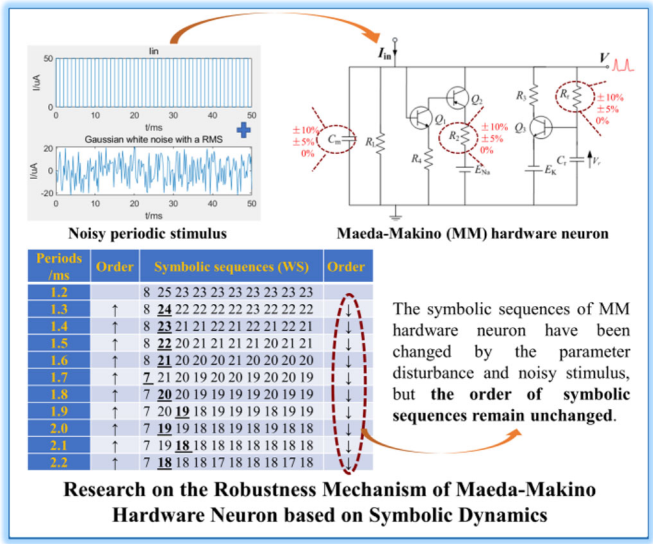
Research on the Robustness Mechanism of Maeda–Makino Hardware Neuron Based on Symbolic Dynamics

Guilei Ma, Menghua Man, Yongqiang Zhang, Xiaoyun Lu, and Shanghe Liu

***Abstract*—Noise permeates every level of the nervous systems, from single neurons to the whole system. However, the noise seems not to take so much trouble to neural information processing in contrast to the electronic system. The robustness of neural information processing inspired us to study the method of neuromorphic hardware systems to resist electromagnetic interference. The dynamics of the neuron model can reflect the inherent mechanism of neural information processing. In this work, we take the Maeda-Makino (MM) hardware neuron as an example to study the robustness mechanism of biological neuron information encoding based on symbolic dynamics. MM hardware neuron is a neuromorphic neuron circuit with biological plausibility. The simulation results show that MM hardware neuron can encode the order of current stimulus periods, even with parameter disturbance and noisy input signals which simulate the effects of electromagnetic interference on neuronal cell membrane permeability, sodium ion channels, potassium ion channels, and action potentials. Choosing a robust hardware neuron is the basis for building a neuromorphic hardware system that can resist electromagnetic interference. This letter not only verifies the robustness of using symbol sequence encoding but also provides an optional hardware neuron solution for neuromorphic hardware designed for anti-electromagnetic interference.**

***Index Terms*—Biological robustness, electromagnetic protection bionics, neural coding, symbolic dynamics.**



I. Introduction

THE ADAPTABILITY and reliability of electronic systems in electromagnetic environment urgently need to be improved, due to the challenges from two directions—the increased vulnerability of electronic systems on the one hand and the more electromagnetically hostile environment on the other [1]. Inspired by the biological robustness, Shanghe Liu has proposed the new research field of Electromagnetic Protection Bionics (EMPB) [2], [3]. The EMPB aims to investigate the mechanisms of biology systems against various unintentional or hostile interference, then apply these mechanisms to electronic systems based on bionic methods, to sustain a certain amount of electromagnetic interference (EMI) without malfunction or permanent damage.

Take-Home Messages:

- MM hardware neuron is an optional hardware neuron for neuromorphic hardware designed for anti-electromagnetic interference.
- The order of the symbolic sequences of MM hardware neuron is consistent with the order of frequency of the perodic stimuli, and contrary to the order fo periods.
- With a certain range of parameter fluctuations and electromagnetic noise interference, the order of the MM hardware neuron's winding symbolic sequence demonstrates remain unchanged.
- If the order of periods is disrupted by the Gaussian white noise, the order of symbolic sequences of MM hardware neuron might be disrupted.
- Neural coding based on symbolic sequences is an important mechanism for biological neuron to resist parameter fluctuations and noise interference.
- Choosing a hardware neuron with symbolic sequence coding is beneficial to improve neuromorphic hardware EMI immunity.

