

Real-time simulations of networks of Hodgkin–Huxley neurons using analog circuits

Q. Zou^{a,*}, Y. Bornat^b, J. Tomas^b, S. Renaud^b, A. Destexhe^a

^aUNIC, CNRS, Gif-sur-Yvette, UPR-2191, France

^bIXL, CNRS, ENSEIRB-Université Bordeaux 1, UMR 5818, France

Available online 7 February 2006

Abstract

The traditional dilemma for performing network simulations with analog circuits is the great difficulty of handling the connectivity in hardware. The main problem is that hardware-based connectivity must be built following predefined plasticity and connectivity rules, and that once the hardware is built, it is usually not possible to change its configuration. We show here an alternative system in which the membrane equations are solved in analog ASIC circuits, but the connectivity remains controlled by a digital computer. We illustrate the behavior of this system by comparing the analog simulations with traditional computer simulations of the same models.

© 2006 Elsevier B.V. All rights reserved.

Keywords: Spike-timing dependent plasticity; Analog integrated circuits; Analog-digital neural simulator

1. Introduction

We describe here a platform for simulating networks of neurons based on the Hodgkin–Huxley (HH) formalism [6] and conductance-based synaptic interactions. The system is based on analog integrated circuits (ASICs) which solve the membrane equations of the neurons. Each ASIC neuron is equipped with a leak conductance, the I_{Na} and I_{Kd} voltage-dependent conductances for generating action potentials (HH model), a slow voltage-dependent K^+ conductance for spike-frequency adaptation, and two conductance-based synaptic currents that implement kinetic models of glutamate and GABA receptors. The connectivity between the neurons is entirely managed digitally using a computer, which is interfaced in real-time (RT-LINUX) with the board containing the ASIC neurons. We demonstrate here the functionality of this system for small networks of excitatory and inhibitory neurons with excitatory synapses endowed with spike-timing dependent plasticity (STDP) and fixed inhibitory synapses. We compare the behavior of the ASIC-based model with numerical simulations of the same models.

Besides variability due to the electronics technology, the ASICs and simulations match remarkably well. This approach should yield efficient platforms for simulating large-scale networks of conductance-based neurons in a near future; it is also an original mean to evaluate the influence of neurons variability on a network activity.

2. Methods

We used a system specifically designed for analog neuron simulations (see scheme in Fig. 1A). This system consisted in custom-designed specific ASICs for simulating conductance-based neuronal models using HH type models. We describe below these models, as well as the architecture of the system and ASIC circuits.

Models implemented. The neuron models implemented on circuits were HH type representations of two main cell classes in cortex, the “regular spiking” (RS) neurons and “fast spiking” (FS) interneurons [3]. All neurons contain an adjustable leak conductance and voltage-dependent Na^+ and K^+ conductances necessary to generate action potentials. These currents define the FS phenotype for inhibitory neurons. Excitatory RS neurons possess in addition a slow voltage-dependent K^+ current responsible

*Corresponding author. Tel.: +33 169 823435.

E-mail address: Quan.Zou@iaf.cnrs-gif.fr (Q. Zou).

