

RHS2000



USB/FPGA Interface: RhythmStim

Version 1.0, 21 March 2017; updated 18 March 2019

Features

- ◆ Open-source Verilog hardware description language (HDL) code configures a Xilinx field-programmable gate array (FPGA) to communicate with multiple RHS2116 digital electrophysiology stimulation/amplifier chips
- ◆ Verilog code is written for a commercially-available Opal Kelly XEM6010 module with integrated high-speed USB 2.0 interface
- ◆ Up to 128 simultaneous stimulator/amplifier channels supported at sample rates up to 30 kS/s/channel
- ◆ Programmable FPGA clock for RHS2000 interface: sample rates of 20, 25, or 30 kS/s/channel supported
- ◆ Open-source host computer application programming interface (API) in C++ for multi-platform support
- ◆ Module can interface with eight 16-bit digital-to-analog converters (DACs) and route selected amplifier channels to selected DACs for analog signal reconstruction or audio monitoring with minimal latency
- ◆ Optional control of eight 16-bit analog-to-digital converters (ADCs) for auxiliary analog inputs synchronized to all RHS2000 amplifier channels
- ◆ Auxiliary digital I/O: 16 digital input lines and 16 digital output lines supported
- ◆ Biphasic and triphasic current pulses generated with timing resolution as fine as 33.3 μ s.
- ◆ Independent or coordinated stimulation sequences on all channels triggered by digital inputs or software commands.
- ◆ Analog output ports can generate custom voltage pulses or reconstruct waveforms from selected amplifier channels in real time.
- ◆ Digital output ports can generate custom TTL pulses or act as low latency threshold-based spike detectors.

Applications

- ◆ Windows, Mac, or Linux-based electrophysiology signal acquisition systems
- ◆ Rapid prototyping of Intan Technologies RHS2000-based products
- ◆ Starting point for the development of custom interfaces to RHS2000 chips

Description

To facilitate the development of electrophysiology interface systems using the RHS2000 series of stimulation/amplifier microchips, Intan Technologies provides the following open-source USB/FPGA interface for developers. Designated **RhythmStim**, the interface consists of Verilog HDL code written for the commercially-available Opal Kelly XEM6010 USB/FPGA interface module and a C++ API. RhythmStim configures the Xilinx FPGA on the Opal Kelly module to communicate with up to eight RHS2116 chips over SPI buses and to stream data from these chips to a host computer over a high-speed USB 2.0 interface.

The Opal Kelly drivers and RhythmStim software interfaces are designed for multi-platform development under Windows, Mac, or Linux. All API software is written in C++ to facilitate rapid development. This datasheet provides documentation on the RhythmStim hardware and software protocols so that developers may quickly link the RHS2000 series chips to a host computer of their choice.

RhythmStim supports real-time streaming of up to 128 amplifier channels from multiple RHS2116 chips, data from up to eight other ADCs, and signals from 16 digital inputs. Independent stimulation protocols may be set for all 128 stimulator channels. All data is synchronized and time-stamped before transmission over a standard USB 2.0 bus to the host computer.