Manuscript received July 12, 2020; revised October 13, 2020; accepted January 20, 2021. Date of publication January 25, 2021; date of current version May 19, 2021. *(Corresponding author: Menghua Man.)*

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Digital Object Identifier 10.1109/LEMCPA.2021.3054239

Biological robustness describes the ability of the biology system to resist behavior change caused by external disturbances or internal parameter perturbation [4]. Exploring the underlying mechanisms producing biological robustness is the basis and premise for carrying out EMPB research [5]–[7]. In this consideration, researchers have studied the robustness of cell system [8] and nervous systems [9] under electromagnetic field disturbance and demonstrated numerous biological robustness mechanisms, such as redundancy [4], degeneracy [5], [10], evolution [11], neuronal synchronization [12], synaptic plasticity, human immunity mechanism [13]. Besides, the RadioBio program [14], [15] announced by the Defense Advanced Research Projects Agency (DARPA) has awarded several projects [15], [16] to investigate the biological robustness mechanisms under complex electromagnetic environment. According to some evidence, the validity of electromagnetic biosignaling has been revealed. The awarded research teams are learning how the structure and function of natural "antennas" are capable of generating and receiving information in a noisy, cluttered electromagnetic environment.

The nervous systems which exhibit rich robustness are the main bionic objects of EMPB. An accepted fact that noise is ubiquitous in nervous systems [17], it includes sensory noise, electrical noise, synaptic noise, and motor noise. Besides, environmental changes and artificial electromagnetic waves are surrounding the biological systems [18]. They interact with the nervous systems all the time, which can cause membrane-potential fluctuations, suppress neuronal firing activities [19], or even influence information transmission [17]. Yet, despite significant interference levels our nervous systems appear to function reliably [20] and can ensure the robustness of neural coding [21]. This fact inspires us to study EMPB based on neural coding.

In the field of neuroscience, it's widely accepted that information is encoded by the spike sequences (trains of action potentials) generated by neurons [22]. The symbolic dynamics of the spike sequences reflect the inherent mechanism of neural coding. Tong et al. have studied the symbolic dynamics of Hodgkin-Huxley neuron [23] and proposed the theory that neural information is encoded in ordination space so that we can quickly distinguish the loudness of the sound, the brightness of the light, the intensity of the smell, etc. In this letter, the same symbolic dynamics analysis method is adopted to explore the underlying mechanisms in a periodically driven MM hardware neuron under parameter disturbance and noise interference. So that some robustness mechanisms of neural coding can be acquired. In Section II, the MM hardware neuron model, and the symbolic dynamics of neuronal coding analysis are briefly introduced. In Section III, the results of how the symbolic sequences encode the period of the input current and symbolic sequences of the MM hardware neuron under the periodic current stimuli with noise are presented. Finally, a discussion of the results and a conclusion are given in Section IV.

II. Model and Method

A. Maeda–Makino (MM) Hardware Neuron Model

The MM hardware neuron model is a successful model which is a simple and physiologically plausible formulation of the Hodgkin-Huxley neural model [24], [25]. As in Fig. 1, V, C_{m}, R_{L}, and I_{in} represent the membrane potential, membrane capacitance, leakage resistance, the input current signal, respectively. The branches (a) and (b) correspond to the V-dependent inward sodium and the delayed outward potassium ionic channels of HH equation, E_{Na} and E_{K} correspond to sodium and potassium Nernst equilibrium potentials in HH, respectively. All the parameters are shown in Table I.

when the amplitude of I_{in} is 50uA, the period is 4ms, and the duty ratio is 50%, the output V of MM hardware neuron is shown in Fig. 2.

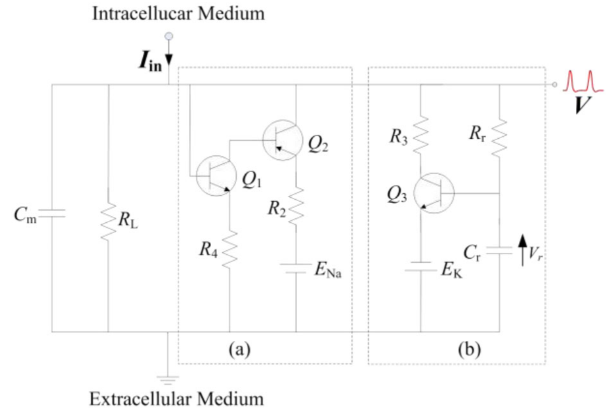

Fig. 1. MM hardware neuron model. The branches (a) and (b) correspond to the inward sodium and the slow outward potassium ionic channels, respectively.

