Designing, tuning and building ultra-low-power neuromodulable mixed-feedback silicon neurons

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Abstract

By drawing inspiration from biology, neuromorphic engineering aims to exceed the limits of digital machines, which are limited by high energy consumption and limited flexibility. The human brain, where computations and memory coexist, indeed displays exceptional versatility and computational power, at a fraction of the energy cost of a digital chip.

Neuromorphic silicon neurons are the key components of neuromorphic computing devices that aim to implement extremely low-power, brain-inspired computing paradigms in electronic chips. Current designs achieve extremely low power consumption and small sizes [1]. However, these designs solely replicate one of the many dynamical behaviors of biological neurons, namely, Type I excitability, where firing rates encode input strength linearly. This restricts their use in contexts requiring adaptive behaviors such as adaptive signal processing or the generation of rhythmic motor patterns capable of robustly actuating and reacting to mechanical systems in uncertain environments.

By rethinking these basic neuromorphic building blocks, our work aims to enhance the modulation and robustness properties of ultra-low-power neuromorphic chips. We view neurons as event-based analog signal processors that use continuous-time feedback dynamics to create asynchronous events called ”spikes”. We represent neurons as nonlinear input-output dynamical systems made of positive and negative feedback loops coexisting at different timescales [2]. By dynamically tuning the feedback loop gains, the mixed-feedback model allows neuromorphic neurons to adapt their computational properties to varying environmental contexts, enabling enhanced modulation and robustness.

This representation not only provides a mathematically tractable framework but can also be naturally implemented in ultra-low-power, current-mode subthreshold CMOS circuits.

To bridge theoretical modeling and circuit implementation, we computed dynamic input conductances (DIC) [3] for the mixed-feedback model. In computational neuroscience, DICs aggregate the contributions of all ionic conductances across distinct timescales, describing and shaping the spiking dynamics of the neuron. By relating the tuning voltages of our neuromorphic neurons to dynamic input conductances, we are able to systematically tune them to achieve the desired DIC profiles. We can precisely predict and modulate neuronal behaviors, such as firing thresholds and transitions between spiking and bursting, where neurons emit ”packets” of spikes, a behavior particularly relevant for creating rhythmic systems [4].

The mixed-feedback model was implemented in an array of neurons on a CMOS neuromorphic test chip. Experimental results confirm that the fabricated circuit successfully replicates the desired spiking and bursting dynamics predicted by the DIC framework in an ultra-low-power setting. On-chip neurons demonstrate robust neuromodulation capabilities, despite mismatches between devices on the chip and variability in nominal parameters.

References

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