RhythmStim FPGA I/O Signals

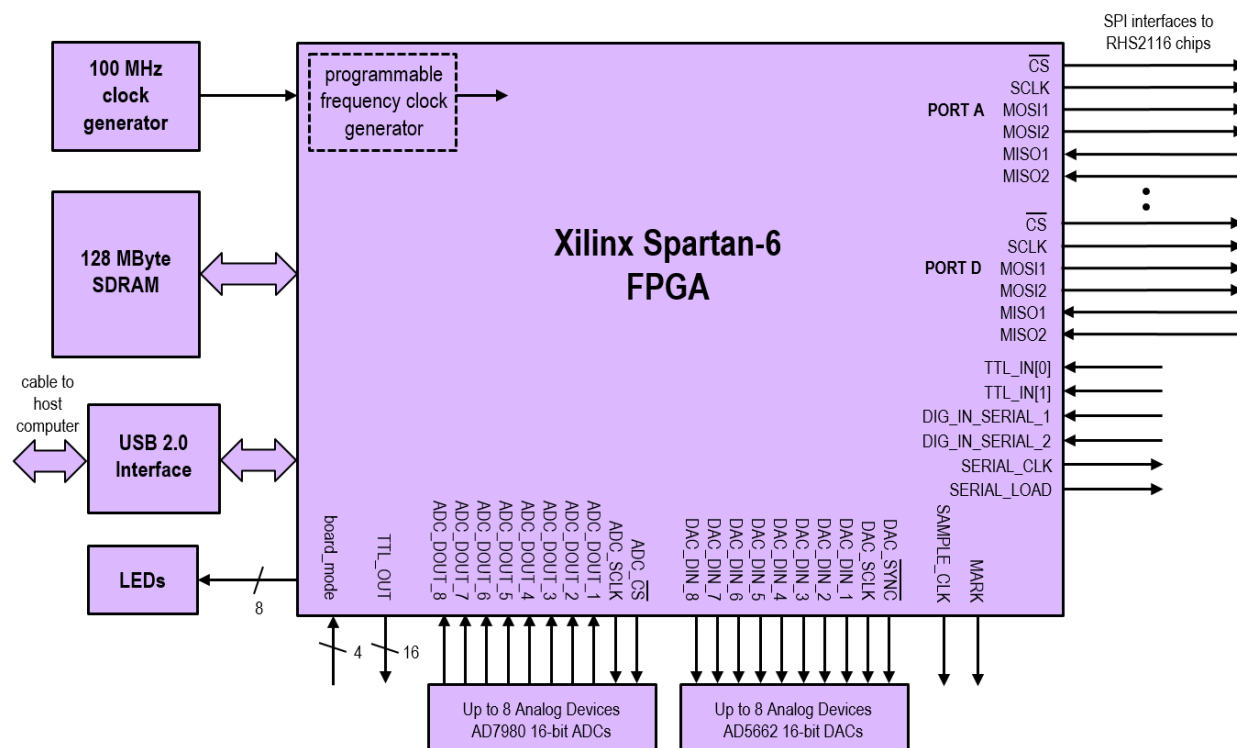
General Description

The RhythmStim interface code is designed for the Opal Kelly XEM6010-LX45 USB/FPGA module which is a small commercially-available circuit board containing a Xilinx Spartan-6 FPGA (XC6SLX45-2), a 128-MByte SDRAM chip, a 100-MHz clock source, I/O connectors, and a USB 2.0 interface chip capable of streaming data to a host computer at rates exceeding 20 MByte/s. (A photo of the board is shown on page 1 of this datasheet. See <http://www.opalkelly.com> for detailed information on this module.)

The Spartan-6 FPGA is a digital chip containing hundreds of thousands of configurable logic gates, flip-flops, and memory cells with programmable connections between them. The FPGA is configured by means of a **bitfile**, which is compiled from Verilog HDL (Hardware Description Language) code using the free Xilinx ISE WebPack software (available from <http://www.xilinx.com>). The bitfile must be uploaded to the FPGA through the host computer interface (USB or PCI Express) every time the board is powered up; it is not stored in non-volatile RAM on the FPGA or the Opal Kelly module. Since this “booting” process takes only a fraction of a second, the flexibility it imparts becomes a useful feature: any changes made to the bitfile can be incorporated into a software release. The FPGA never needs to be programmed using a special EEPROM programmer or JTAG interface.

Opal Kelly also offers the XEM6010-LX150 USB/FPGA module which is identical to the XEM6010-LX45 except for the use of an XC6SLX150-2 FPGA which contains approximately three times as many logic gates as the XC6SLX45-2. Developers who wish to add significant amounts of processing at the FPGA level may wish to use this module. However, to compile Verilog HDL into bitfiles for this larger FPGA, developers must use Xilinx’s ISE Logic Edition software instead of the free WebPack.

The diagram below shows the main elements on the Opal Kelly XEM6010 board and the I/O signals defined by RhythmStim.



RHS2000 USB/FPGA Interface: RhythmStim

RHS2000 SPI Interfaces

RhythmStim sets up four SPI ports (labeled A, B, C, and D) that can send independent command streams to different sets of RHS2116 chips. Unlike the RHD2000 version of Rhythm, LVDS signals are not generated directly by the FPGA, requiring the user to add external CMOS-to-LVDS interfacing chips (e.g., the SN65LVDT41 from Texas Instruments) if LVDS signals will be used to interface with the RHS2000 chips. LVDS signaling is recommended for operation over long cables.

Each SPI port on the FPGA has four output signals that coordinate communication with RHS2116 chips and send commands: \overline{CS} , SCLK, and two MOSI (Master Out, Slave In) signals: MOSI1 and MOSI2. The FPGA always acts as the SPI master device, and each RHS2116 acts as an SPI slave device. Each SPI port in RhythmStim has two MISO (Master In, Slave Out) inputs for receiving data from an RHS2116 chip: MISO1 and MISO2. This means that each port can be connected to two RHS2116 chips and send these chips independent commands. This permits the construction of compact 32-channel stimulation/recording modules using two RHS2116 chips, for example. Each module requires a 16-conductor cable to support six LVDS SPI signals plus +3.3V power, ground, and positive and negative stimulation voltage supplies VSTIM+ and VSTIM-.

The use of LVDS signals permits robust data transfer over cables several meters in length. However, long cables will introduce significant delays to the SPI signals. Typical cable propagation velocities are two-thirds the speed of light – about 20 cm/ns – so a three-meter cable will have a round-trip signal delay of 30 ns. (At high sampling rates, the SCLK period may be less than 50 ns.) RhythmStim allows users to adjust the MISO sampling delay independently on all four SPI ports to account for cable delays.

Using dual MISO and MOSI signals on each of four ports, the FPGA can stream data from up to eight RHS2116 chips, so a total of 128 amplifier channels may be acquired in real time. The USB 2.0 interface on the Opal Kelly XEM6010 module is capable of reliably streaming data from 128 channels to a host computer at per-channel sampling rates up to 30 kS/s, even with typical USB protocol overhead and software overhead.

RhythmStim sends commands to all RHS2116 chips in a repeating 20-command sequence: every sampling period, the FPGA sends the commands CONVERT(0), CONVERT(1), CONVERT(2), and so on up to CONVERT(15) to sample from all 16 amplifiers on the chip. These 16 CONVERT commands are followed by four “auxiliary” commands that may be used to perform a variety of other tasks on an RHS2116 chip, like controlling stimulation pulses, activating amplifier fast recovery circuits, synthesizing a waveform for electrode impedance testing, or reading and writing other registers. Under RhythmStim, the first 16 CONVERT commands are fixed, but the remaining auxiliary commands may be programmed from the host computer.