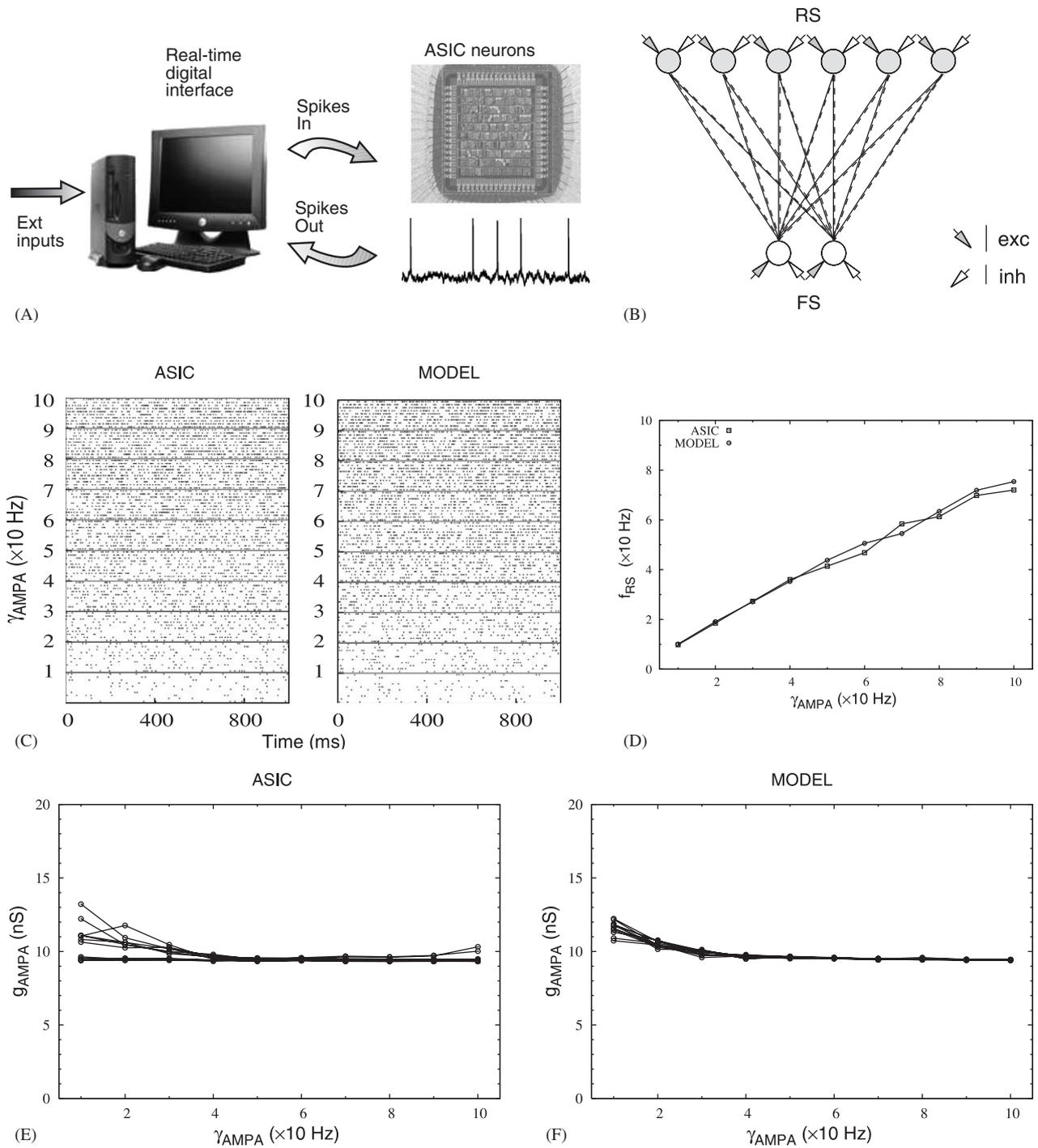


Fig. 1. Network simulations using analog neurons. (A) Scheme of the system architecture for performing analog simulations. Membrane equations are solved on analog ASIC chips, but the connectivity is handled by a computer in real time. (B) Scheme of the network used as an example. The system was tested using a 8-neuron circuit comprising 6 “regular spiking” (RS) excitatory neurons and 2 “fast spiking” (FS) inhibitory neurons. These neurons were reciprocally connected with excitatory (AMPA, solid lines, maximal conductances of 10 nS) and inhibitory (GABA, dashed lines, maximal conductances of 5 nS) synapses, and each cell received random synaptic activity at both AMPA (gray arrow) and GABA (white arrow) synapses, with maximal conductances of 0.1 and 0.05 mS, respectively. (C) Firing properties of a single ASIC neuron bombarded by random synaptic inputs. Poisson-distributed random synaptic (AMPA) inputs were used at different rates γ_{AMPA} (maximal conductance of 0.1 mS). The raster plots show the spikes produced by the neuron during 10 successive simulations of 1 s, for ASIC (left; 1 kHz sampling frequency) and model (right) simulations. (D) Comparison of firing rates in ASIC and model simulations. The average firing rate was computed from the simulations shown in C, and represented as a function of the mean input rate of the synaptic bombardment. (E) Steady-state synaptic weights in ASIC simulations of the 8-neuron circuit shown in B. Synaptic plasticity (STDP) was incorporated at excitatory synapses from RS to FS cells, and the final weight is shown after 50 s simulation time. The simulation was repeated for different input rates of the random excitatory inputs (from 10 to 100 Hz), while the inhibitory input rate was fixed at 20 Hz. (F) Same model run numerically.

