Implementing the Hodgkin-Huxley Neuron Model on a FPAA Platform

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Overview

This paper provides a general overview of the work done on the FPAA board this semester as well as documented steps on how to debug, interface, and perform every test on the FPAA with the Digilent Analog Discovery 2 done by the team during the fall.

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Semester Progress Summary

We started the semester by working together to characterize the general behavior of the FPAA board. We initially tried to reproduce the results of previous students by running an LPF on the FPAA and had trouble obtaining results from on-chip tests so we decided to conduct off-chip tests. In the process of doing so, we learned how to interface the FPAA and the Digilent Analog Discovery board. We compiled the steps required to interface the two boards, which have also been included in this report. Specifically, we found out how to implement IO pads in our circuit designs and became familiar with the signal generator and oscilloscope functions on the Analog Discovery board. Once we were able to interface the two boards, we still had trouble with obtaining results from the LPF design - we eventually discovered that we needed to place an OTA block before and after the filter to act as a buffer. After making this adjustment, we found that the LPF was functional, but still retained non-ideal behavior (i.e. the cutoff frequency we specified in the design varied from the measured cutoff frequency).

After implementing the LPF, we moved onto working with the Hodgkin-Huxley Neuron block. We initially consulted the resources that Dr. Hasler had uploaded for her FPAA workshops. The workshops provided a good overview of how to implement the HHN block on the FPAA board. Though the resources were a good starting point, we ran into a lot of issues when implementing the design. Initially, we unintentionally used an outdated version of the HHN design - after updating the design, we continued to run into problems with the “Ramp ADC” and “Arb Waveform” blocks. We consulted with Dr. Hasler and Aishwariya Natarajan about our problems with the board - they suggested independently testing each of the blocks to determine which one wasn’t functioning properly. Though we spent some time testing the blocks, we struggled to produce the spiking behavior of the neuron. We were able to create a signal that was qualitatively similar to the desired spiking behavior, but this signal was actually produced by a filtering effect on the board.

After consulting with Dr. Hasler and Aishwarya again, we found that the board was not properly grounded - after fixing this issue we were able to produce spikes from the HHN block. We also made adjustments to the initial HHN circuit design so we could input signals from the Analog Discovery board and isolate the behavior of only the HHN block. Despite this success, we still ran into difficulties with characterizing the neuron block - we found that the neuron continues to spike even when there is no input signal. Additionally, the output of the signal is inconsistent, as the sodium channel voltage needs to be adjusted between 1.3-1.4V every time the design is tested to ensure that the spiking behavior occurs. The behavior of the circuit is also very sensitive to small bumps to the board and may require reconnecting certain wires to ensure correct behavior. As a next step, the behavior of multiple neuron blocks can be characterized and the neuron synapse can be implemented in the circuit design.

Overview of Digilent Analog Discovery 2

The Digilent Analog Discovery 2 is a multi-function oscilloscope and signal generator that can be controlled via USB. The board can be used to measure signals and generate waveforms of higher frequency, making it useful for completing off-chip testing on the FPAA board.

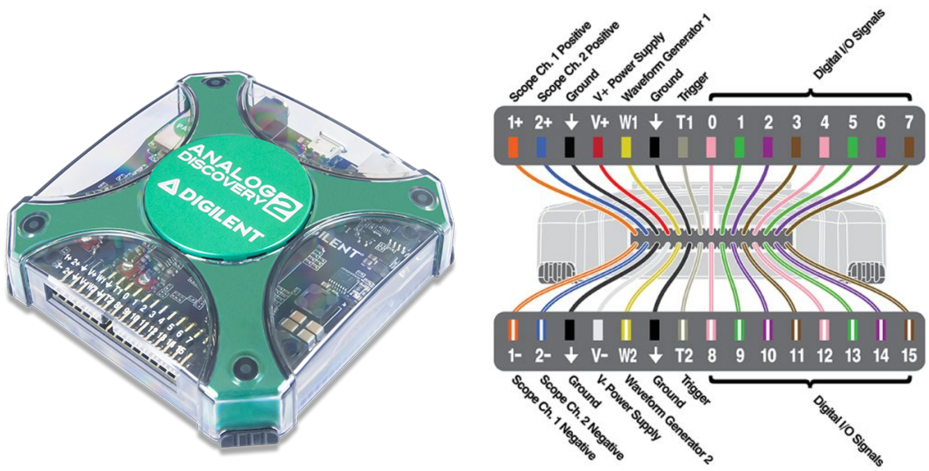

Figure 1. *Analog Discovery Board and Pinout*

I. Downloading the Digilent Analog Discovery 2 Software

The device itself can be configured through the WaveForms software, which is distributed for free by Digilent and functions for Windows, Mac, and Linux. The software can be downloaded through this link:
https://store.digilentinc.com/waveforms-previously-waveforms-2015/
The following YouTube link contains the tutorial videos provided by Digilent Inc. which detail the setup of the instrument as well as software instructions and usage:
https://www.youtube.com/playlist?list=PLSTiCUiN_BoLtf_bWtNzhb3VUP-KDvv91
A PDF copy of the reference manual can be found through this link:
https://reference.digilentinc.com/_media/reference/instrumentation/analog-discovery-2/ad2_rm.pdf

