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A digital implementation of neuron–astrocyte interaction for neuromorphic applications

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ABSTRACT

Recent neurophysiologic findings have shown that astrocytes play important roles in information processing and modulation of neuronal activity. Motivated by these findings, in the present research, a digital neuromorphic circuit to study neuron–astrocyte interaction is proposed. In this digital circuit, the firing dynamics of the neuron is described by Izhikevich model and the calcium dynamics of a single astrocyte is explained by a functional model introduced by Postnov and colleagues. For digital implementation of the neuron–astrocyte signaling, Single Constant Multiply (SCM) technique and several linear approximations are used for efficient low-cost hardware implementation on digital platforms. Using the proposed neuron–astrocyte circuit and based on the results of MATLAB simulations, hardware synthesis and FPGA implementation, it is demonstrated that the proposed digital astrocyte is able to change the firing patterns of the neuron through bidirectional communication. Utilizing the proposed digital circuit, it will be illustrated that information processing in synaptic clefts is strongly regulated by astrocyte. Moreover, our results suggest that the digital circuit of neuron–astrocyte crosstalk produces diverse neural responses and therefore enhances the information processing capabilities of the neuromorphic circuits. This is suitable for applications in reconfigurable neuromorphic devices which implement biologically brain circuits.

1. Introduction

Astrocytes, the predominant type of glial cell in the central nervous system (CNS), have long been believed to provide only structural and metabolic supports (Koizumi, 2010). However, recent researches have demonstrated that astrocytes intervene actively in information processing and control of synaptic transmission (Kuga, Sasaki, Takahara, Matsuki, & Ikegaya, 2011; Papa, De Luca, Petta, Alberghina, & Cirillo, 2014). Bidirectional communications between astrocytes and neuronal cells are necessary for the normal functioning of the nervous system during signal processing (Dallérac, Chever, & Rouach, 2013). Although astrocytes cannot generate action potentials, they respond to neuronal activities with an elevation of their intracellular calcium levels. In this way, astrocytes can respond to neurotransmitters with calcium elevations that lead to the *release* of gliotransmitters including glutamate or ATP and generate feedback signals to neurons in order to modulate synaptic transmission between nearby neurons, neuronal excitability and to an extent also plasticity (Linne & Jalonen, 2014; Reato, Cammarota, Parra, & Carmignoto, 2012; Sasaki, Kuga, Namiki, Matsuki, & Ikegaya, 2011). In this way, the astrocyte "listens and responds" to the synapse and regulates normal operation of synapses via astrocytic mechanisms (Fellin, 2009; López-Hidalgo & Schummers, 2014). In recent studies, several analog and digital brain-inspired electronic systems have been recently proposed as dedicated solutions for fast simulations of spiking neural networks (Joshi, Parker, & Hsu, 2009; Pfeil et al., 2013). While the interest in understanding the biological operations and computational modeling of neuron–astrocyte signaling is continuously increasing, the neuromorphic neuron–astrocyte cross-talk circuit is less studied (Amiri, Bahrami, & Janahmadi, 2012a, 2012b; Amiri, Hosseinmardi, Bahrami, & Janahmadi, 2013a; Nazari et al., 2014). An increasing interest in neuron–astrocyte signaling has paralleled our development of neuromorphic circuits incorporating astrocytes (Joshi, Parker, & Tseng, 2011). Therefore, it is essential to develop digital and analog circuits which consider neuron–astrocyte signaling.

Although, the focus of this paper is to propose a digital neuron–astrocyte circuit to verify that the circuit can produce similar

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responses as the biophysical model does, we present a first step in an ongoing effort to integrate the functional contribution of astrocytes in neuromorphic engineering which can be used as a platform for developing and emulating simple brain like computing system (Ambroise, Levi, Joucla, Yvert, & Saïghi, 2013; Cassidy, Georgiou, & Andreou, 2013). This also supports to understand how the astrocytes shape the neural information processing from hardware point of view. Therefore, in the present research, we have implemented a functional approach to develop a digital neuromorphic circuit and to explore the feasibility of using field-programmable gate arrays (FPGA) for implementing bidirectional communication neuron–astrocyte. Neuromorphic VLSI is an important tool for investigating and implementing neural algorithms. Recent studies in computational intelligence have shown a strong tendency towards a better understanding of biological systems and the details of neuronal signal processing. Such research is motivated by the desire to form a more comprehensive understanding of information processing in biological networks and to investigate how this understanding could be used to improve traditional information processing techniques (Misra & Saha, 2010). When we implement biological networks on hardware, we can take full advantage of their inherent parallelism and run orders of magnitude faster than software simulations, becoming thus, adequate for real-time applications. Since VLSI implementation cannot be reconfigured easily (Indiveri & Horiuchi, 2011; Wijekoon & Dudek, 2012), here we chose FPGAs for hardware implementation. FPGAs are devices that permit the implementation of digital systems, providing an array of logic components that can be configured in a desired way (Sepulveda, Muñoz, Espinoza, Figueroa, & Melin, 2013). The device is reconfigurable such that a change to the system is easily achieved. Previous work has indicated that these devices provide a suitable platform for designing neuromorphic systems (Li, Cheung, Chan, Song, & Berger, 2013; Rice, Bhuiyan, Taha, Vutsinas, & Smith, 2009). Recently, some researchers have made full use of parallelism characteristics of FPGA to process neural signal and dramatically improved the computation speed. Arthur et al. (2012) fabricated a building block of a modular neuromorphic architecture using the FPGA as a simulation tool. This approach consists of 256 integrate-and-fire neurons and a 1,024_256 SRAM crossbar memory for synapses, so that the core is fully configurable in terms of neuron parameters, axon types, and synapse states. Wang et al. (2013) presented an FPGA implementation of a re-configurable, polychronous spiking neural network. They used a time multiplexing approach to implement 4096 (4k) neurons and up to 1.15 million programmable delay axons on a Virtex 6 FPGA. Bonabi, Asgharian, Safari, and Ahmadabadi (2014) presented efficient implementation of Hodgkin–Huxley-based (H–H) model of a neural network on FPGA. They employed different techniques such as sharing resources, CORDIC algorithm and can provide an opportunity to construct large FPGA-based network models to investigate the effect of different neurophysiological mechanisms. Indeed, trying to mimic biology, neuro-inspired systems have been extended in the recent years. High degree of parallelism and scalability makes this emerging computing technology especially interesting for real time applications.

