Analog Subthreshold Implementation of a Biomimetic Model for Bidirectional Communication with the Brain

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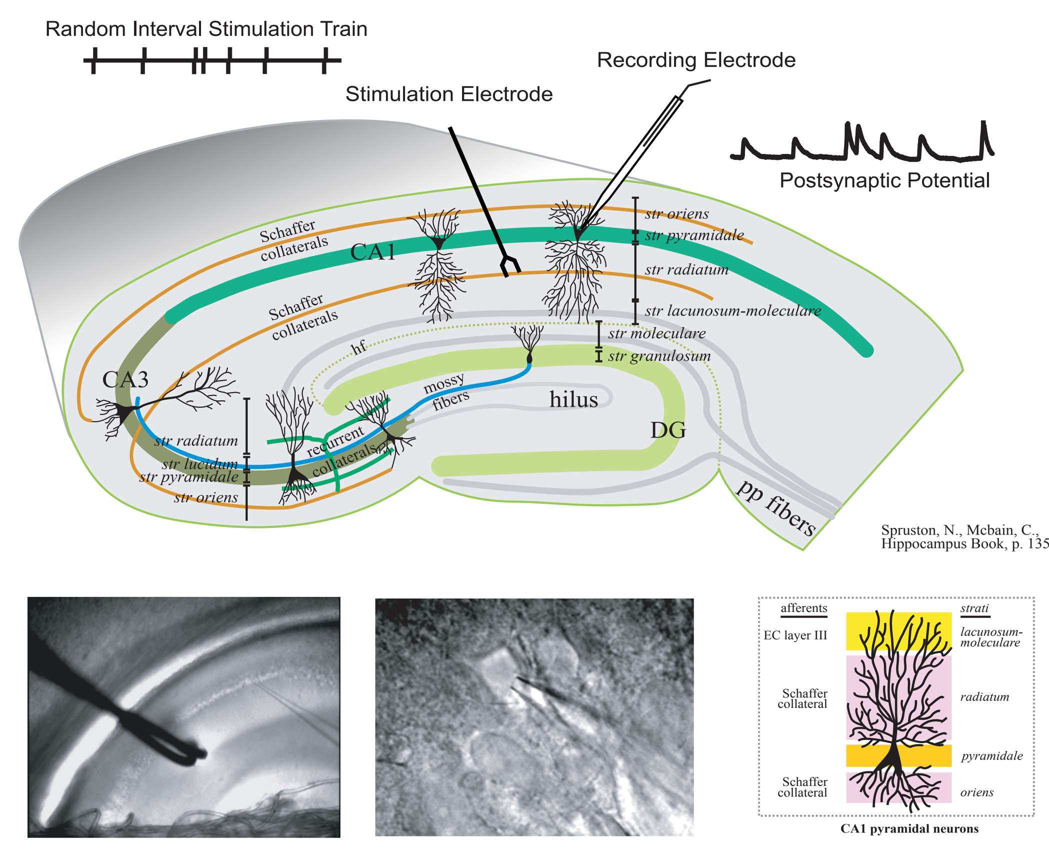
Abstract