II. Calibrating the Digilent Analog Discovery 2

Before using the instrument, first calibrate the device using a separate oscilloscope and multimeter. This is to ensure that nothing generated on the device is incorrect. The instructions can be found in the link below:
https://www.instructables.com/id/How-to-Calibrate-the-Analog-Discovery-2/

Checking the Equipment

Before beginning to use the Analog Discovery 2, first make sure that both the oscilloscope and multimeter are functioning properly. To check the oscilloscope, perform a scope checkout on it. Connect the VCC and ground prongs to the VCC and ground on the oscilloscope (located either underneath the screen or to the bottom right of the screen, depending on model).

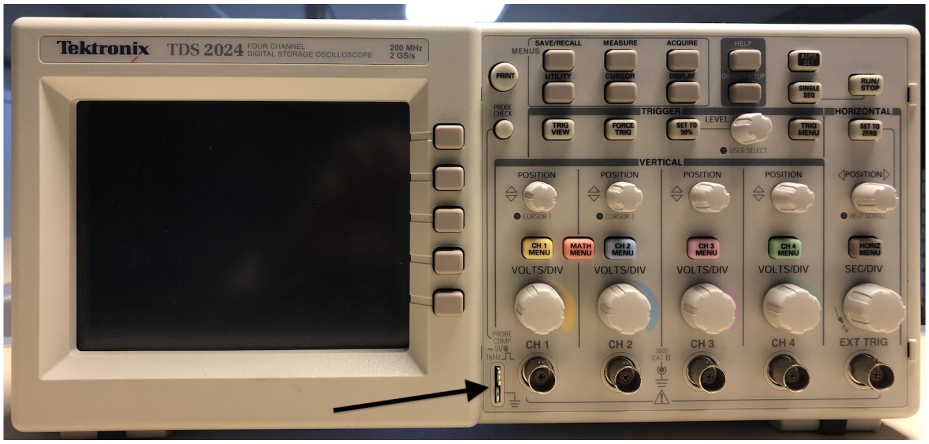

Figure 2. *VCC and ground location on oscilloscope*

The waveform generated by this should be a square wave of 5V. The image below has both of the channels of the oscilloscope on, however only one channel is needed for the calibration.

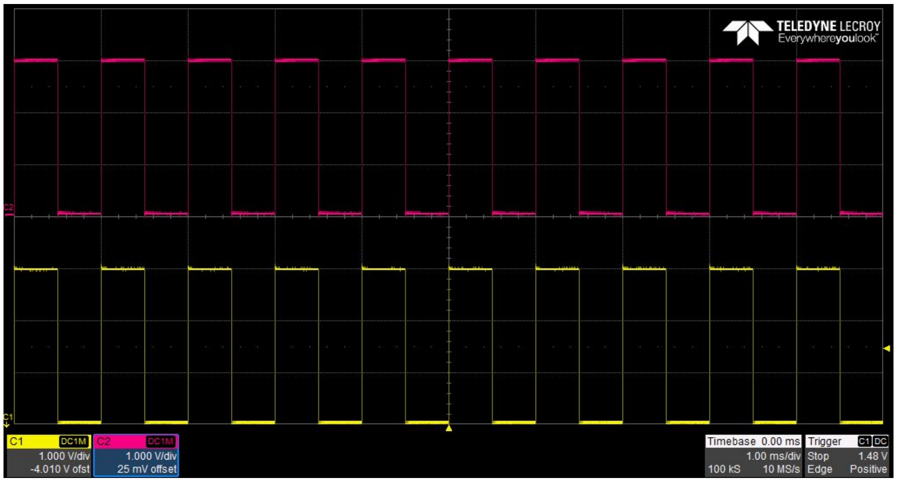

Figure 3. *Result of a completed scope checkout*

To check that the multimeter is working, run a simple voltage through it and make sure that the numbers match up.