A clock generator on the Opal Kelly circuit board provides a 100-MHz clock to the FPGA; this clock is used to run the USB interface logic. RhythmStim controls an on-FPGA frequency synthesizer that is used to generate a programmable-frequency clock that can be reconfigured by the host computer to produce many different SPI data rates so that the RHS2116 amplifiers can be sampled at per-channel rates of 20, 25, or 30 kS/s. The minimum timing resolution of stimulation pulses is equal to the reciprocal of the per-channel sampling rate, so with a sampling rate of 30 kS/s, the minimum stimulation timing resolution is 33.3 μ s.

Other I/O Signals

RhythmStim also defines I/O pins that can be connected to several commercially-available 16-bit DACs and ADCs. The Verilog code supports up to eight 16-bit DACs and eight 16-bit ADCs that communicate using a three-wire SPI interface. RhythmStim is designed to support the Analog Devices AD5662 DAC and the Analog Devices AD7980 ADC (**note:** the older Rhythm code for RHD2000 chips supported the AD7680 ADC, which has a different command protocol); other DACs and ADCs could be supported by modifying the Verilog code. RhythmStim permits the user to select particular RHS2116 amplifier channels to be routed directly to selected DACs through the FPGA, eliminating any USB or host computer latency. Analog output ports can also be configured to generate custom voltage pulses. Alternatively, any of the DACs may be controlled by a dedicated data stream from the host computer if more latency can be tolerated.

The optional ADCs are sampled in synchrony with the RHS2116 amplifiers, and their results are streamed back to the host computer over the USB interface.

RhythmStim also supports 16 digital inputs and 16 digital outputs. Although these are labeled as “TTL” I/O, the FPGA pins operate at 3.3V, but most input pins are tolerant of 5V signals. Two digital inputs are sampled directly; more can be implemented using 74HC165 shift register integrated circuits (contact Intan Technologies for more information). Digital and analog inputs may be used to trigger RHS2116 stimulation pulses.

Eight of the digital outputs may serve as low-latency threshold comparators for the signals routed to the DACs. Threshold levels and polarities may be specified, and the FPGA will trigger the appropriate digital outputs if each threshold is exceeded.

RHS2000 USB/FPGA Interface: RhythmStim

The Opal Kelly board has an array of eight red LEDs (in addition to a green power LED) that may be controlled by the host computer. Additional FPGA pins are allocated for the control of eight SPI port LEDs and three general-purpose status LEDs.

A digital output signal **sample_clk** is provided on FPGA pin L51P as a convenience. This signal is a clock running at the per-channel amplifier sampling rate. The duty cycle of the signal is 1/20. For example, if the board is configured to sample each RHS2116 amplifier channel at 20 kS/s then the period of this clock will be 50 μ s. It will be high for 2.5 μ s, and low the rest of the cycle. (The signal goes high at the falling edge of CS that begins the CONVERT(0) command, and it goes low at the falling edge of CS that begins the CONVERT(1) command.)

Power Supply

The total current consumption of the XEM6010 board running RhythmStim is approximately 500 mA from 5V, not including current consumed by RHS2116 chips and other ADCs and DACs. Current supplied from a USB port is limited to 500 mA. Since a RhythmStim-based module will likely exceed this limit once RHS2116 chips and other ADCs and DACs are added, it is recommended to power the Opal Kelly XEM6010 board from a 5V DC power supply capable of sourcing sufficient current and having a 2.1mm inner-diameter / 5.5mm outer-diameter connector. Opal Kelly offers a PSS050-25 power supply that provides up to 2.5 A of current. Digi-Key (<http://www.digikey.com>) offers a medical-rated power supply that mates with the XEM6010 board, supplies up to 2.0 A of current, and includes connectors for AC plugs in a variety of countries (part number T1233-P5P-ND).

The Opal Kelly board provides regulated 1.2V, 1.8V, and 3.3V supplies. See the Opal Kelly documentation for current limits on these supplies.

If RHS2116 chips will be powered over long cables, it is a good idea use a linear regulator to generate a 3.5V power supply from the 5V power delivered to the board. RHS2116 chips may be safely powered at 3.5V, and the excess 0.2 V above the nominal power supply voltage of 3.3V will make up for some of the IR losses incurred over long cables with thin power wires.

I/O Pin Locations

The I/O pin tables on the following two pages are based information in the Opal Kelly XEM6010 User's Manual. Due to reuse of some circuit board design layouts at Intan Technologies, there are naming inconsistencies with the SPI port I/O pins as noted in these tables. The pins for SPI Port A are listed as CS_A, SCLK_A, MOSI_A1, etc., as expected. However, the pins for SPI Port B are listed as CS_C, SCLK_C,... The pins for SPI Port C are listed as CS_E, SCLK_E,... The pins for SPI Port D are listed as CS_G, SCLK_G,... The pins ending in _B, _D, _F, and _H are not used in RhythmStim. (These pins are used in Rhythm USB3, which is designed to operate the RHD2000 recording-only chips. Some circuit boards used at Intan Technologies are designed to work with FPGA modules running either interface API. RhythmStim uses alternating ports due to the physical width of SPI interface daughterboards that are added to the motherboard.)