TABLE I
PARAMETERS FOR THE MM HARDWARE NEURON

Parameters	Values
C_{m}	0.47uF
R_{L}	100kΩ
R_2	1kΩ
R_3	620Ω
R_4	100 kΩ
R_{r}	100 kΩ
NPN-type transistor	2N3904
PNP-type transistor	2N3906
E_{Na}	5V
E_{k}	-0.4V

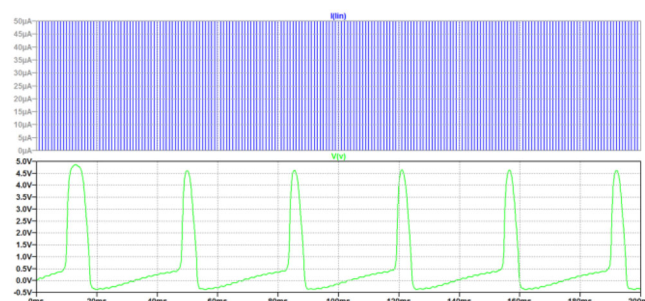

Fig. 2. Output of MM hardware neuron, when the amplitude of I_{in} is 50uA, the period is 2ms, and the duty ratio is 50%.

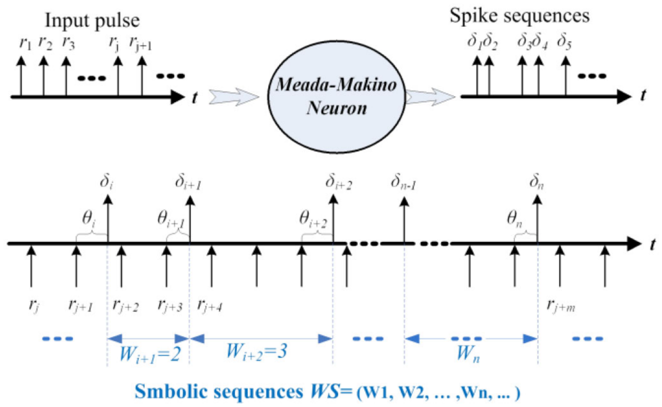

Fig. 3. Phase sequence $(\theta_1, \theta_2, \ldots, \theta_n)$. Note that r and δ are the a pulse of the periodic current stimulus and an action potential, respectively. θ_i is the phase of the i-th neuron spike δ_i in the periodic drive current.

B. Neural Coding Based on Symbolic Dynamics

Symbolic dynamics is an efficient method to reflect the mechanism of neural information processing in the nervous system [23]. In order to confirm whether the coding of MM hardware neuron can be analyzed with symbolic dynamics, the return map is introduced to study the phase sequence $(\theta_1, \theta_2, \ldots, \theta_i, \ldots, \theta_n)$ of the neuronal spike trains. As in Fig. 3, the variable θ_i represents the phase of the external current stimulation sampled stroboscopically at the spike of each action potential. We can draw the phase return map according to the phase shift function defined as $\theta_{i+1} = \mathrm{FS}(\theta_i)$ in Fig. 4. The dynamical states of (a) and (b) in Fig. 4 correspond to the phase-locking and quasiperiod, respectively. Therefore we can analyze neuronal spike trains with a symbolic method based on the winding numbers [23]. The winding number is the number of stimulus cycles between the adjacent spikes. We can covert the relationship between the periodic current stimulus and the neuronal spike sequence into a train of winding numbers, called winding symbolic sequence.

The steps of neural coding based on symbolic dynamics are as follows: (i) Take the winding numbers in chronological order. We use *WS* to denote the winding symbolic sequence $(W_1, W_2, \ldots, W_n, \ldots)$. (ii) Judge the orderable relationship of the winding symbolic sequences. Given two winding number symbolic sequences, $WS_1 = C{*}\alpha$ and $WS_2 = C{*}\beta$, where $C{*}$ denotes their common leading symbol and $\alpha \neq \beta$, the order of these two symbolic sequences is:

$$WS_1 > (<) WS_2, \text{ if } \alpha > (<) \beta \tag{1}$$

III. RESULTS

A. Neural Coding of the MM Hardware Neuron

The amplitude of the periodic pulse current I_{in} (Fig. 1) is chosen to be 50 μA. The width of the current waveform is set to be 50%. The period changes from 1.2 ms to 2.2 ms. We draw a conclusion that the phase return map of the MM hardware neuron is monotonically increasing within the period scope of 1.2ms-2.2ms. Following the steps of neural coding based on symbolic dynamics in part II.B, the symbolic sequences based on winding numbers under different periodic