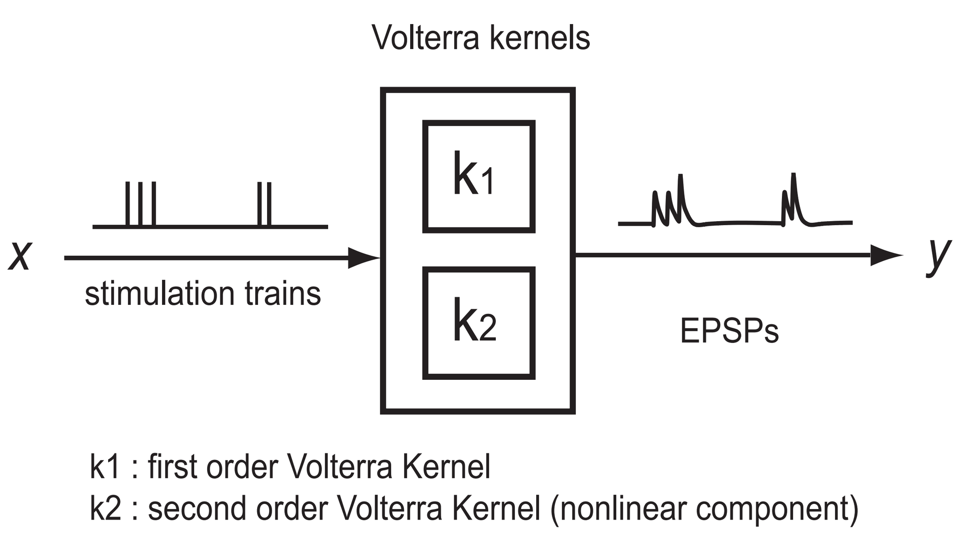
The right level of abstraction for a model mimicking a neural function is often difficult to determine. There are trade-offs between capturing biological complexities on one hand and the scalability and efficiency of the model on the other. In this work, we describe a nonlinear Laguerre-Volterra model of the synaptic temporal integration of input spikes to postsynaptic potentials. This model is then efficiently implemented using analog subthreshold circuits and can serve as a foundation for future large-scale hardware systems that can emulate multi-input multi-output (MIMO) spike transformations in populations of neurons. The normalized mean square error in estimating real data using the circuit implementation of this model is less than 15%. The model components are modular and its parameters are adjustable. The total power consumption of this nonlinear Laguerre-Volterra system is approximately 5nW.

Experimental Setup



Experimental Setup. The postsynaptic potential (PSPs) obtained from whole- cell patch- clamp recordings. CA1 pyramidal neurons were stimulated with random interval trains to mimic the spiking behavior observed in CA3 hippocampal neurons. The mean stimulation frequency: 2Hz. The stimulation intensity was adjusted so no action potentials were induced. The PSPs were recorded at the soma of the cell.

PSP Estimation and Prediction



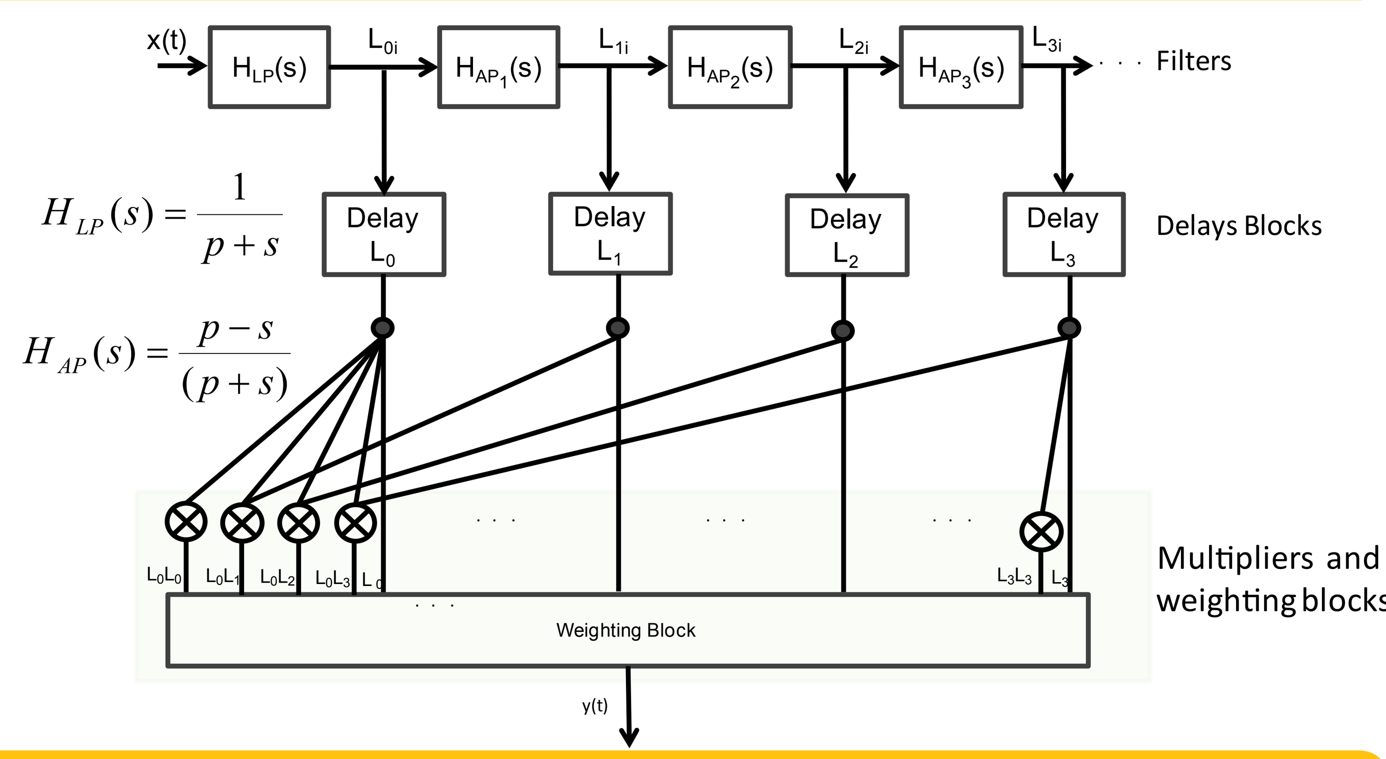
Laguerre Expansion of Volterra Kernel (LEV) model.