How to Connect the FPAA Board to the Digilent Analog Discovery 2

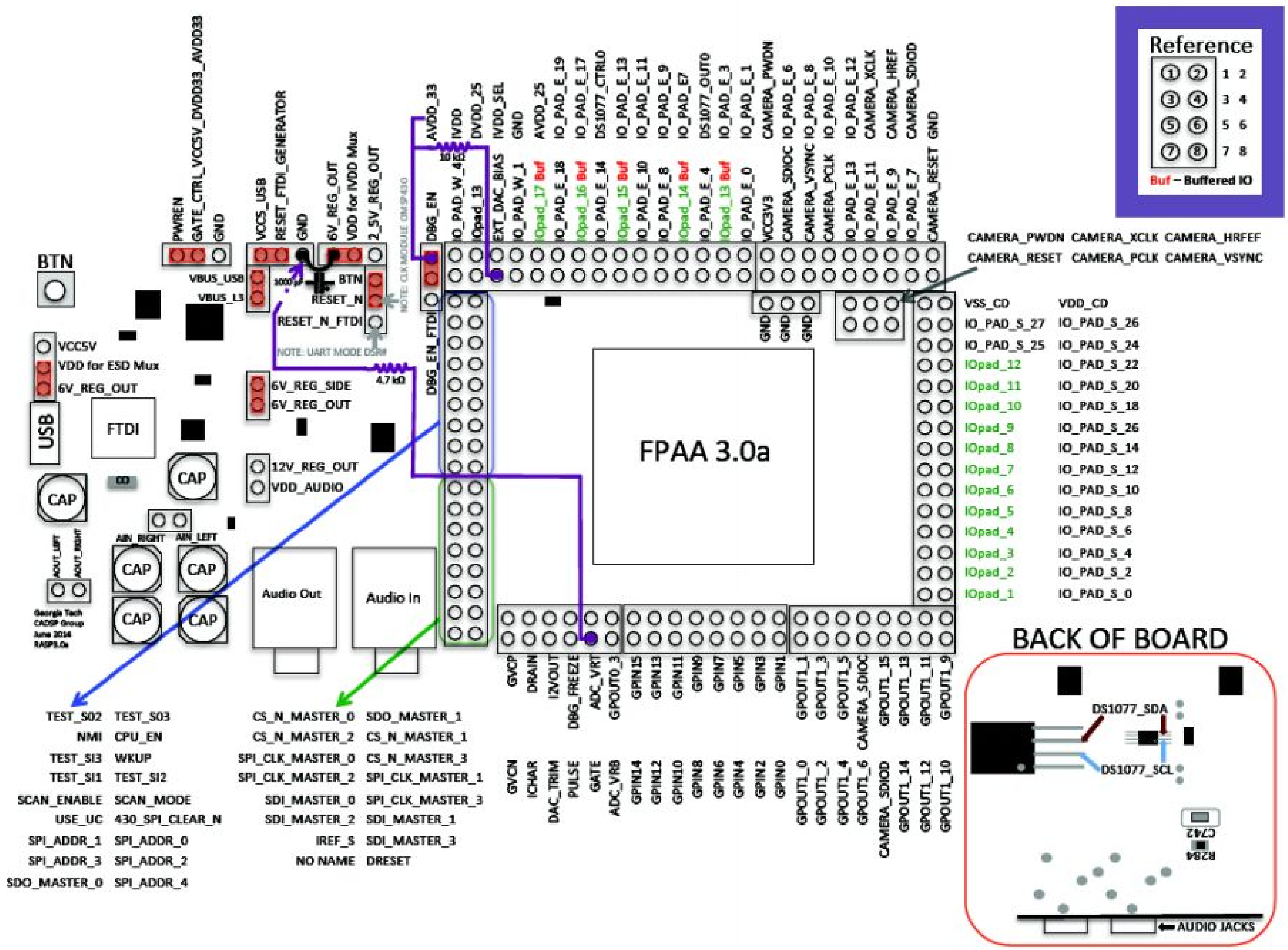

Figure 4. *FPAA Pinout*

When using the blue GUI, you can insert input and output blocks called 'IO PAD'. To get the 'IO PAD' blocks go to the palette browser -> FPAA -> Input/Output Blocks -> I/O Pins. These blocks correlate to the green 'IOpad_#' seen on the right side of figure 4. You can adjust the pinouts in the GUI diagram by double clicking on them and changing the 'pin_num'. Leave the 'Number of IO' as 1.

Sending a Signal from the Digilent Analog Discovery 2 to the FPAA Board

Figure 5. *Off-chip input to output schematic*

Circuit Setup

Connect the waveform generator (yellow wire) to oscilloscope channel 2+ (solid blue wire) and IO pin 1 (white wire). Then connect IO pin 2 to oscilloscope channel 1+ (solid orange wire). Ground oscilloscope channel 1- (striped orange wire) any ground on the FPAA board (grounds can be found in figure 4).

NOTE: in the image, oscilloscope channel 2 and the black ground are not connected to a ground, but they should be while in use.

NOTE: When passing a signal through, the input and output should be identical.

