Pulse-Density Modulation with an Ensemble of Single-Electron Circuits Employing Neuronal Heterogeneity to Achieve High Temporal Resolution

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Abstract. We investigated the implications of static noises in a pulse-density modulator based on Vestibulo-ocular Reflex model. We constructed a simple neuromorphic circuit consisting of an ensemble of single-electron devices and confirmed that static noises (heterogeneity in circuit parameters) introduced into the network indeed played an important role in improving the fidelity with which neurons could encode signals whose input frequencies are higher than the intrinsic response frequencies of single neurons. Through Monte-Carlo based computer simulations, we demonstrated that the heterogeneous network could corectly encode signals with input frequencies as high as 1 GHz, twice the range for single (or a network of homogeneous) neurons.

Keywords: neuromorphic LSIs, neural networks, single-electron circuits.

1 Introduction

Nano-electronic devices are viewed as promising building blocks for the next generation of so-called *Beyond CMOS LSIs*. The *Beyond CMOS devices* include single-electron devices [1], which operate by regulating the flow of single or a few electrons. Single-electron circuits are thus viewed as promising building blocks for ultra-low power electronic systems. In addition, because of the high device integration as a result of the minute physical sizes of individual devices, single-electron devices have the potential for applications in parallel-signal processing systems that would require a high density of arrayed devices. In spite of these advantages, single-electron devices suffer from high fabrication mismatches (i.e. variance in individual device parameters), and also have low tolerance to internal and external noises. Therefore to effectively utilize the merits of single-electron devices in creating reliable and efficient electronic systems, there is need to come up with a method to either (i) eradicate these set backs through improved fabrication techniques or compensate for the drawbacks through additional circuitry incorporated into the systems or (ii) effectively utilize these setbacks to create new circuit architectures. If we look at how neuronal systems function, we find

A. Schmid et al. (Eds.): Nano-Net 2009, LNICST 20, pp. 51–56, 2009.

that they have high heterogeneity in intrinsic response properties of individual neurons; they have diverse variances in firing rates, and some of the neurons are even defective. However, in spite of these set backs neurons, as systems, accurately encode signals as they are relayed from sensory organs to the central nervous system, or to other organs. A number of reports suggest that neurons in fact employ heterogeneity to effectively encode signals. Hospedales et al. ([3]) demonstrated that neurons in the VOR can encode high frequency signals with a high temporal precision as a result of their heterogeneity.

In this study, toward establishing new circuit architectures for single-electron devices, we investigate the implications of parameter heterogeneity in reliable transmission of signals in an ensemble of single-electron integrate-and-fire neurons (IFNs). Through Monte-Carlo based computer simulations, we show that heterogeneity in device parameters indeed reduces synchrony among individual neurons, consequently increasing the temporal fidelity with which neurons can encode input signals with frequencies higher than the intrinsic response frequencies of individual neurons.

2 Model, Circuit Structure and Simulation Results

This study is based on a model of the vestibulo-ocular reflex (VOR) proposed by Hospedales et al. ([3]). In their work, they reported that noises and heterogeneity in the intrinsic response properties of neurons account for the high-fidelity in VOR functionality. Fig. 1(a) shows the part of the model, which converts head movements into neural spikes in the VOR, consisting of n neurons. The structural heterogeneity in the membrane time constants of individual neurons is represented by ξ_i. We refer to this heterogeneity as static noises. The neurons receive a common analog input and produce spikes whose temporal density corresponds to the amplitude of the input signal. The output terminal receives pulses from all the neurons in the network to produce a spike train. The noises introduced into the network lead to random and independent firing events in the neurons, reducing the probability of synchrony in the network. This enhances the precision with which the neurons in the network can encode signals with input frequencies higher those of individual neurons.

The above network is implemented with single-electron IFNs (oscillators) as shown in Fig. 1(b). A single-electron oscillator consists of a tunneling junction C_j, resistance R and a bias voltage source. The node voltage of the oscillator remains stable, if the bias voltage is lower than the tunneling threshold. When the node voltage of the oscillator increases beyond the threshold voltage, say as a result of an incoming input pulse, an electron tunnels from the ground to the node, leading to an abrupt change in the node voltage. This is referred to a firing event. The node voltage is recharged back to the resting potential to repeat the same process. Each neuronal element in the network is implemented with a single-electron neuron. From a previous study, we established that the minimum number of neuronal elements required in such a network could be as small as three. Therefore in the present investigation the number of neurons was set

