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Noise-shaping pulse-density modulation in inhibitory neural networks with subthreshold neuron circuits

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Abstract. We designed subthreshold analog MOS circuits implementing an inhibitory network model that performs noise-shaping pulse-density modulation (PDM) with noisy neural elements. The aim of our research is to develop a possible ultralow-power delta–sigma type one-bit analog-to-digital converter. Through circuit simulations we confirmed that the signal-to-noise ratio (SNR) of the network was improved by 7.9 dB compared with that of the uncoupled network as a result of noise shaping. © 2007 Elsevier B.V. All rights reserved.

Keywords: VLSI; Pulse-density modulation; Noise shaping; Chaotic neural networks

1. Introduction

We have developed a one-bit analog-to-digital converter (ADC). The ADC converts analog input signals to digital pulse streams where the analog information is represented in the time domain. A similar function is performed with spiking neurons, e.g. integrate-and-fire neurons (IFNs). The firing rate of the neuron depends on the amount of inputs. Hence, the spike trains, e.g. the density of spikes per second, represent analog values consisting of digital 1–0 streams. Therefore, a one-bit ADC could theoretically be developed by implementing such a neuron circuit on analog VLSIs. But, it is not practical to develop such a one-bit ADC due to quantization, static and dynamic noises from the natural environment. The quantization noises can be eliminated by employing a delta-sigma modulator, but eliminating the static noises requires an additional calibration process after the chip fabrication, and eliminating the dynamic noises requires a special isolation device.

In this work, we explore possible ways to handle static and dynamic noises in VLSIs by employing neuromorphic architectures. To achieve this we consider two network models: a

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population model of spiking neurons that exhibits noise shaping [1] and a chaotic neural network based on a Lotka–Volterra system [2]. Through numerical simulations of the network model circuits, we demonstrate that these networks can improve a system's signal-to-noise ratio (SNR) by effectively using static and dynamic noises.

2. Model and method

The network consists of N IFNs or chaotic neurons (CNs) based on a 3-variable Lotka–Volterra system [2] with all-to-all inhibitory connections [1]. Since the wiring complexity of the network; i.e., $O(N^2)$ in [1], can be reduced to $O(N)$ by introducing a global inhibitor [3], we designed a network circuit as shown in the top of Fig. 1. A common analog input is given to all the IFNs (or CNs), while a one-bit digital output is given by the sum of the firing events of the IFNs (or CNs). In the case of IFNs, static and dynamic noises are introduced into the analog input and the reset potential of IFNs after each firing, respectively. Static and dynamic noises are fed to the circuit as device mismatches of current sources (I_i) and external random (Poisson) spikes, respectively. On the other hand, in the case of CNs, the neurons' intrinsic noises were naturally utilized to obtain the equivalent noises in the IFNs.

3. Simulation Results

Fig. 1B shows simulation results of the network circuit shown in Fig. 1A ($N=3$, $I_1=1$ nA, $I_2=1.1$ nA, $I_3=1.2$ nA). The amplitude and width of the Poisson spikes were set at 1 nA and 10 μs, respectively. The mean and variation of the Poisson spikes (λ) were set at 5000. When the IFNs were uncoupled ($K=0$: mirror rate of the pMOS current mirror in the network circuit), inter-spike intervals (ISIs) of the output spike trains looked almost random (top of Fig. 1B), whereas they were almost uniform when the IFNs were coupled with $K=3$ (bottom of Fig. 1B). Fig. 2A shows a histogram of ISIs for $K=0$ and 3. As expected in [1], the coupled network produced a Gaussian-like distribution of ISIs, while the uncoupled one had a broad distribution. Fig. 2B shows the power spectrum density (PSD) of the coupled and uncoupled network with sinusoidal inputs ($I_i=I_0+A\ \sin(2\pi\ ft)$, $I_0=1$ nA, $A=50$ pA, $f=100$ Hz). The measured SNR of the uncoupled network was 10.2 dB, while that of the coupled one was 18.1 dB, which indicated that the network reduced the noise significantly, although noise-sensitive (but low-power) subthreshold CMOS devices were used in the

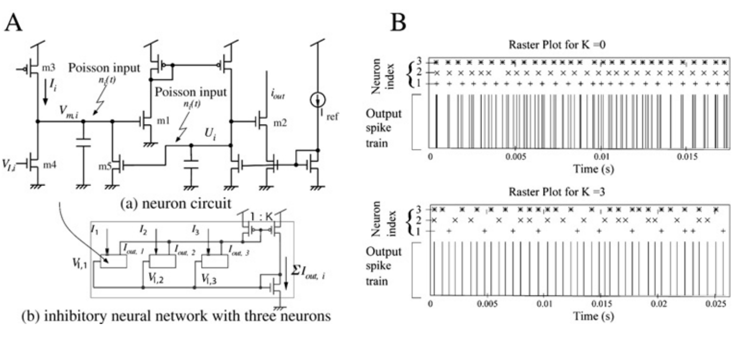

Fig. 1. A. Circuit structure of neuron and network. B. Output spikes of the network circuit.