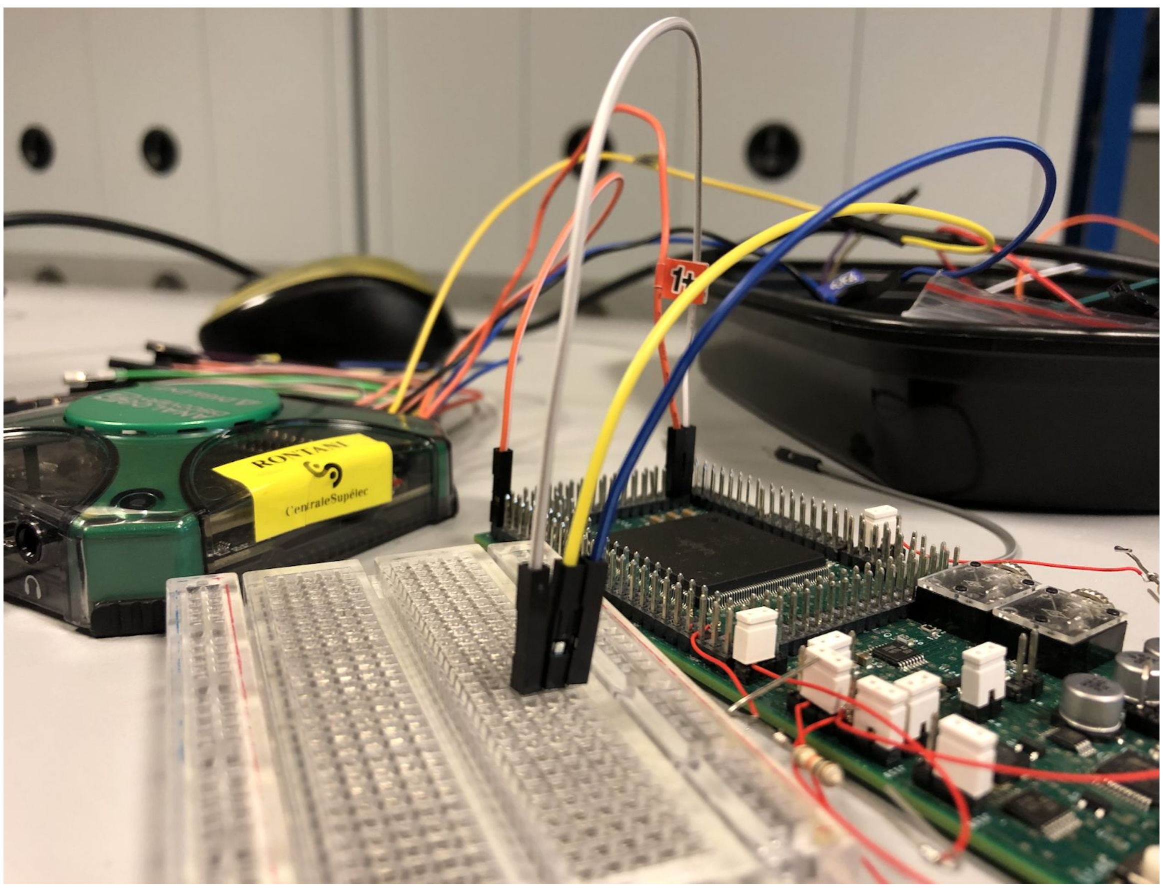

Figure 6. *Breadboard connections for off-chip input pin 1 and output pin 2*

How to Implement the Lowpass Filter Given by the GUI

To implement a low pass filter on the FPAA, create the design shown in Figure 7 using the FPAA GUI (see *FPAA for Dummies* for more details).

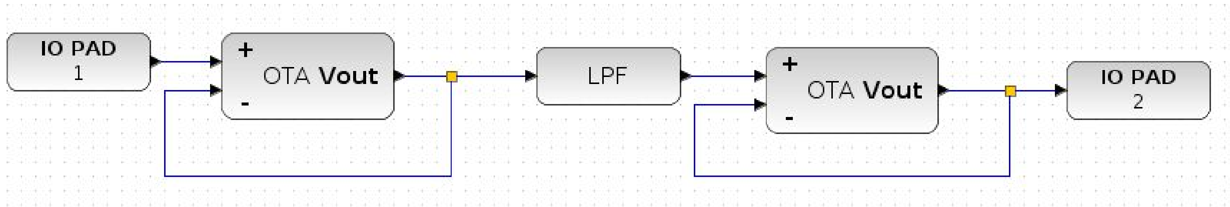

Figure 7. *Off-chip low pass filter implementation on GUI*

Circuit Setup

Note that the design utilizes the first order LPF block ('lpfota', found under the "Mixed Signal Blocks" section) and OTA block (ota, found under the "Level 1 Analog Blocks" section). The OTA blocks balance the impedances at the input and output of the filter - without the OTA blocks, the LPF will not function correctly. As described above, use the oscilloscopes on the Analog Discovery board to measure the input and output waveforms. When sending a signal to the FPAA board, make sure to add a DC offset, as the board cannot produce negative voltages. Additionally, be careful that the peak voltage of the signal is not greater than 2V, as high amplitude signals may damage the board.

Use the same breadboard set up as used in 'Sending a Signal from the Digilent Analog Discovery 2 to the FPAA Board'.

Generated Output

When passing a waveform through this design, the output signal should lag the input signal (as seen in the below figure where the blue is the input and the yellow is the output). Note that the filter does not behave like an ideal first order low-pass filter - the measured cutoff frequency tends to deviate from the cutoff specified in the design by up to 200Hz. In general, the measured cutoff frequency is greater than the specified cutoff for high frequency signals and less than the specified cutoff for low frequency signals.