Users may wish to purchase the BRK6110 breakout board which can be connected to the XEM6010 module, and which brings the I/O pins out to convenient 2mm-pitch headers.

FPGA pin names come in pairs of positive and negative signals that can be used as LVDS pairs (e.g., L34P_1 and L34N_1 are I/O pin pairs in FPGA Bank 1). An inspection of the **xem6310.ucf** file provided with RhythmStim shows that the IOSTANDARD="LVDS_33" flag is used for LVDS signals, while IOSTANDARD="LVCMOS33" is used for standard CMOS signals. If the RhythmStim code is modified to include additional LVDS signals, it is important to note that LVDS outputs can only be instantiated on Bank 0 of this FPGA (i.e., pin names ending in "_0").

LVDS inputs, like all the MISO signals, have on-FPGA 100- Ω termination resistors activated by the DIFF_TERM=TRUE flag in the **xem6310.ucf** file.

JP2 I/O Connections

JP2 Pin	Connection	FPGA Pin	RhythmStim Interface Pin Name
1	DGND		GND
3	VBATT		
5	JTAG_TCK		
7	JTAG_TMS		
9	JTAG_TDI		
11	U12	L22N_2	
13	DGND		GND
15	G16	L9P_1	SAMPLE_CLK
17	G17	L9N_1	MARK
19	H19	L34P_1	SERIAL_LOAD
21	H18	L34N_1	SERIAL_CLK
23	F16	L10P_1	SPI_LED_H
25	F17	L10N_1	SPI_LED_G
27	J17	L36P_1	SPI_LED_F
29	K17	L36N_1	SPI_LED_E
31	K16	L21P_1	SPI_LED_D
33	J16	L21N_1	SPI_LED_C
35	+VCCO1		
37	V21	L52P_1	SPI_LED_B
39	V22	L52N_1	SPI_LED_A
41	T21	L50P_1	MISO_H2 (not used)
43	T22	L50N_1	MISO_H1 (not used)
45	P21	L48P_1	MOSI_H2 (not used)
47	P22	L48N_1	MOSI_H1 (not used)
49	M21	L46P_1	SCLK_H (not used)
51	M22	L46N_1	$\overline{\text{CS}}_H$ (not used)
53	L20	L45P_1	MISO_G2 (Port D)
55	+VCCO1		
57	L22	L45N_1	MISO_G1 (Port D)
59	H21	L41P_1	MOSI_G2 (Port D)
61	H22	L41N_1	MOSI_G1 (Port D)
63	F21	L37P_1	SCLK_G (Port D)
65	F22	L37N_1	$\overline{\text{CS}}_G$ (Port D)
67	D21	L31P_1	MISO_F2 (not used)
69	D22	L31N_1	MISO_F1 (not used)
71	B21	L19P_1	MOSI_F2 (not used)
73	B22	L19N_1	MOSI_F1 (not used)
75	A21	L20N_1	SCLK_F (not used)
77	J20	L43P_1	$\overline{\text{CS}}_F$ (not used)
79	J22	L43N_1	MISO_E2 (Port C)

JP2 Pin	Connection	FPGA Pin	RhythmStim Interface Pin Name
2	+3.3VDD		VDD
4	+3.3VDD		VDD
6	+3.3VDD		VDD
8	JTAG_TDO		
10	VREF_1		
12	RFUSE		
14	DGND		GND
16	G19	L33P_1	$\overline{\text{CS}}_A$ (Port A)
18	F20	L33N_1	SCLK_A (Port A)
20	H20	L38P_1	MOSI_A1 (Port A)
22	J19	L38N_1	MOSI_A2 (Port A)
24	D19	L29P_1	MISO_A1 (Port A)
26	D20	L29N_1	MISO_A2 (Port A)
28	F18	L30P_1	$\overline{\text{CS}}_B$ (not used)
30	F19	L30N_1	SCLK_B (not used)
32	M16	L58P_1	MOSI_B1 (not used)
34	L15	L58N_1	MOSI_B2 (not used)
36	DGND		GND
38	K20	L40P_1	MISO_B1 (not used)
40	K19	L40N_1	MISO_B2 (not used)
42	U20	L51P_1	$\overline{\text{CS}}_C$ (Port B)
44	U22	L51N_1	SCLK_C (Port B)
46	R20	L49P_1	MOSI_C1 (Port B)
48	R22	L49N_1	MOSI_C2 (Port B)
50	N20	L47P_1	MISO_C1 (Port B)
52	N22	L47N_1	MISO_C2 (Port B)
54	M20	L42P_1	$\overline{\text{CS}}_D$ (not used)
56	DGND		GND
58	L19	L42N_1	SCLK_D (not used)
60	K21	L44P_1	MOSI_D1 (not used)
62	K22	L44N_1	MOSI_D2 (not used)
64	G20	L39P_1	MISO_D1 (not used)
66	G22	L39N_1	MISO_D2 (not used)
68	E20	L35P_1	$\overline{\text{CS}}_E$ (Port C)
70	E22	L35N_1	SCLK_E (Port C)
72	C20	L32P_1	MOSI_E1 (Port C)
74	C22	L32N_1	MOSI_E2 (Port C)
76	A20	L20P_1	MISO_E1 (Port C)
78	DGND		GND
80	DGND		GND