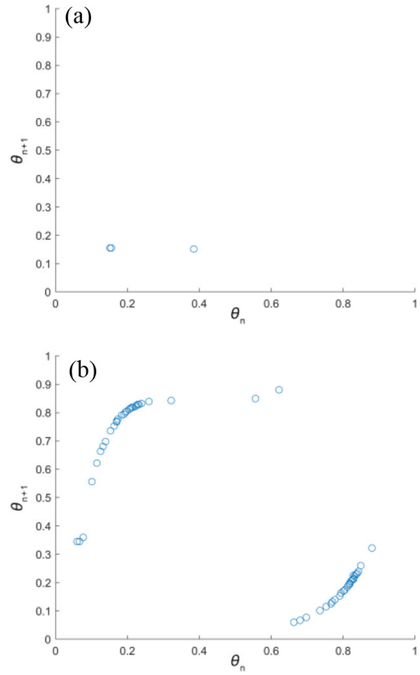

Fig. 4. Phase return maps under different dynamical states: (a) phase-locking, (b) quasiperiod, the two branches are monotonically increasing.

TABLE II
WINDING SYMBOLIC SEQUENCES UNDER DIFFERENT PERIODS

Periods/ms	order	Symbolic sequences (*WS*)	order
1.2		8 23 23 22 22 22 22 22 22 22	
1.3	↑	**7** 23 22 21 21 21 22 21 21 21	↓
1.4	↑	7 **22** 21 20 21 20 21 20 21 20	↓
1.5	↑	7 **21** 20 20 20 20 20 20 19 20	↓
1.6	↑	7 **20** 20 19 19 20 19 19 20 19	↓
1.7	↑	7 20 **18** 19 19 19 19 19 18 19	↓
1.8	↑	7 **19** 18 19 18 18 19 18 18 19	↓
1.9	↑	7 **18** 18 18 18 18 18 18 18 18	↓
2.0	↑	7 18 **17** 18 18 17 18 17 18 17	↓
2.1	↑	7 **17** 18 17 17 17 17 18 17 17	↓
2.2	↑	**6** 18 17 17 17 17 17 17 17 17	↓

current stimulus are shown in Table II. The symbols which are marked as both bold and underlined letters in the whole table are the first different symbols between the neighboring symbolic sequences. The order of these symbolic sequences is obvious according to the ordering rule defined in expression (1). Ascending order is indicated by '↑', and descending order is indicated by '↓', as is shown in Table II. The results show that the symbolic sequences are very sensitive to the change of the stimulus parameters. As the periods of the periodic current stimulus increase, the winding symbolic sequences decreases. In other words, the winding symbolic sequences encode the frequency order of the periodic current stimulus.

B. Neural Coding of the MM Hardware Neuron Under the Parameters Disturbance

Because of various disturbances in neural systems, such as the random opening of ion channels, fluctuations in

TABLE III
WINDING SYMBOLIC SEQUENCES UNDER DIFFERENT PARAMETERS DEVIATIONS ($C_{\mathrm{m}} = 527$nF (DEVIATED BY 10%), $R_2 = 950\Omega$ (DEVIATED BY -5%), $R_3 = 558\Omega$ (DEVIATED BY -10%))

Periods/ms	order	Symbolic sequences (*WS*)	order
1.2		8 25 23 23 23 23 23 23 23 23	
1.3	↑	8 **24** 22 22 22 22 23 22 22 22	↓
1.4	↑	8 **23** 21 21 22 21 22 21 22 21	↓
1.5	↑	8 **22** 20 21 21 21 21 20 21 21	↓
1.6	↑	8 **21** 20 20 20 21 20 20 20 20	↓
1.7	↑	**7** 21 20 19 20 20 19 20 20 19	↓
1.8	↑	7 **20** 20 19 19 19 19 20 19 19	↓
1.9	↑	7 20 **19** 18 19 19 19 18 19 19	↓
2.0	↑	7 **19** 19 18 18 19 18 19 18 18	↓
2.1	↑	7 19 **18** 18 18 18 18 18 18 18	↓
2.2	↑	7 **18** 18 18 17 18 18 18 17 18	↓

neurotransmitter release, and electromagnetic radiation, neuronal cell membrane permeability, sodium ion channel and potassium ion channel may be affected. Therefore, the trains of action potentials from neurons show instability and uncertainty. It's important to study the neural coding of the MM hardware neuron under the parameter disturbance. Therefore, we conducted experiments to investigate the effects on the neural coding of MM hardware neuron with the parameters of C_{m}, $R_{2,}$ and R_3 deviated by $\pm 10\%$, $\pm 5\%$, and 0%, respectively.