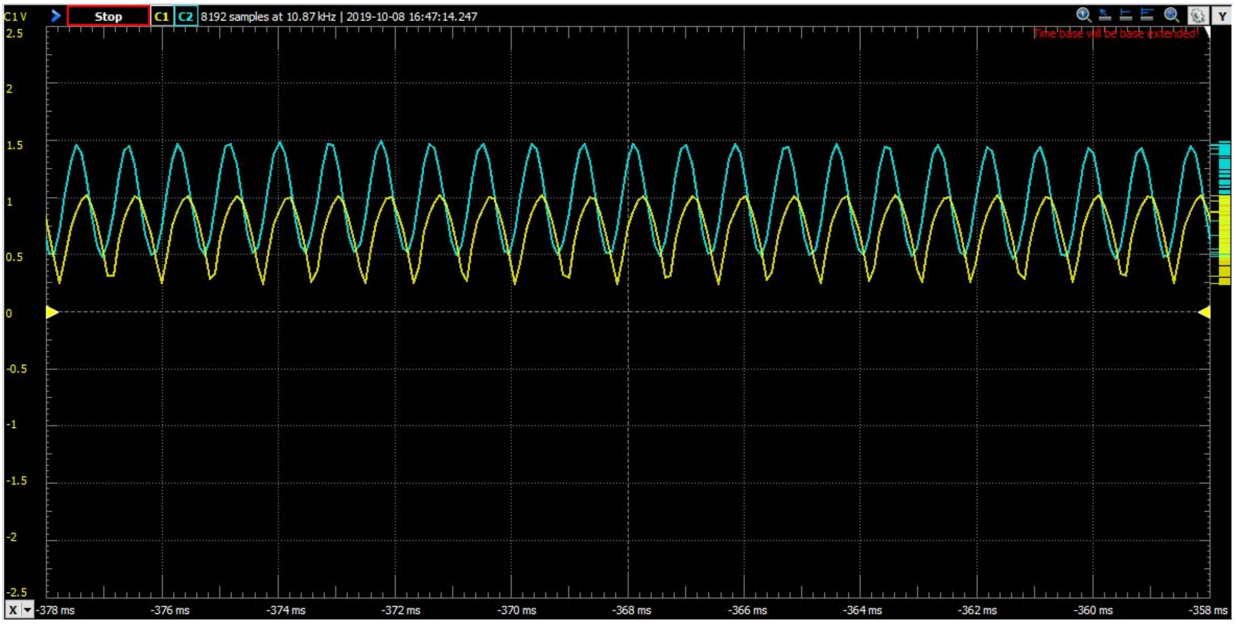

Figure 8. *Output of off-chip LPF; input signal (blue) of 1Vpp, 1.15kHz, 1V offset, cutoff frequency set to 750Hz*

Implementing the Hodgkin-Huxley Neuron on the GUI

Before doing anything, make sure that the GUI has been reset and updated. See 'Common Errors Encountered and How to Fix Them' for more details about this. As a starting point, we will use the HHneuron example design from the SciLab toolbox under the "On chip" tab.

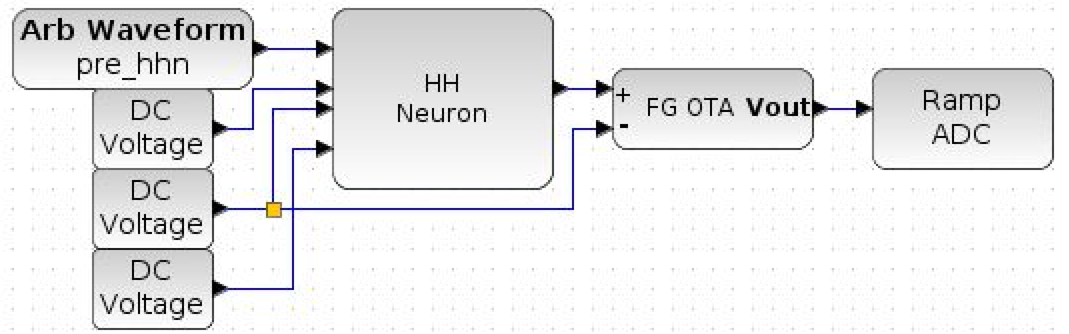

Figure 9. *Hodgkin-Huxley Neuron model from on-chip examples in the GUI*

When opening the example in the GUI, a pop-up window will ask if you would would like to create your own variable via the Scilab Console for the Arbitrary Waveform block - select the "No" option, as the block has already been predefined. Delete the "Arb Waveform" and third "DC Voltage" block and replace with input IO pads. Then delete the "OTA" and "Ramp ADC" blocks and replace with an output IO pad. Your circuit diagram should be formatted as follows:

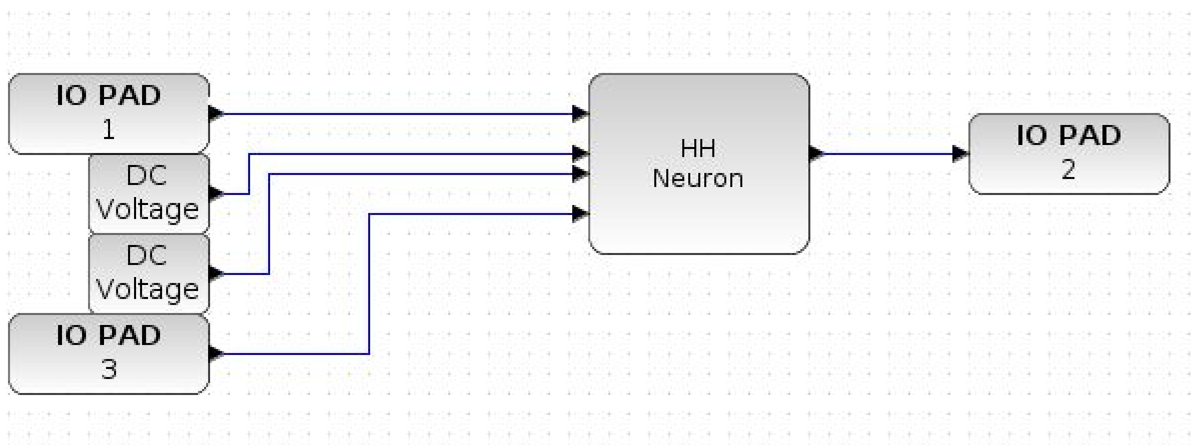

Figure 10. *Adjusted Hodgkin Huxley Neuron block for off-chip testing*

The parameter values for each of the non-IO pad blocks are as follows:

Block Name	Parameter	Value
DC Voltage (Top)	Number of DC blocks	1
	DC values	1.1
	Fix_location	[0;0;0]
DC Voltage (Bottom)	Number of DC blocks	1
	DC values	.85
	Fix_location	[0;0;0]
HH Neuron	Number of blocks	1
	hhn_fgswc_ibias	10e-6
	hhn_fgota1_ibias	1e-5
	hhn_fgota1_pbias	1.5e-6
	hhn_fgota1_nbias	1.5e-6
	hhn_fgota0_ibias	1.2e-6
	hhn_fgota0_pbias	250e-9
	hhn_fgota0_nbias	1e-6
	hhn_ota0_ibias	8e-9
	hhn_ota1_ibias	10e-6
	hhn_cap0_64fF_x_1to7	1
	Fix_location	[0;0;0]

The parameters can be adjusted as needed, but the above values provide a baseline for conducting tests. When testing the output of the neuron make sure that the FPAA board is grounded to the Digilent board - failure to ground the FPAA will result in erroneous results. Also make sure to correctly compile and program your design and to hit the “Take Data” button before measuring the output.

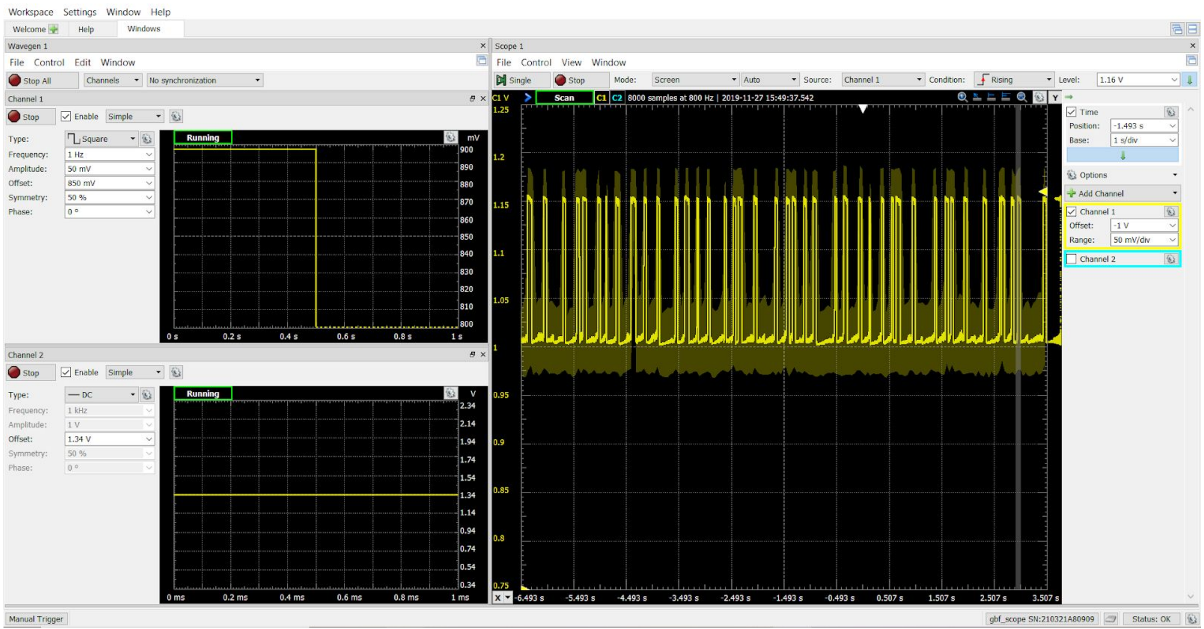

Figure 11. *Hodgkin-Huxley Neuron inputs and outputs*

In the above example, Channel 1 is connected to IO Pad 1 and Channel 2 is connected to IO Pad 3. The input signals can be adjusted to alter the behavior of the neuron. Note that spiking represents a very specific waveform - oftentimes, erroneous waveforms can be measured from the HHneuron without representing true spikes. If an incorrect waveform is measured, verify that the board is properly wired and grounded and check the input parameters of the DC Voltage and HHneuron blocks in the circuit design.