JP3 I/O Connections

JP3 Pin	Connection	FPGA Pin	RhythmStim Interface Pin Name
1	+VDC		+5V
3	+VDC		+5V
5	+VDC		+5V
7	+1.8VDD		
9	+3.3VDD		VDD
11	+3.3VDD		VDD
13	+3.3VDD		VDD
15	W20	L60P_1	ADC_CNVS
17	W22	L60N_1	DAC_SCLK
19	U19	L70P_1	DAC_SYNC
21	V20	L70N_1	DAC_DIN_8
23	C5	L2P_0	LVDS_1+
25	A5	L2N_0	LVDS_1-
27	D14	L49P_0	DAC_DIN_7
29	C14	L49N_0	DAC_DIN_6
31	E16	L66P_0	LVDS_2+
33	D17	L66N_0	LVDS_2-
35	DGND		GND
37	D7	L32P_0	DAC_DIN_5
39	D8	L32N_0	DAC_DIN_4
41	L17	L61P_1	LVDS_3+
43	K18	L61N_1	LVDS_3-
45	D6	L3P_0	LVDS_4+
47	C6	L3N_0	LVDS_4-
49	A3	L1P_0	unused
51	A4	L1N_0	DAC_DIN_3
53	B8	L6P_0	DAC_DIN_2
55	DGND		GND
57	A8	L6N_0	DAC_DIN_1
59	B10	L34P_0	ADC_DOUT_2
61	A10	L34N_0	ADC_DOUT_1
63	C13	L38P_0	DIG_IN_SERIAL_2
65	A13	L38N_0	DIG_IN_SERIAL_1
67	C15	L51P_0	EXP_ID
69	A15	L51N_0	EXP_DETECT
71	C17	L64P_0	STATUS_LED_3
73	A17	L64N_0	STATUS_LED_2
75	A18	L65N_0	STATUS_LED_1
77	C11	L35P_0	LVDS_5+
79	A11	L35N_0	LVDS_5-

JP3 Pin	Connection	FPGA Pin	RhythmStim Interface Pin Name
2	DGND		GND
4	+1.2VDD		
6	+1.2VDD		
8	T14	L23P_2	
10	Y9	L43P_2	
12	AB9	L43N_2	
14	DGND		GND
16	T19	L74P_1	ADC_SCLK
18	T20	L74N_1	TTL_OUT[0]
20	P17	L72P_1	TTL_OUT[1]
22	N16	L72N_1	TTL_OUT[2]
24	M17	L71P_1	TTL_OUT[3]
26	M18	L71N_1	TTL_OUT[4]
28	P18	L73P_1	TTL_OUT[5]
30	R19	L73N_1	TTL_OUT[6]
32	D9	L7P_0	board_mode[0]
34	C8	L7N_0	board_mode[1]
36	+VCCO0		
38	D10	L33P_0	board_mode[2]
40	C10	L33N_0	board_mode[3]
42	D11	L36P_0	TTL_OUT[7]
44	C12	L36N_0	TTL_OUT[8]
46	D15	L62P_0	TTL_OUT[9]
48	C16	L62N_0	TTL_OUT[10]
50	B6	L4P_0	TTL_OUT[11]
52	A6	L4N_0	TTL_OUT[12]
54	C7	L5P_0	TTL_OUT[13]
56	+VCCO0		
58	A7	L5N_0	TTL_OUT[14]
60	C9	L8P_0	TTL_OUT[15]
62	A9	L8N_0	ADC_DOUT_8
64	B12	L37P_0	ADC_DOUT_7
66	A12	L37N_0	ADC_DOUT_6
68	B14	L50P_0	ADC_DOUT_5
70	A14	L50N_0	ADC_DOUT_4
72	B16	L63P_0	ADC_DOUT_3
74	A16	L63N_0	TTL_IN[1]
76	B18	L65P_0	TTL_IN[0]
78	DGND		GND
80	DGND		GND

General Description of Interface Operation

Host Computer Interface

Most electrophysiology recording applications require that data is sampled at a steady rate for long periods of time. To interface this steady stream of data with a host computer that uses a modern, multitasking operating system requires a hardware FIFO (First In, First Out) buffer to store data during brief intervals while the computer is busy performing other tasks. Luckily, the Opal Kelly board includes a 128 MByte SDRAM chip that can be used for just such a purpose. The RhythmStim code implements an SDRAM-based FIFO as a circular queue of 16-bit words. Two on-FPGA 4 kByte "mini-FIFOs" regulate the flow of data into and out of the main SDRAM FIFO. The output of the FIFO is connected to a "PipeOut" endpoint for transfer across the USB port to the host computer (see details below).

The FIFO is capable of reporting the number of 16-bit words it is currently holding. There is no mechanism in the FIFO to protect against underflow. That is, if the computer tries to read more data than the FIFO is currently holding, the FIFO will just repeat the last word after it runs out of data. To prevent underflow, it is essential for the host to monitor the amount of data in the FIFO and never attempt to read more words than the FIFO contains.

