synchronization, and took advantage of this model to interconnect by excitatory and inhibitory neurons with noisy electrical coupling synapse. Some researchers confirmed that the behavior of memristor is similar to those described by synapse [49,50]. In the electrical-biological term, the nonvolatile nature of memristor makes them an attractive candidate for the simulated synapses. Chain network is effective to describe the collective behaviors in a large number of neurons, for example, La Rosa et al. [51] observed the arising of a new slow regular rhythm along the chain of unidirectional coupled neurons whose individual dynamics is periodic spiking, and the transition from a irregular spiking-bursting regime to a regime with regular bursts is detected. Fortuna et al. [52] presented some appealing applications of Cellular Neural Networks (CNNs) to illustrate complex image, visual and spatio-temporal dynamics processing. Panahi et al. [53] suggested an effective way to describe epilepsy behavior based on chaotic artificial neural network.

Therefore, motivated by the above discusses, we will confirm that synapse with the memristor of characteristic can be employed to the neuron models. The electrical activity of neuron is detected by observing the time series of membrane potential and calculating bifurcation diagram for parameters. Development of spatiotemporal patterns, based on the two bidirectional coupling-neurons by the memristive synapses, will be discussed. That is, electromagnetic induction and radiation, injury in neuron [54] can cause disturbance and even attack on neuronal activities. Seriously, some nervous diseases can be induced due to the blocking in signal propagation and encoding in neuronal activities. Most of the presented neuron models emphasize the contribution from ion currents across the membrane potentials induced by exchange of charged ions. However, effect of electromagnetic induction and injury on neuron is missed. Indeed, both electromagnetic induction, radiation, blocking in ion channels-induced injury can cause imperfect on neurons, and the presented models should be improved to describe the damage effect. In a word, improved neuron model should consider the imperfect effect so that the mode transition, synchronization and pattern stability on neuronal network can be estimated in exact way.

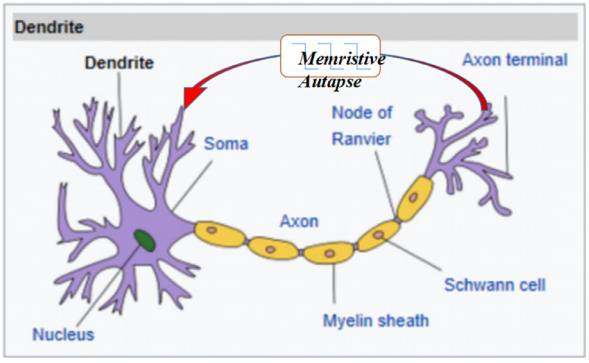

Fig. 1. Structure of a typical neuron with memristive autapse.

2. Model descriptions

A neural unit has three major factors, involving the dendrite to collect electrical signals, the nucleus and soma to encode information, and the axon to propagate electrical signals to dendrites of another cell. Synapse is just responsible for this coupling function between two neurons by linking the presynaptic axon terminal to the anterior membrane of dendrite. Autapse is a class of specific synapse which connects to its body via a close loop. As confirmed in Ref. [54], the formation of autapse could result from injury in axon and thus an auxiliary loop is developed to help signal propagation and self-adaption of neuron is enhanced. In most of previous works, the gain in autapse is fixed though the memory effect can be described by the variable of magnetic flux. The magnetic flux is time-varying when the electromagnetic filed is changed continuously. Inspired by the scheme in Refs. [55,56], magnetic-controlled gain in autapse is proposed to model the synapse current by using memristor coupling. In this way, a reduced diagram is plotted for a new neuronal model with a memristive autaptse connection, and a self-delayed feedback is triggered in Fig. 1.

Considering the dynamic state of Hopfield-type model, FitzHugh et al. [57] developed the FitzHugh–Nagumo model by using the Bonhoeffer-van der Pol model in 1961. It suggests that the oscillating variable x is also modulated by a damping function depended on quadratical nonlinear term x, and the dynamical equation is described by

$$\frac{d^2x}{dt^2} - \frac{1}{a}\left(1 - x^2\right)\frac{dx}{dt} + x = 0 \tag{1}$$

where $1/a$ is a positive constant, and $(1 - x^2) / a$ represents nonlinear function dependent on the variable x. For available dynamical analysis, an auxiliary variable y is used to approach a two-variable