The rest of this paper is organized as follows: In Section 2, the dynamic model of the astrocyte, the biological description of the Izhikevich neuron model, and its interaction with the astrocyte are covered. The digital circuits for neuron, astrocyte and the coupled neuron–astrocyte are described in Section 3. The MATLAB, ModelSim simulations and FPGA implementations are presented and discussed in Section 4. Finally, Section 5 concludes the paper.

2. Dynamic models of neuron and astrocyte

In this section, we first present the mathematical description of the astrocyte and then we explain the Izhikevich dynamic model of neuron.

2.1. The astrocyte model

Astrocytes, the dominant glial cell type, have become the focus of much attention in the past two decades. In addition to their roles in many of the supportive functions of the brain, new functions are beginning to emerge. Abundant evidence now supports the notion that astrocytes are actively involved in synaptic transmission in most brain regions (Halassa, Fellin, & Haydon, 2009; Volterra, Liaudet, & Savtchouk, 2014). Although astrocytes cannot elicit propagating action potentials (APs) like neurons do, their "unit of excitation" is the transient increase in intracellular calcium (Ca^{2+}) levels that is elicited by various neurotransmitters (e.g., glutamate, ATP, etc.). These astrocytic Ca^{2+} transients in turn lead to astrocytic release of transmitters (often referred to as "gliotransmitters") and to propagating Ca^{2+} waves (Di Castro et al., 2011; Giugliano, 2009; Newman, 2003). Astrocytes also communicate in a feedback mode with neurons. In response to elevated levels of intracellular Ca^{2+}, astrocytes can release gliotransmitters such as glutamate which bind to extrasynaptic receptors on the post synaptic neuron (Colangelo, Alberghina, & Papa, 2014; Corlew, Brasier, Feldman, & Philpot, 2008). This bidirectional communication between astrocytes and neurons indicates that astrocyte is a third signaling element at the "tripartite synapse" (Fellin, Pascual, & Haydon, 2006; Newman, 2003) that is shown in Fig. 1.

Postnov and colleagues introduced a mathematical model of the astrocyte that models the dynamics of the intracellular Ca^{2+} waves (Postnov, Koreshkov, Brazhe, Brazhe, & Sosnovtseva, 2009). This is a generalized and simplified mathematical model for a small neuron–astrocyte ensemble which considers the main pathways of bidirectional neuron–astrocyte signaling. Consequently, this model will be useful to study the main types of astrocyte response to neural activities and the resulting dynamical patterns and thereby, it will allow us to predict their changes with varying control parameters. This model is explained with the following set of equations (Postnov et al., 2009)

$$\tau_c \frac{dc}{dt} = -c - c_4 f(c, c_e) + (r + \beta S_m) \tag{1}$$

$$\varepsilon_c \tau_c \frac{dc_e}{dt} = f(c, c_e) \tag{2}$$

$$f(c, c_e) = c_1 \frac{c^2}{1 + c^2} - \left(\frac{c_e^2}{1 + c_e^2}\right)\left(\frac{c^4}{c_2^4 + c^4}\right) - c_3 c_e \tag{3}$$

$$\tau_{Sm} \frac{dS_m}{dt} = (1 + \tanh[S_{Sm}(z - h_{Sm})]) \times (1 - S_m) - \frac{S_m}{d_{Sm}} \tag{4}$$

$$\tau_{Gm} \frac{dG_m}{dt} = (1 + \tanh[S_{Gm}(c - h_{Gm})]) \times (1 - G_m) - \frac{G_m}{d_{Gm}}. \tag{5}$$

In these equations c and c_e are the calcium concentration in the astrocyte cytoplasm and within the endoplasmic reticulum, respectively. The calcium influx from the extracellular space is sensitive to the production of secondary messenger S_m (IP_3), which is controlled by the factor β. Interaction between cytoplasmic calcium and calcium in endoplasmic reticulum is defined by the nonlinear function $f(c, c_e)$. We set the control parameters r, β, τ_c, τ_{Sm}, τ_{Gm}, S_{sm}, S_{Gm}, h_{sm}, h_{Gm}, d_{sm}, d_{Gm}, ε_c to the values listed in Table 1. The values are taken from Amiri, Montaseri, and Bahrami (2011b); Amiri et al. (2012a); Postnov et al. (2009). As a result of augmentation of calcium concentration in the cytoplasm, astrocyte mediator G_m is released. The interaction between astrocyte and neuron is denoted with the parameter z (astrocyte input) that shows the synaptic activity of the neuron.

2.2. Neuron model

Izhikevich neuron model is a mathematical model that reproduces spiking and bursting behavior of known types of