Neither is there a mechanism in the FIFO to protect against overflow. If the FIFO fills up, it will "lap" the unread data and begin writing over old data in the SDRAM. So the host computer must monitor the number of words in the FIFO and make sure it doesn't get too full. The capacity of the FIFO is dominated by the 128-Mbyte SDRAM. This can hold $2^{27} = 134,217,728$ bytes, or $2^{26} = 67,108,864$ 16-bit words. The on-FPGA "mini-FIFOs" add a couple of thousand more words to this total, but it is good practice never to allow the FIFO to get more than 75% full in case the computer OS hangs for a moment.

In order to completely "clean out" the FIFO after pausing or stopping the flow of data into it, it is necessary to always write an integer multiple of **four** 16-bit words to the FIFO. The SDRAM chip reads data only in 64-bit chunks, so if there are one, two, or three 16-bit words of data remaining in the input mini-FIFO, they will not be read into the SDRAM (and passed to the output mini-FIFO and thence the USB bus) after the flow of data from the source has stopped. The RhythmStim Verilog code is structured to ensure that data frames are always integer multiples of four 16-bit words.

The RhythmStim interface is capable of transmitting up to eight simultaneous **data streams**. In RhythmStim, a data stream is defined as the SPI output of one MISO line from an RHS2116 chip. In most cases, the eight data streams will correspond to the eight MISO inputs to the FPGA in Ports A, B, C, and D. Each data stream conveys 16 amplifier channels. Data streams may be disabled if they are not used; this will reduce the amount of data flowing through the FIFO and across the USB interface to the computer.

Data Frame Format

A data frame of identical format is transmitted to the FIFO once per amplifier sampling period. The size of the data frame depends on the number of data streams that are enabled. The data frame has the following structure:

64-bit header: a "magic number" always equal to 0x8D542C8A49712F0B that can be used to check for data synchrony.

32-bit timestamp: a 32-bit counter that starts at zero and increments by one every data frame.

32-bit MISO result 1 from data stream 1 (if data stream 1 is enabled)
32-bit MISO result 1 from data stream 2 (if data stream 2 is enabled)
32-bit MISO result 1 from data stream 3 (if data stream 3 is enabled)
32-bit MISO result 1 from data stream 4 (if data stream 4 is enabled)
32-bit MISO result 1 from data stream 5 (if data stream 5 is enabled)
32-bit MISO result 1 from data stream 6 (if data stream 6 is enabled)
32-bit MISO result 1 from data stream 7 (if data stream 7 is enabled)
32-bit MISO result 1 from data stream 8 (if data stream 8 is enabled)

32-bit MISO result 2 from data stream 1 (if data stream 1 is enabled)
32-bit MISO result 2 from data stream 2 (if data stream 2 is enabled)
32-bit MISO result 2 from data stream 3 (if data stream 3 is enabled)
32-bit MISO result 2 from data stream 4 (if data stream 4 is enabled)
32-bit MISO result 2 from data stream 5 (if data stream 5 is enabled)
32-bit MISO result 2 from data stream 6 (if data stream 6 is enabled)

RHS2000 USB/FPGA Interface: RhythmStim

32-bit MISO result 2 from data stream 7 (if data stream 7 is enabled)

32-bit MISO result 2 from data stream 8 (if data stream 8 is enabled)

...

32-bit MISO result 20 from data stream 1 (if data stream 1 is enabled)

32-bit MISO result 20 from data stream 2 (if data stream 2 is enabled)

32-bit MISO result 20 from data stream 3 (if data stream 3 is enabled)

32-bit MISO result 20 from data stream 4 (if data stream 4 is enabled)

32-bit MISO result 20 from data stream 5 (if data stream 5 is enabled)

32-bit MISO result 20 from data stream 6 (if data stream 6 is enabled)

32-bit MISO result 20 from data stream 7 (if data stream 7 is enabled)

32-bit MISO result 20 from data stream 8 (if data stream 8 is enabled)

16-bit stimulation on/off present value from data stream 1 (if data stream 1 is enabled)

16-bit stimulation on/off present value from data stream 2 (if data stream 2 is enabled)

16-bit stimulation on/off present value from data stream 3 (if data stream 3 is enabled)

16-bit stimulation on/off present value from data stream 4 (if data stream 4 is enabled)

16-bit stimulation on/off present value from data stream 5 (if data stream 5 is enabled)

16-bit stimulation on/off present value from data stream 6 (if data stream 6 is enabled)

16-bit stimulation on/off present value from data stream 7 (if data stream 7 is enabled)

16-bit stimulation on/off present value from data stream 8 (if data stream 8 is enabled)

16-bit stimulation polarity present value from data stream 1 (if data stream 1 is enabled)

16-bit stimulation polarity present value from data stream 2 (if data stream 2 is enabled)

16-bit stimulation polarity present value from data stream 3 (if data stream 3 is enabled)

16-bit stimulation polarity present value from data stream 4 (if data stream 4 is enabled)

16-bit stimulation polarity present value from data stream 5 (if data stream 5 is enabled)

16-bit stimulation polarity present value from data stream 6 (if data stream 6 is enabled)

16-bit stimulation polarity present value from data stream 7 (if data stream 7 is enabled)