for spike-frequency adaptation, which is adjustable. Synaptic interactions were described by conductance-based synaptic currents that implement kinetic models of glutamate and GABA receptors [4]. These models were conceived such as to handle any number and frequency of presynaptic signals, and therefore can represent multiple synapses. Plasticity rules were included at excitatory synapses, according to STDP, in which the synaptic weight varies as a function of the relative timing of pre- and post-synaptic spikes [1]. The particular implementation of STDP included saturation terms which make the synaptic weight converge to a steady-state value (not shown). This type of convergence dynamics is particularly useful to compare the activity of analog networks (see description below), with the same networks simulated using traditional means (for this purpose we used the NEURON simulation environment [5]).

ASIC circuits. Specific analog VLSI circuits were designed and fabricated using a sub-micron BiCMOS (bipolar and CMOS) technology (see ASIC microphotograph in Fig. 1A). In those devices, electronic currents modeling ionic currents of the HH formalism are produced by an analog modular circuit and summed on a capacitance. The voltage on this capacitance is equivalent to the neuron membrane voltage. Each module of the circuit, designed in current-mode, compute a mathematical function present in the RS and FS cells model description [9]; electronics modules are dimensioned at the transistor level and arranged to compute the ionic current models (4 types for the RS neurons, 3 for the FS neurons). An identical arrangement is made to calculate on-chip the kinetic synapse currents, injected on the membrane capacitance. Kinetics and time constants of the original models are reproduced with no change in time scale, which imposes that the VLSI neurons run in biological real-time. This design principle and the electronics modules for neuro-morphic devices have been validated in previous application [10,8]. The devices we used here are specifically-designed prototypes, in which specific I/O have been added to allow the control of synaptic weights by STDP plasticity rules: the neuron activity is available in the form of a time-stamped event (1 bit). The kinetic synapse inputs (one excitatory and one inhibitory) are digitally coded using a simple width modulation for the weights.

Analog-digital interface. The connectivity is handled using a computer, via a PCI interface board supporting the ASICs and an FPGA to control digital inputs and outputs from and to the analog neurons (see scheme in Fig. 1A). The computer runs a LINUX operating system in soft real-time mode, and a specific software interface. The computer reads in real-time the spike events from the board, computes synaptic plasticity algorithms, and dispatches the spike signals as inputs to the ASIC neurons, where they will trigger synaptic conductance changes. This way allows us to implement arbitrary schemes of connectivity and plasticity, since it is entirely managed by the computer, providing a great flexibility to the system.

3. Results

We first characterized the individual ASIC neurons based on their frequency/current (f/i) curves obtained by constant current injection. The measurements were performed for both FS and RS neurons using different parameters, such as different levels of adaptation. The f/i curves were also computed from computer simulated neurons, and despite neuron-to-neuron variations in the ASIC circuits (the ASIC full-custom fabrication process results in circuits dispersion and mismatch at the transistor level), the agreement was excellent (not shown). A second comparison was to measure the frequency response of the ASIC neurons in response to synaptic noise (mixture of Poisson trains of excitatory and inhibitory events). In this case, ASIC and model neurons displayed similar responses, as shown by the raster plots in Fig. 1C. However, the exact timing of spikes of the model was in general not reproduced by the ASICs (due to dispersion of parameters). This difference is visible in the raster-plots in Fig. 1C, but it was also quantified by calculation the cross-correlation between model and ASICs spike trains (for the same injected noise). Correlations were broadly peaked (half-width of about 3 s) and weak (peak included between 0.01 and 0.02). Despite these differences in spike timing, the frequency response of model and ASICs was remarkably similar (Fig. 1D).