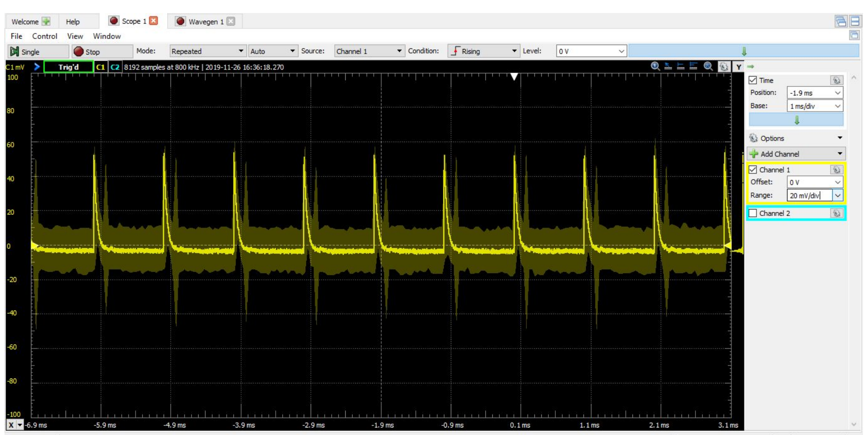

Figure 12. *Erroneous output from Hodgkin-Huxley Neuron Block*

Next Steps with the HHN Block

We are still in the process of characterizing the HHN block by adjusting the different input parameters.

Finding the Threshold Voltage

Leaving a constant 0V input signal, we modify the other parameters. Our goal is to find a set of parameters for which we don't see spikes anymore (i.e we are below the threshold). Once that's done, we'll modify the input until we see spikes again, thus measuring the value of the threshold:

- K channel value: influence the amplitude of spikes. When EK = 1.5V (instead of 1.1V), we obtain spikes more than twice higher (0.37V). When EK = 0.9V, we don't obtain spikes but see some noise. When EK 0.8V we obtain a flat signal. We didn't get an excitable signal by modifying the input signal (frequency, amplitude, offset).
- Vref value: at 1V (instead of 0.85V) we lose the excitable behavior. At 0.75V, almost no spikes at offset 0V. But, when we increase the offset of the input signal, we start seeing regular spikes again. But, still, it wasn't very easy to determine a threshold. So, we decided to lower even further Vref. At 0.35V, we think we have found the correct combination of values. For this value of Vref, no spikes were seen for an offset < 500mV. And regular and periodic spikes appear for an offset > 600mV. We believe this means that we have set the threshold to a value between 500 and 600mV.
- Other remarks:
    - The amplitude of the input signal has an influence on the size of the peaks. When the amplitude increases, the size of the peaks increases a little. When it decreases, the size of the peaks decreases by a lot. The minimum value of amplitude for which peaks are seen is around 50mV. We chose to work with an amplitude of 100mV.
    - The value of ENa is very delicate. Every time the Digilent module is plugged/unplugged, or the card is reprogrammed etc. it is necessary to reset the value of ENa so that we can see the expected excitable behavior of the neuron (not too excitable, but excitable). Here we worked with ENa=1.319V

- The symmetry of the square signal is very important. For 50% we obtained the following (here Vref at 0.75V but same observations for other values of Vref):