The consistent results obtained by simulating the MM hardware neuron with the parameters of C_{m}, $R_{2,}$ and R_3 deviated by -5%, -10%, and 5% respectively, are illustrated in Table III. Comparing the symbolic sequences in Table II, the symbolic sequences in Table III are changed under parameter disturbance, but the ordination of these symbolic sequences remain unchanged according to the ordering rule defined in expression (1). All experimental results indicate that neural coding of the MM hardware neuron is robust to parameters disturbance of C_{m}, $R_{2,}$ and R_3. The underlying robustness mechanism may greatly relate to the order rule of the symbolic dynamics based on the winding number. These results were also supported by the report of [23].

C. Neural Coding of the MM Hardware Neuron Under the Periodic Current Stimuli With Noise

The electromagnetic interference on circuits finally forms a transient interference voltage or current in transmission lines such as signal line, power, and ground. In order to investigate the neural coding of the MM hardware neuron under the periodic current stimulus with electromagnetic interference noise, gaussian white noise with Root Mean Square (RMS) ranging from 5uA $\sim$ 100uA is injected at the input of MM hardware neuron. Fig. 5(a) displays the periodic current stimulus with gaussian white noise with an RMS value of 25uA, and the period of the current stimulus is 2ms. The experimental results show that the symbolic sequences of the MM hardware neuron can sort the periods of the input current stimulus, although the stimuli are interfered by Gaussian white noise with RMS in the range of 5uA to 30uA. In another word, MM hardware neuron can process information exactly. As shown in

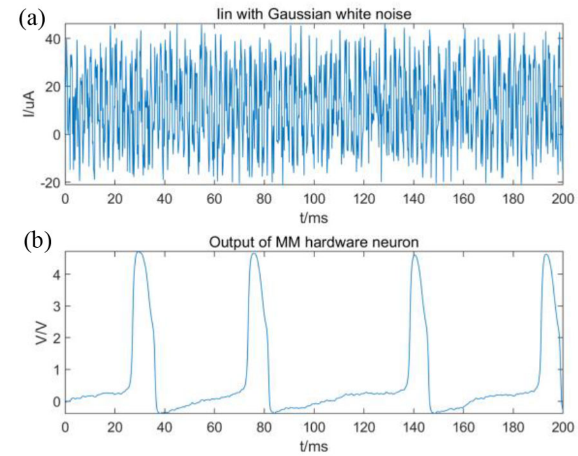

Fig. 5. (a) Periodic current stimuluse with Gaussian white noise with RMS value of 25uA, (b) the output of MM hardware neuron periodic current stimuluse with Gaussian white noise with RMS value of 25uA.

TABLE IV
WINDING SYMBOLIC SEQUENCES UNDER DIFFERENT PERIODS WITH GAUSSIAN WHITE NOISE WITH RMS VALUE OF 25UA

Periods/ms	order	Symbolic sequences (*WS*)	order
1.2		10 22 22 22 22 22 22 22 22 22	
1.3	↑	**9** 21 22 21 21 21 22 21 21 21	↓
1.4	↑	9 **20** 21 20 21 20 21 21 20 21	↓
1.5	↑	9 20 **20** 20 19 20 20 19 21 20	↓
1.6	↑	9 **19** 19 20 19 19 19 19 20 19	↓
1.7	↑	**8** 19 19 18 19 19 19 19 19 18	↓
1.8	↑	8 19 **18** 18 18 19 18 19 18 18	↓
1.9	↑	**7** 20 18 18 17 18 19 17 18 19	↓
2.0	↑	7 **17** 18 18 17 18 17 18 18 17	↓
2.1	↑	7 17 **17** 17 18 17 17 17 18 16	↓
2.2	↑	7 17 17 17 **17** 17 17 18 16 17	↓

Table IV, the gaussian white noise has a significant effect on the symbolic sequences comparing the data in Table II. Besides, as shown in Fig. 5(b), the time interval between spikes has increased comparing Fig. 2, and irregular fluctuation occurred in the part before each spike. However, the order of the symbolic sequences remains unchanged. These results highlight the robustness of neural coding based on symbolic dynamics. When the RMS of the Gaussian white noise reaches 50uA, the order of the symbolic sequences will be disrupted according to the symbols which are marked as both red bold and underlined letters in Table V, due to the order of periods is disrupted by the gaussian white noise. That is to say, as long as the noise does not affect the order of periods, the MM hardware neuron can encode the periods based on symbolic dynamics.