$$y(t) = c_0 + \sum_{n=1}^{L} c_1(n) v_n(t) + \sum_{n_1=1}^{L}\sum_{n_2=1}^{n_1} c_2(n_1,n_2) v_{n_1}(t) v_{n_2}(t)$$

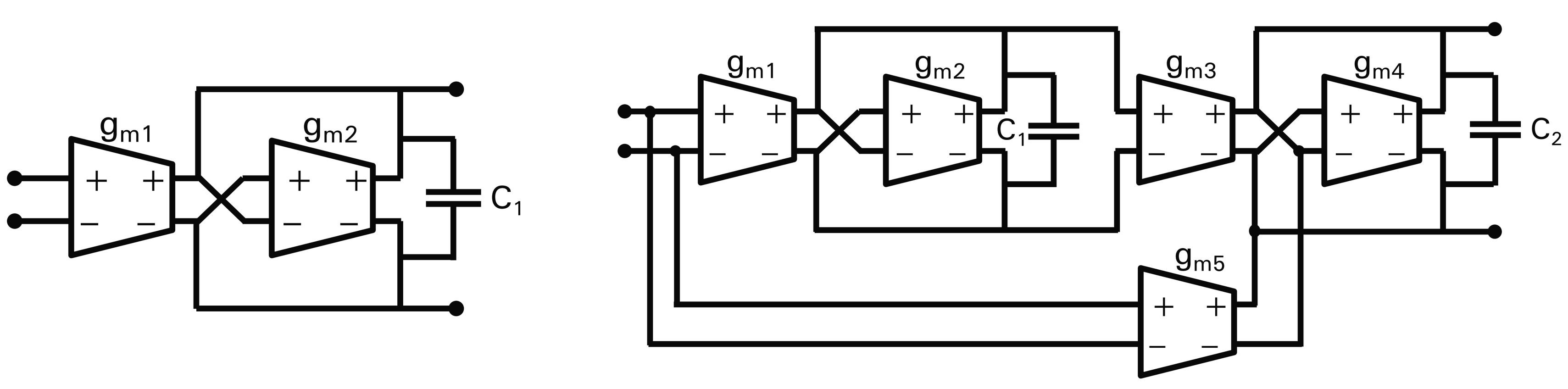
where $v_n(t) = \int_0^\infty l_n(\tau) x(t-\tau) d\tau$

It can be shown that ln(t) is the impulse response of a linear system with transfer function