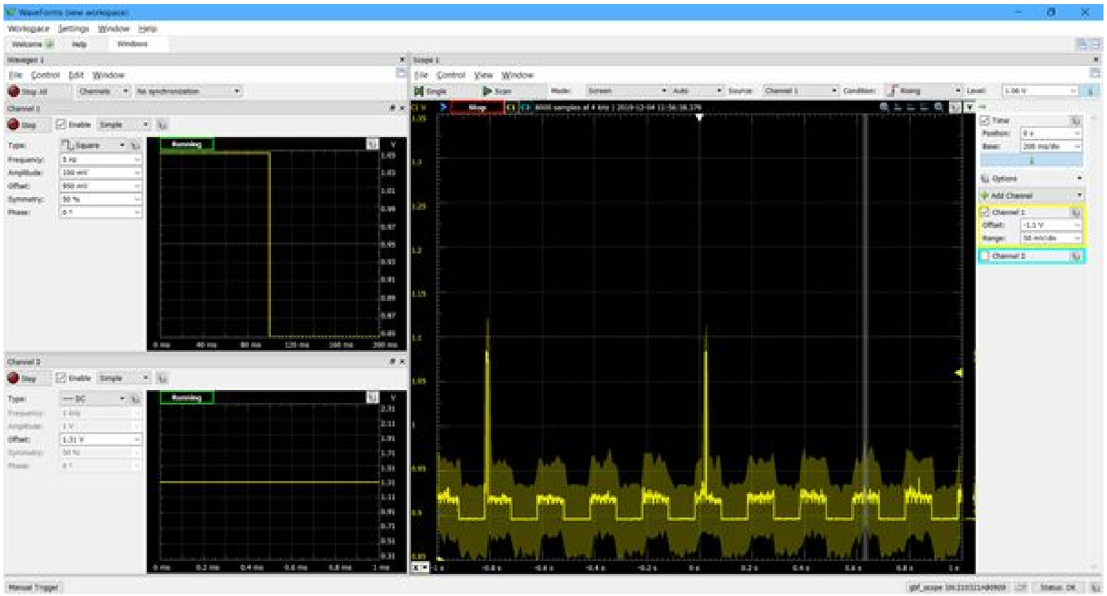

Figure 13. *HHN Output with 50% symmetric square wave*

- We were able to measure the refractory period of the neuron by using a symmetry value of 1%. Indeed, at more than 50%, the neuron never goes back to ground state while the input signal is in a high plateau. We think this means that the neuron hasn't been able to repolarize, and thus cannot spike several times when the input signal stays high.
- The refractory period we measured is around 200ms. So, we decided to work with a frequency between 1 and 5Hz.
- To reproduce our experiment (that gave a neuron that behaved as expected), we can use the following set of values (will probably need some finetuning every time we start an experiment, especially ENa) These values should produce a threshold at around 500-600mV and refractory period of ~200ms:
  - Input signal:

    Frequency = 1Hz

    Offset = 600 mV (to see spikes; and <500mV to avoid spiking)

    Amplitude = 100 mV

    Symmetry = 1%
  - ENa = 1.319 V

- EK = 1.1V
- Vref = 0.35V

Common Errors Encountered and How to Fix Them

- The breadboard and pins are very sensitive, bumping into them can cause the waveform to fluctuate. Try to fix the wires into a position that provides the most stable waveform and leave it in that position. Connection from the board to the computer can randomly disconnect if the board is moved too much.
- Pin connections for the oscilloscope on the Digilent Analog Discovery 2 go after the output pin on the FPAA board.
  - FPAA output -> Oscilloscope plus -> Oscilloscope minus -> Ground
  - See 'Sending a Signal from the Digilent Analog Discovery 2 to the FPAA Board' for a better idea.
- When using off-chip designs, sometimes a OTA buffer is needed do correct impedance mismatches that occur as a signal passes through the different blocks.
  - An example of the implementation can be seen in the section detailing the low pass filter.
- If the GUI designs do not match the ones in this paper, try resetting the GUI. On the blue GUI on the upper left corner, there is a drop-down menu under 'UPDATE'. Reset the GUI before updating it.
  - Do this weekly to ensure that the designs are up do date, it will only take a minute.
  - If the GUI stops working, delete the VM and reinstall it.
- The Digilent Analog Discovery 2 is limited in the frequency that it can output. Try to keep the frequency under 3000 Hz or the waveform will distort as seen below.

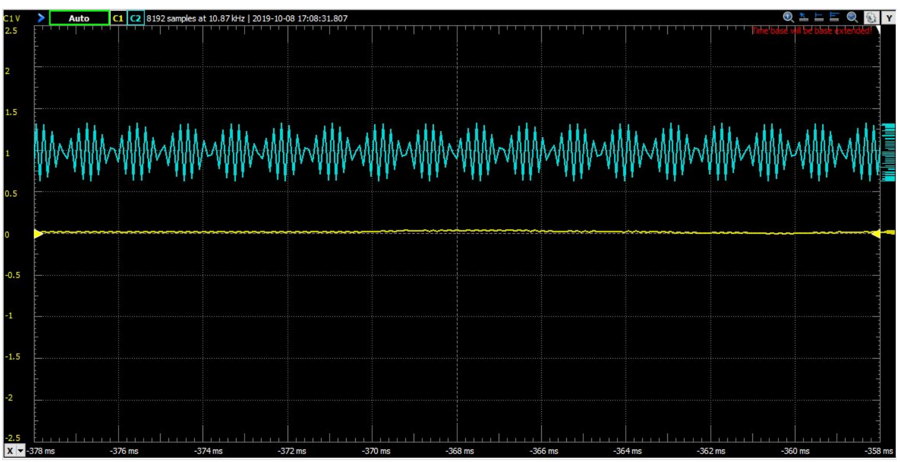

Figure 14. *Output of a 3000hz waveform on the Digilent Analog Discovery 2*

- Even when the function generator isn't running, changing the DC offset of the signal will cause the output signal to change.