IV. DISCUSSION AND CONCLUSION

Hardware neurons are the basic computing units of neuromorphic hardware, and many hardware neurons which are simple and capable of producing rich firing patterns as biological neurons have been proposed by researchers, some most popular models: Maeda and Makino [24],

TABLE V
WINDING SYMBOLIC SEQUENCES UNDER DIFFERENT PERIODS WITH GAUSSIAN WHITE NOISE WITH RMS VALUE OF 50UA

Periods/ms	order	Symbolic sequences (*WS*)	order
1.2		10 22 22 22 21 22 22 23 22 22	
1.3	↑	**9** 22 21 22 21 21 21 21 21 22	↓
1.4	↑	**6** 24 20 21 20 21 20 21 20 21	↓
1.5	↑	**9** 20 19 20 20 20 20 20 20 19	↑
1.6	↑	9 **19** 19 18 20 19 19 20 19 20	↓
1.7	↑	**8** 19 19 18 19 19 18 19 18 20	↓
1.8	↑	8 **18** 19 18 18 18 19 18 18 18	↓
1.9	↑	8 18 **18** 17 18 19 17 18 19 17	↓
2.0	↑	**7** 18 18 18 17 18 17 17 18 17	↓
2.1	↑	**8** 17 17 17 17 17 17 17 17 18	↑
2.2	↑	8 **16** 18 16 17 17 17 17 17 17	↓

Integrate-and-fire [26], Hindmarsh-Rose [27], Wijekoon and Dudek [28] and Babacan *et al.* [29]. For building neuromorphic hardware with anti-interference ability, it is very necessary to design and choose a robust hardware neuron. The paper takes MM hardware neuron as an example to demonstrate a robust mechanism of the biological neurons and artificial neuron circuits against interference and discusses the reason why the neural coding of MM hardware neuron is robust against parameter disturbance and input noise. On one hand, the MM hardware neuron can encode the input signal periods based on symbolic dynamics, these results are consistent with the symbolic dynamics of the Hodgkin-Huxley neuron [23], which once again proves the theory that biological neurons can encode information in ordination space. On the other hand, to a certain extent, the value disturbance of C_m, R_2, and R_3 and the input signal with noise simulate the effects of electromagnetic interference on neuronal cell membrane permeability, sodium ion channels, potassium ion channels, and action potentials. The simulation results indicate that the symbolic sequences generated by the disturbed MM hardware neuron under different periods of periodic current stimuli have changed significantly. However, the MM hardware neuron can still accurately sort the periods of the input stimuli. It demonstrates the anti-interference characteristics and adaptability of neural coding of a single neuron under the interference of the electromagnetic environment.

In addition, the neural coding based on symbolic sequences depends on the ordering of periods of input signals. If the ordering of the periods is affected by the noise, the ordering of symbolic sequences will not reflect the ordering of the input signal periods.

As Moore's Law of integrated circuits is unsustainable, emerging neuromorphic hardware, as an alternative to traditional von Neumann architecture computing chips, will play a huge advantage in electronic systems dominated by artificial intelligence. In a complex electromagnetic environment, electromagnetic protection of neuromorphic hardware should be paid attention to. The simulation results show that the neural coding of MM hardware neuron based on symbolic dynamics can resist a certain intensity of electromagnetic interference to the input port and parameters. Therefore, MM hardware neuron is an optional hardware neuron for neuromorphic hardware designed for anti-electromagnetic interference. If a hardware neuron is designed or proved to have this kind of robust mechanism, it has the anti-interference ability. This work provides a new idea for the popular neuromorphic hardware to deal with complex electromagnetic interference problems, and verifies neuronal anti-electromagnetic interference characteristics from the perspective of a single hardware neuron, which is the first step towards a mature application. Combining many hardware neurons into a network and forming neuromorphic hardware with high EMI immunity will be our next research direction.

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