$$H(s) = \left(\frac{1}{p+s}\right)\left(\frac{p-s}{p+s}\right)$$



Hardware Implementation of the LEV

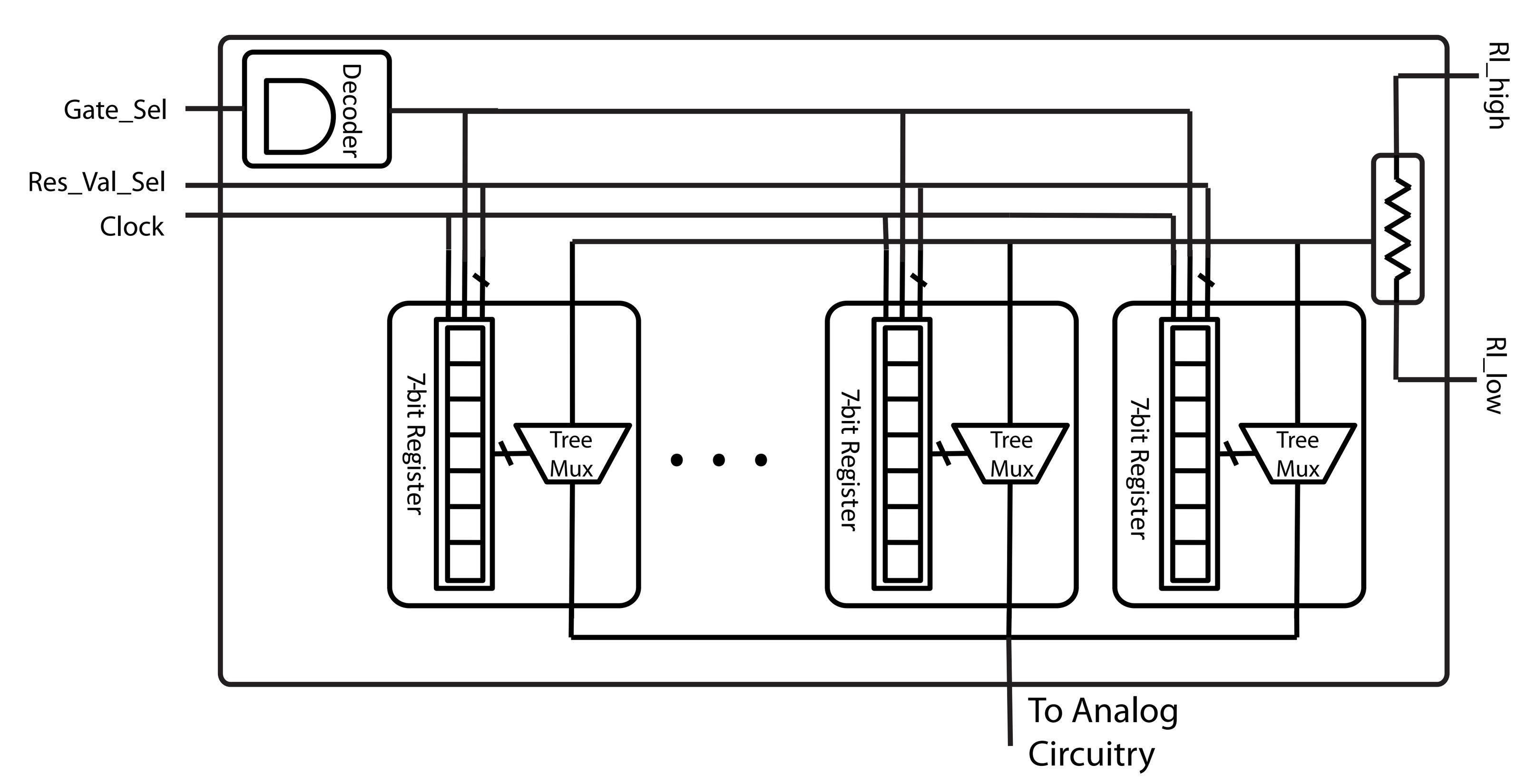


$$\frac{v_{out}}{v_{in}} = \frac{\frac{gm_1}{C_1}}{s + \frac{gm_2}{C_1}}$$

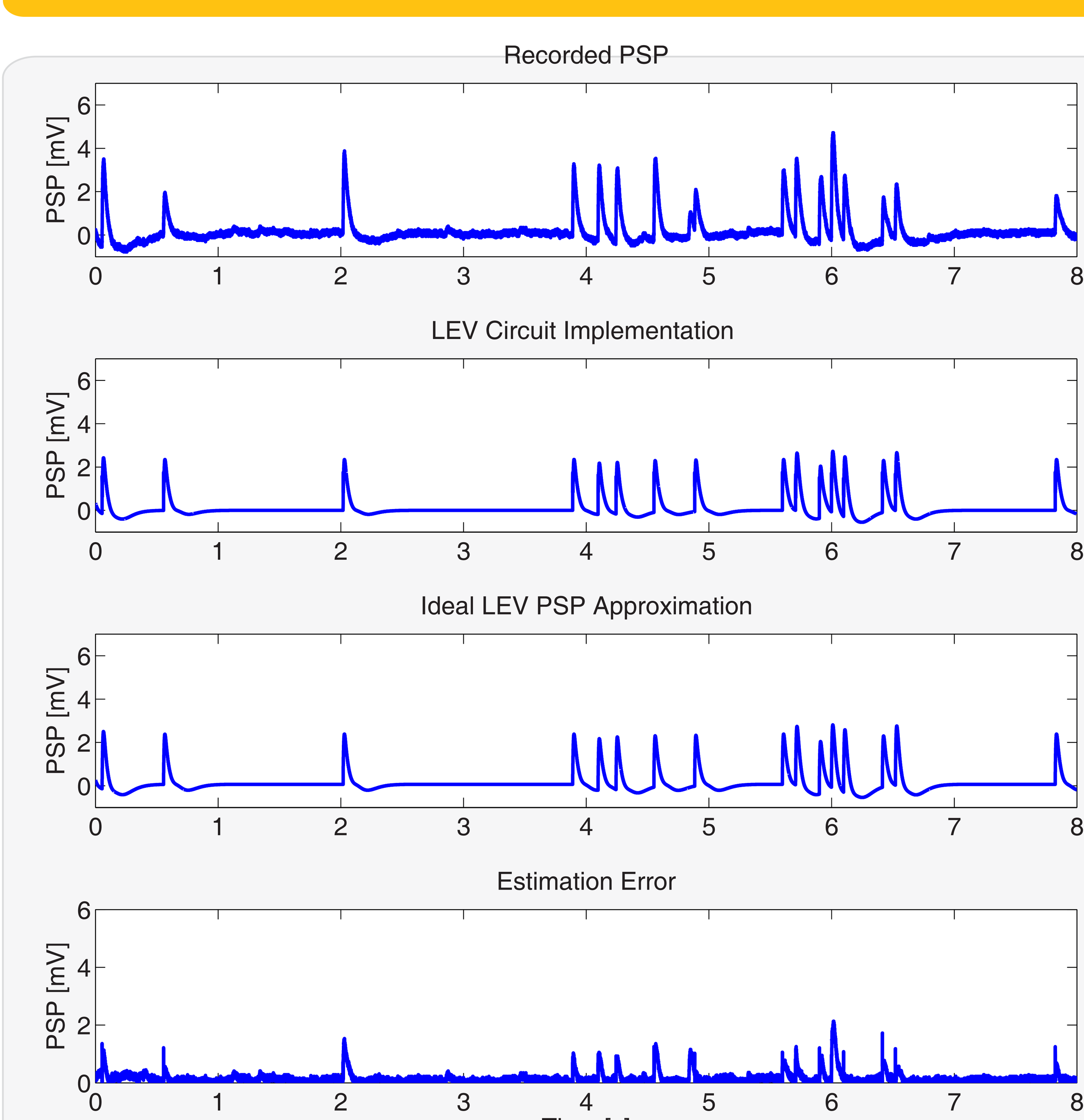
$$\frac{v_{out}}{v_{in}} = \frac{\left(\frac{gm_1 gm_3}{gm_5 C_1} - \frac{gm_2}{C_1}\right) - s}{s + \frac{gm_2}{C_1}}$$

Low-Pass and All-Pass Filter Implementations and Transfer Functions

Digital Calibration



Results



Input: Train of pulses with 200µs duration and amplitude of 80mV applied differentially. The ideal second order LEV approximation is shown in the third trace. The bottom graph shows the absolute value of the difference between the recording and the circuit output.

- The rms error between the signals generated by the circuit and ideal LFs is less than 5%.
- The normalized mean square error between circuit estimation and data is 14.98%.
- The total power consumption is 5.3nW.
- Subthreshold Gilbert Cells implement the Multipliers in the LEV model
- A modified version of a subthreshold Gilbert cell is also used to implement the weighting blocks
- Each cell can be individually calibrated to compensate for mismatch and process variation, to change the time constants or weighting coefficients.