16-bit stimulation polarity present value from data stream 8 (if data stream 8 is enabled)

16-bit amplifier settle on/off present value from data stream 1 (if data stream 1 is enabled)

16-bit amplifier settle on/off present value from data stream 2 (if data stream 2 is enabled)

16-bit amplifier settle on/off present value from data stream 3 (if data stream 3 is enabled)

16-bit amplifier settle on/off present value from data stream 4 (if data stream 4 is enabled)

16-bit amplifier settle on/off present value from data stream 5 (if data stream 5 is enabled)

16-bit amplifier settle on/off present value from data stream 6 (if data stream 6 is enabled)

16-bit amplifier settle on/off present value from data stream 7 (if data stream 7 is enabled)

16-bit amplifier settle on/off present value from data stream 8 (if data stream 8 is enabled)

16-bit charge recovery on/off present value from data stream 1 (if data stream 1 is enabled)

16-bit charge recovery on/off present value from data stream 2 (if data stream 2 is enabled)

16-bit charge recovery on/off present value from data stream 3 (if data stream 3 is enabled)

16-bit charge recovery on/off present value from data stream 4 (if data stream 4 is enabled)

16-bit charge recovery on/off present value from data stream 5 (if data stream 5 is enabled)

16-bit charge recovery on/off present value from data stream 6 (if data stream 6 is enabled)

16-bit charge recovery on/off present value from data stream 7 (if data stream 7 is enabled)

16-bit charge recovery on/off present value from data stream 8 (if data stream 8 is enabled)

16-bit DAC 1 present value

16-bit DAC 2 present value

16-bit DAC 3 present value

16-bit DAC 4 present value

16-bit DAC 5 present value

16-bit DAC 6 present value

16-bit DAC 7 present value

16-bit DAC 8 present value

16-bit ADC 1 result

RHS2000 USB/FPGA Interface: RhythmStim

16-bit ADC 2 result
16-bit ADC 3 result
16-bit ADC 4 result
16-bit ADC 5 result
16-bit ADC 6 result
16-bit ADC 7 result
16-bit ADC 8 result

16-bit TTL input result

16-bit TTL output present value

This format ensures that each data frame contains an integer multiple of four 16-bit words, as required by the FIFO (see previous section). Each data frame contains $(44 \cdot N + 24)$ words or $2 \cdot (44 \cdot N + 24)$ bytes, where N is the number of data streams that are enabled. The Opal Kelly USB interface sends data in bytes. In RhythmStim, the least-significant byte of each multi-byte word is always sent first.

If we know the size of the data frame and the sampling rate, we can calculate the capacity of the FIFO. For example, a 32-channel system ($N = 2$) will have a data frame 224 bytes in length. Running at the maximum rate of 30 kS/s, the data rate will be 6.72 MByte/s. At this rate, the FIFO can hold up to 20 seconds of data. A 128-channel system ($N = 8$) will have a data frame 752 bytes in length. Running at the maximum rate of 30 kS/s, the data rate will be 22.56 MByte/s. At this rate, the FIFO can hold up to 5.9 seconds of data. These calculations demonstrate that the FIFO has plenty of capacity to handle typical brief operating system pauses during USB data transfers.

The Opal Kelly USB interface can easily handle 22.56 MByte/s data rates, provided a reasonably fast host computer is used. A Dell Precision T1650 Windows 7 PC purchased in 2012 with a 3.4 GHz Xeon processor routinely achieved maximum USB data rates exceeding 29 MByte/s with the Opal Kelly XEM6010 board and C++ software. Data rates of 35-38 MByte/s for USB 2.0 are not reached unless very large packet transfers (1 MByte or greater) are executed, which would lead to significant latency in most applications.

The bulk of each data frame consists of MISO results received from the SPI interface from each RHS2116 chip. These MISO results are numbered 1 through 20, and correspond to the 20 repeated commands sent over the MOSI lines to each device during each sampling period. The repeating MOSI command structure is as follows:

```
CONVERT(0)
CONVERT(1)
CONVERT(2)
...
CONVERT(15)
auxiliary command 1
auxiliary command 2
auxiliary command 3
auxiliary command 4
```

It is important to remember that the RHS2116 uses a pipelined communication protocol; each command sent over the MOSI line generates a 32-bit result that is transmitted over the MISO line two commands later (see the “SPI Command Words” section of the RHS2116 datasheet for details). The FPGA introduces another one-command pipeline delay in the received MISO results, so **every MISO result received through the RhythmStim FPGA corresponds to the MOSI command sent three steps earlier.** Thus “MISO result 1” is the result of the “auxiliary command 2” from the previous sampling period; “MISO result 4” corresponds to the “CONVERT(0)” command from the current sampling period; and “MISO result 20” corresponds to the “auxiliary command 1” command from the current sampling period. To see the result of auxiliary commands 2-4 at the end of a sampling period, the next data frame must be read.

