Team ID - 408D-3

Spike Encoder and Neural Network Chip for Cognitive State Detection

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Motivation

- **Challenge:** Sleep and attention states are hard to quantify in real-time
- **Physiological Indicators:** Eye blinks (amplitude and time)[1]
- **Need:** This project addresses the need for an energy-efficient, real-time, low-power system capable of decoding such biosignals and is suitable for wearable devices




Applications

- Sleep and attention monitoring in high-risk environments (e.g., driving, flying) [2]
- Cognitive performance analysis
- Neurofeedback training
- Biological stimulation (such as nerve or muscle activation)
- Treatment of neurodegenerative disorders through targeted neuromodulation [3]

Project Introduction

What is this project about?

Performs on-chip analog signal conditioning and delta-modulation-based spike encoding, and routes the resulting spike trains into a Spiking Neural Network (SNN) for real-time classification of biomedical signals.

Input: EEG signal acquisition via scalp electrodes
Output: Classified blinks for cognitive state analysis

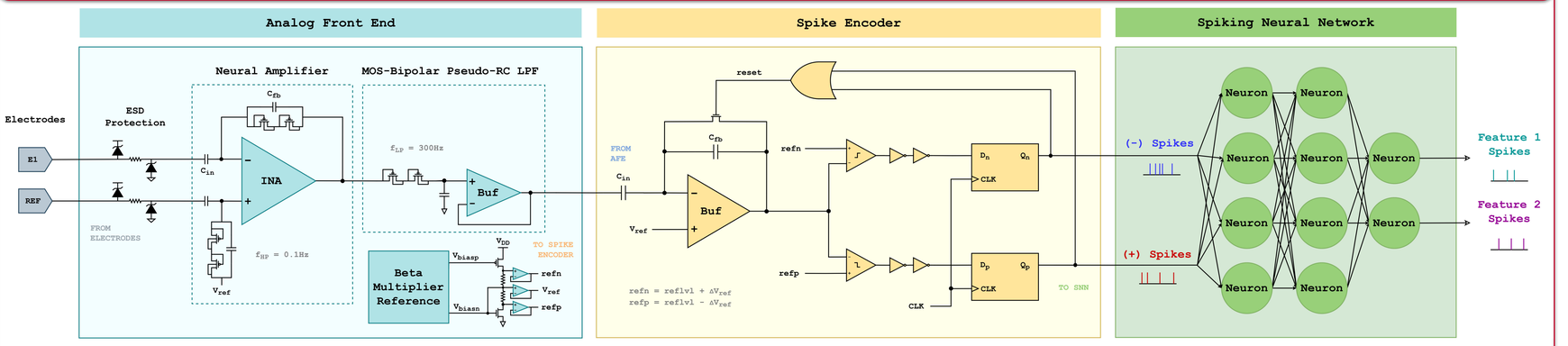
- Inspired by OpenBCI Cyton; extended for full integration and low power!!

Aim:

- Optimized design for a high input-channel throughput and minimal area
- Designed for embedded, mobile, and wearable biosignal systems
- Open-source hardware contribution to neuromorphic computation

- A Skywater 130nm Process Custom CMOS IC

Architecture and Design



AFE [4]

Amplifier:

- High resistance pseudo resistor elements to to allow for bandlimiting
- Midband Gain: 40dB
- Wide-band amplification 10 Hz to 10 kHz

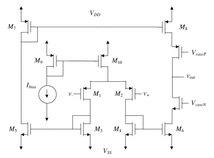


Fig. 1: INA Schematic

Buffer:

- LFP-recording bandwidth
- Bandwidth: <1 Hz–300 Hz
- Uses pseudo resistor elements to form poles

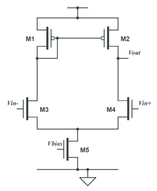


Fig. 2: Buffer Schematic

Encoder

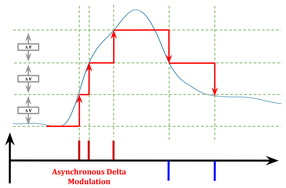


Fig. 3: Delta Modulation

Delta Modulation:

- Converts filtered analog signals into spikes
- Uses async delta modulation
- Outputs ON/OFF spikes based on threshold crossings
- Adjustable threshold levels for higher encoding resolution

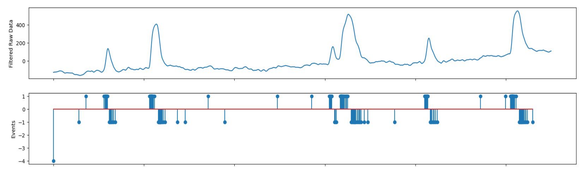


Fig. 4: Simulated Output of the Spike Encoding using Delta Modulation from Filtered Raw Data

SNN

- Izhikevich Neuron Model[5]

$$C\frac{dv}{dt} = k(v - v_r)(v - v_t) - (u - i)$$

$$\frac{du}{dt} = a[b(v - v_r) - u]$$

if $v \geq v_{peak}$:

$$v_{new} = v_{min}$$

$$u_{new} = u + d$$

- Exponential Decay Synapse Model
- Euler method to solve ODE
- Implemented digitally using Verilog[6]
- 16-bit resolution
- 20MHz clock frequency
- 2-4-4-2 structure
- Weights were pre-trained using snnTorch
- Achieved 95% accuracy