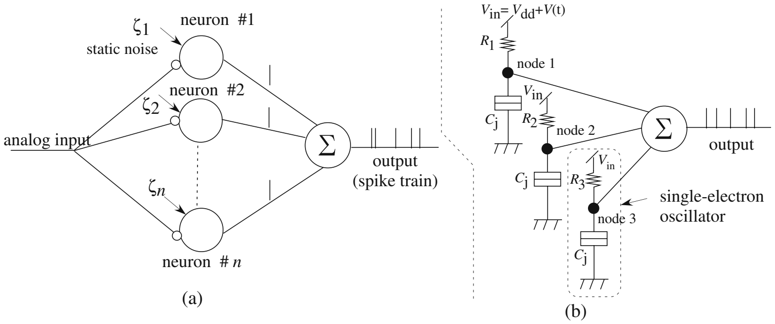

Fig. 1. (a) Neural network model of signal encoding in the VOR consisting of n neurons, (b) Implementation with single-electron oscillators

to three. The heterogeneity in the model was introduced in the circuit as a variation in the series resistance R. Note that R is a critical parameter in setting the intrinsic response frequency of each neuron. Therefore, by tuning the values of R, we could simulate the heterogeneity of membrane time constants of actual neurons.

In the simulations, all the neurons were connected to an input voltage $V_{\text{in}} = V_{\text{dd}} + V(\text{t})$, where V_{dd} (bias voltage) was set to 7.8 mV to achieve a monostable stable operation in the absence of input signals, $V(\text{t})$ is a pulsed input signal with an amplitude of 0.8 mV. The capacitance of the tunneling junctions C_{j} was set to 10 aF. The simulation time was set to 800 ns, while the operation temperature T was set to 0.5 K for simulation results shown in Figs. 2, and 3 ((A) and (B): (b) and (c)). Fig. 2 shows the transient response of a single neuron. Fig. 2(a) and (c) show the respective input signals with a frequency of 600 MHz and 250 MHz, respectively. Fig. 2(b) shows the neuron response to input "(a)", while "(d)" shows the neuron respone to input "(c)". The series resistance was set to 100MΩ. Fig.2(d) shows successful encoding of the input signal (the neuron fires once for each pulse in the input signal) whose frequency is within the intrinsic firing rate of a single neuron. In Fig. 2(b), the neuron could only encode some of the input pulses, leading to a lower firing rate as compared to the input rate. In other words, the neuron in (b) could only transmit some of the input pulses toward the output. This degrades the fidelity of signal transmission along the neural network. Fig. 2(e) shows the response of a single neuron over a wide range of input frequencies. The horizontal axis shows the input frequency, while the vertical axis shows the average firing rate of the neuron. The neuron response was linear for input signals with a frequency of upto 500 MHz. Beyond this range, the output was highly distorted. This shows that a single neuron can successfully encode (respond to) signals with a maximum input frequency of 500 MHz. The response of a population of neurons to various input frequencies was investigated with two sets of neuron ensembles: homogeneous and heterogeneous networks. In the homogeneous ensemble, the series resistances R_1, R_2, and R_3 were set to the same value, whereas in the second set, heterogeneity (static

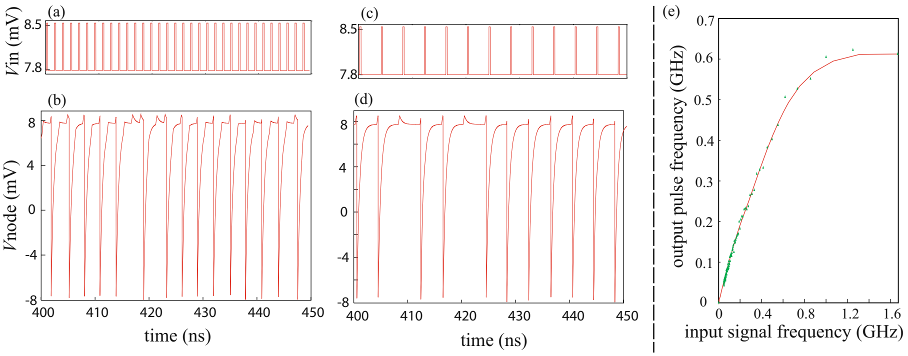

Fig. 2. Transient response of a single neuron. (a) and (c) show input signals with input frequencies of 600 MHz and 250 MHz, respectively. (b) and (d) show the output characteristics of neurons fed with input signals of 600 MHz and 250 MHz, respectively. (e) Output firing rate of a single neuron plotted against the input pulse frequency.

noises) was introduced by varying the values of series resistances in the three neurons. Fig. 3(A)(a) shows the input signal with a frequency of 600 MHz. Figs. 3(b-1) and (c-1) show the response of the homogeneous network, where the series resistances R_1, R_2 and R_3 were set to 100 MΩ. Fig. (b-1) shows the firing events of individual neurons in the network. Fig. (c-1) shows the summed spike output (spike train) at the output terminal. We could confirm that the neurons in the homogeneous network tend to synchronize, emitting pulses at almost the same timing.