A more severe test of the ASIC circuits was to build a network of neurons in which the synaptic weights are subject to changes according to a well-defined plasticity rule. We used a network of 6 RS and 2 FS neurons, interconnected with excitatory (AMPA) and inhibitory (GABA) recurrent synapses, as shown in Fig. 1B. We used a paradigm in which neurons were subject to random synaptic inputs in addition to recurrent synapses from other neurons in the network. STDP [1] was applied to the recurrent excitatory synapses (from RS to FS cells), and their steady-state synaptic weight is represented as a function of the input rate for both ASIC (Fig. 1E) and model simulations (Fig. 1F). Although the synaptic weights in the ASIC network were generally more variable (presumably due to ASICs' fabrication—see above), the agreement between the ASIC and model neurons was excellent, for the whole range of inputs considered. In this case, the run time of the simulation was significantly faster on ASICs (real time) compared to PC-based workstations (about 5 times slower than real time).

4. Conclusions

We have shown here a prototype system for real-time simulations of networks of neurons, in which the membrane equations are solved in analog ASIC circuits, but the connectivity remains controlled by a digital computer. This configuration offers a great flexibility because any type of learning rule can be used, with arbitrarily complex connectivity between excitatory and inhibitory neurons.

The prototype shown here works well, and was also tested in different configurations including recurrent excitatory synapses subject to STDP (Zou et al., submitted). This system is a novel solution to run real-time neuromorphic devices of complex neural models while keeping a modular and dynamic connectivity. Other approaches propose solutions either with less precise neuron models [2], or without programmability at the network level [11].

The main limitation of such a system is that the digital interface must compute synaptic weights in real time, which may represent a difficulty for applying complex plasticity algorithms to large networks. Further work is needed to evaluate the limit of such analog/digital architectures. In parallel, architectural solutions are already studied to process the network connectivity at the hardware level, using reconfigurable digital circuits (FPGA). However, the fact that networks of HH neurons can be simulated in real time opens the possibility of interfacing them with real neurons (see Ref. [7]). Another interesting approach will be to evaluate how neuron variability, emulated here by the dispersion in the ASICs characteristics, influences the activity patterns at the network level.

Acknowledgements

This work was supported by CNRS, HFSP and the European Community (IST-2001-34712 and IST-2005-015879).

References

- [1] G.Q. Bi, M.M. Poo, Synaptic modifications in cultured hippocampal neurons dependence on spike timing, synaptic strength, and postsynaptic cell type, *J. Neurosci.* 18 (1998) 10464–10472.
- [2] L. Carota, G. Indiveri, V.E. Dante, A software–hardware selective attention system, *Neurocomputing* 58–60 (2004) 647–653.
- [3] B.W. Connors, M.J. Gutnick, Intrinsic firing patterns of diverse neocortical neurons, *Trends Neurosci.* 13 (1990) 99–104.
- [4] A. Destexhe, Z.F. Mainen, T.J. Sejnowski, An efficient method for computing synaptic conductances based on a kinetic model of receptor binding, *Neural Comput.* 6 (1994) 14–18.
- [5] M.L. Hines, N.T. Carnevale, The neuron simulation environment, *Neural Comput.* 9 (1997) 1179–1209.
- [6] A.L. Hodgkin, A.F. Huxley, A quantitative description of membrane current and its application to conduction and excitation in nerve, *J. Physiol. London* 117 (1952) 500–544.
- [7] G. Le Masson, S. Renaud-Le Masson, D. Debay, T. Bal, Feedback inhibition controls spike transfer in hybrid thalamic circuits, *Nature* 417 (2002) 854–858.
- [8] S. Renaud-Le Masson, G. Le Masson, L. Alvado, S. Saighi, J. Tomas, A neural simulation system based on biologically-realistic electronic neurons, *Inf. Sci.* 161 (2004) 57–69.
- [9] S. Saighi, J. Tomas, L. Alvado, Y. Bornat, S. Renaud, Integration of Biological Neurons Models, XVIII Conference on Design of Circuits and Integrated Systems—DCIS2003, Ciudad real, Spain, 2003.
- [10] S. Saighi, J. Tomas, Y. Bornat, S. Renaud, A conductance-based silicon neuron with dynamically tunable model parameters, in: Proceedings of Second International IEEE EMBS Conference on Neural Engineering, Arlington, VA, USA, 16–19 March 2005, pp. 285–288 ISBN 0-7803-8710-4, 2005.
- [11] M. Simoni, G. Cymbalyuk, M. Sorensen, R. Calabrese, S. DeWeerth, A multi-conductance silicon neuron with biologically matched dynamics, *IEEE Trans. Biomed. Eng.* 51 (2004) 342–354.