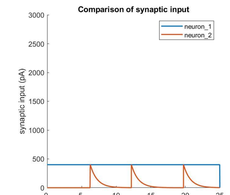


Fig. 5: Synaptic current of exponential decay synapse

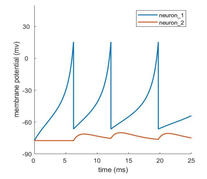


Fig. 6: Membrane potential of IZ neuron

Design Analysis

Goals

- To design and simulate a successful neural interface circuit that reads in EEG signals, encodes the analog signals into spikes, and extracts features to identify soft and hard blinks
- To ultimately create a layout of a VLSI chip design that can be realistically implemented using Skywater 130 technology

Constraints

- **Health and safety:** Must not have adverse biological effects
- **Manufacturability:** Must be Compatible with Sky 130 process
- **Sustainability:** reduce power consumption
- **Cultural/social:** device must be adaptable to all types of headwear
- **Legal/regulatory:** adhere to IEEE standards

Ethics and Standards

IEEE 2010-201	Recommended Practice for Neurofeedback Systems
IEEE 1058-2003	Standard for Scalp Electroencephalography
IEC 60601-1	Safety and Essential Performance Standard
ISO 10993	Biological Evaluation of Medical Devices Part 1: Evaluation and Testing Within a Risk
IEEE 2010-2023	Standards for EEG Neurofeedback Systems
IEEE 1801-2018	Standard for Design and Verification of Low Power Integrated Circuits
IEEE 360-2022	Standard for Wearable Consumer Electronic Devices

Simulation Results

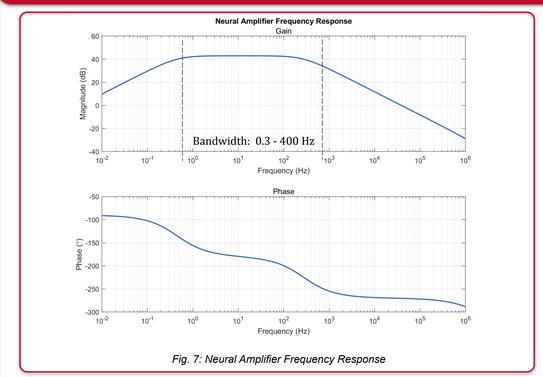


Fig. 7: Neural Amplifier Frequency Response

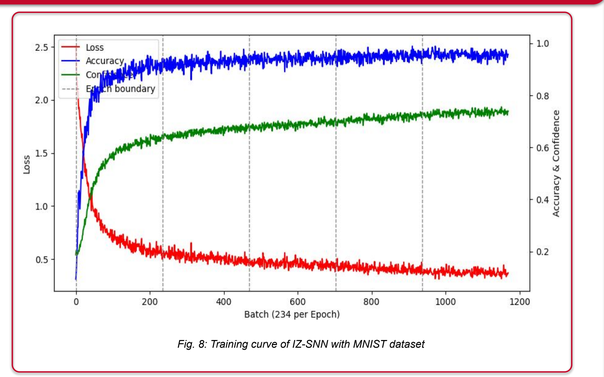


Fig. 8: Training curve of IZ-SNN with MNIST dataset

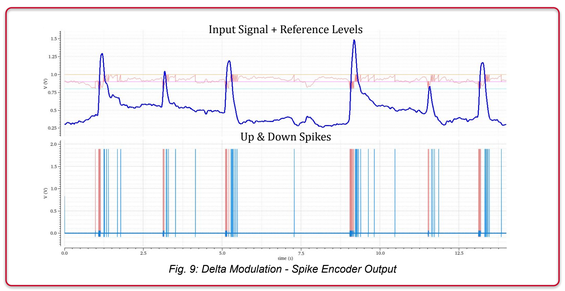


Fig. 9: Delta Modulation - Spike Encoder Output

Table of Specifications	
VDD	1.8V
Open loop Gain	35.3dB
Closed Loop Gain	42dB
Bandwidth	0.3 Hz to 400 Hz
Resolution	2 bit (Up/Down)
Spike Width	1 bit
Minimum Refractory Period	3 ns

References

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[3] K. Burelo, G. Ramantani, G. Indiveri, and J. Sarnthein, “A neuromorphic spiking neural network detects epileptic high frequency oscillations in the scalp EEG,” Sci. Rep., vol. 12, no. 1, p. 1798, Feb. 2022, doi: 10.1038/s41598-022-05883-8.
[4] W. Wattanapanitch and R. Sarpeshkar, “A Low-Power 32-Channel Digitally Programmable Neural Recording Integrated Circuit,” IEEE Trans. Biomed. Circuits Syst., vol. 5, no. 6, pp. 592–602, Dec. 2011, doi: 10.1109/TBCAS.2011.2163404.
[5] E. M. Izhikevich, "Simple model of spiking neurons," in IEEE Transactions on Neural Networks, vol. 14, no. 6, pp. 1569-1572, Nov. 2003, doi: 10.1109/TNN.2003.820440.
[6] A. Cassidy and A. G. Andreou, "Dynamical digital silicon neurons," 2008 IEEE Biomedical Circuits and Systems Conference, Baltimore, MD, USA, 2008, pp. 289-292, doi: 10.1109/BIOCAS.2008.4696931.

Acknowledgements

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