Figs. 3(A) (b-2) and (c-2) show the response of neurons in the heterogeneous network, where the series resistances were set to 110 MΩ for neuron 1, 100 MΩ

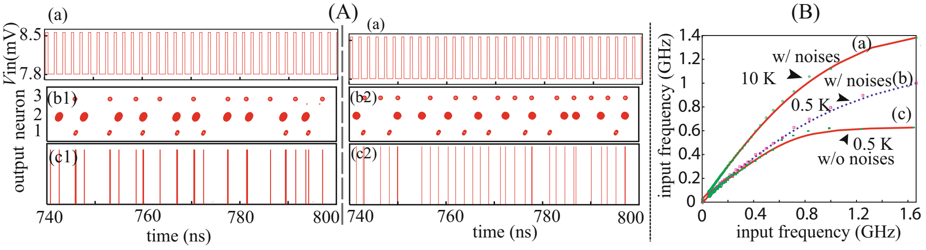

Fig. 3. (A): Transient responses of both homogeneous and heterogeneous networks. (a) shows the input signal. (b-1) shows the firing events of each neuron, while (c-1) whows the summed pulse output for the three neurons in the homogeneous network. (b-2) shows the firing events, and (c-2) shows the summed pulse output of the heterogeneous network.(B):Output firing rate of an ensemble of neurons plotted against the input pulse frequency. (a) and (b) show response characteristics of a heterogeneous network simulated at a temperature of 10 K and 0.5 K, respectively. (c) shows response characteristics of a homogeneous network simulated at 0.5 K.

for neuron 2 and 90 MΩ for neuron 3. The firing events in the heterogeneous network are more or less random as shown in Fig. 3(A)(b-2). The probability of having a neuron with a potential near the threshold value, at any given moment, is higher than in the case of a homogeneous network. Thus the network can respond to any incoming pulses at a higer probability. This results in an improved encoding of the input as illustrated by the spike train shown in Fig. 3(A)(c-2). In other words, since the neurons fired irregularly, they could transmit the input pulses with a higher temporal precision as opposed to the homogeneous network. This is elaborated in more detail in Fig. 3(B) (curves (b) and (c)), where the transmission of signal over a wide range of frequencies is demonstrated. The horizontal axis represents the frequency of input signals, while the vertical axis shows the average firing rate (output frequency) for both neuron sets. In the case of the homogenous network, since the neurons tend to synchronize with time, their encoding frequency is the same as that of individual neurons. Contrary, neurons in the heterogeneous network could correctly encode signals with input frequencies upto 1 GHz, twice that of the homogeneous network. This demonstrates that heterogeneity in the circuit parameters (presence of static noises) plays an important role in improving the fidelity with which neurons can encode signals with input frequencies far beyond the encoding capacity of individual neurons. It is also important to note the role of dynamic noises. As the temperature increases, thermally induced tunneling events in single-electron neurons increase, resulting in an increase in the average firing rate in the network. This is illustrated by the increased firing rate at a temperature of 10 K in Fig. 3(B) (curve (a)). Although this work suggests that dynamic noises don't play a critical role in increasing the maximum response frequency of the network, they however, increase the fidelity with which the network can sample input signals within the maximum input signal frequency range determined by heterogeneity in the network elements. This is evident at higher input frequencies, where the ratio of the output pulse rate to the input pulse rate starts to roll-off rapidly. The roll off is compensated for by the dynamic noises, which reduces the effect of waiting time in electron tunneling.

In summary, in this paper, we proposed and investigated the implication of heterogeneity in transmission of high frequency signals in a single-electron neuronal network. Through Monte-Carlo based computer simulations, we confirmed that heterogeneity in device parameters indeed improved the temporal precision with which the network could transmit signals with high input frequencies within the network. A heterogeneous network could correctly encode signals of upto 1 GHz, as compared to 500 MHz in single neurons (or a network of homogenous neurons). We also showed that as the temperature increases, the dynamic noises also increase compensating for the roll-off in response of the network, especially at high frequencies. We should however, note that at higher temperatures, beyond the results presented here, random tunneling as a result of dynamic noises would increase rapidly leading to degradation of signal transmission. Therefore, the value of dynamic noises to be introduced to the network to achieve the best performance needs to be optimized.

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