Programming Auxiliary Command Sequences

Each RHS2000 SPI port (A, B, C, and D) can send a different set of commands in the four auxiliary command slots described above, which we will abbreviate as **auxcmd1**, **auxcmd2**, **auxcmd3**, and **auxcmd4**. Sequences of auxiliary commands can be uploaded into on-FPGA RAM banks that each hold up to 8192 commands for each of the four slots. These command sequences

RHS2000 USB/FPGA Interface: RhythmStim

will be transmitted over both MOSI lines from each port, but **WireInAuxEnable** (0x0C; see below) can be used to mask off particular MOSI lines so that individual RHS2116 chips can be sent unique command sequences (e.g., for setting stimulation current amplitudes on different headstages).

A concrete example will make things clearer: Let's assume that we always use the **auxcmd1** slot for updating the RHS2116 on-chip DAC used to generate waveforms for electrode impedance testing (i.e., **Zcheck DAC** in Register 3). We can construct a list of commands of the form **WRITE(6, x)** that generate a sine wave at a particular frequency and amplitude. We can upload this sequence of commands to a RAM bank on the FPGA that is associated with the **auxcmd1** slot, as long as the sequence has 8192 or fewer commands.

For each auxiliary command slot (**auxcmd1**, **auxcmd2**, **auxcmd3**, and **auxcmd4**), the user must specify the length of the command sequence. This **command sequence length** is the same for Ports A, B, C, and D. When data acquisition is started, all auxiliary command sequences start at the beginning of their selected RAM banks and increment to the next command every sampling period. When the command index reaches the specified command sequence length, the command index resets to a **command loop index**. In many cases, the command loop index will be set to zero so that the entire command sequence repeats in its entirety (e.g., the DAC waveform generator commands). However, the command loop index may be set to a number greater than zero so that the first part of the command sequence is executed only once, and a later sequence is executed in a loop. This may be used, for example, to initialize the registers on the chip only once at the beginning of data acquisition.

Any changes made in the command sequence length or the command loop index only take effect when the current command sequence reaches its end, or when the SPI interface is stopped and restarted.

Automatic Stimulation Command Mode

Once the registers on all RHS2116 chips have been initialized, the FPGA can be put into **automatic stimulation command mode** (see **WireInStimCmdMode** below). In this mode, auxiliary command slots are controlled by the Stimulation Sequencer state machines described below. These state machines generate independent stimulation commands for each channel on every chip, and can be triggered by a variety of hardware and software events. The duration and shape of each stimulation pulse can be defined by programming registers in these Sequencer state machines.

If automatic stimulation command mode is enabled, the first auxiliary command slot is always a **WRITE** command to Register 42, which turns individual current stimulators on or off for all 16 channels on each chip. The second auxiliary command is always a **WRITE** command to Register 44, which sets the stimulation polarity for all 16 channels.

The third auxiliary command can be a **WRITE** command to Register 10 or 12 to activate or deactivate amplifier settling for fast artifact recovery. However, if the FPGA detects that no channels on a particular chip need amplifier settling parameters to be changed at a particular time then this command slot is used to read from the compliance monitor (Register 40) to detect voltage compliance problems.

The fourth auxiliary command slot is used to **WRITE** to Register 46 or 48 to activate or deactivate charge recovery circuitry for each channel. This command always has its U flag set to trigger a simultaneous update of the triggered registers that were updated in the last four commands. If the previous command was reading from the compliance monitor, then the M flag is also set in order to reset the compliance monitor.

Detailed Description of Interface Operation

Opal Kelly provides platform-specific driver files (e.g., a DLL file for Windows) and a C++ API (application programming interface) that defines software **endpoints** used to communicate with XEM boards. **WireIn** and **TriggerIn** endpoints transfer information from the host computer to the FPGA, while **WireOut** and **PipeOut** endpoints transfer information from the FPGA to the host computer. Opal Kelly provides all drivers and API software on a CD with the purchase of an XEM board. In the sections below, we list all the Opal Kelly endpoints used by Rhythm, and we provide sample C++ code for communicating over these endpoints to a Rhythm-powered XEM6010 board.

Opening and Initializing the Opal Kelly Board

The following C++ code shows how an Opal Kelly XEM6010 board is opened and initialized. Additional code should be added to check for errors and other exceptions (e.g., board not connected, multiple boards connected). The **main.bit** bitfile contains the compiled RhythmStim Verilog code provided by Intan Technologies. After this bitfile is uploaded to the XEM6010 board, it behaves as the RhythmStim interface described in this document.

```
okCFrontPanel *dev;

dev = new okCFrontPanel;

// If only one Opal Kelly board is plugged in to the host computer, we can use this.
dev->OpenBySerial();

// Set XEM6010 PLL to default configuration to produce 100 MHz FPGA clock.
dev->LoadDefaultPLLConfiguration();

// Upload RhythmStim bitfile which is compiled from RhythmStim Verilog code.
dev->ConfigureFPGA("main.bit");
```

USB Software Endpoints: WireIn and TriggerIn Ports

WireIn ports are virtual 16-bit wires that transfer data asynchronously from the host computer to the FPGA. Up to 32 **WireIn** ports (with addresses from 0x00 to 0x1F) are available for use with each Opal Kelly module. The following C++ code shows how data is sent over **WireIn** ports.

```
okCFrontPanel *dev;
// Code to open Opal Kelly board not shown here.

// Set WireIn port 0x00 to 0x1234.
dev->SetWireInValue(0x00, 0x1234);

// Optional third term is a bit mask; this command sets bits 0 and 1 of
// WireIn port 0x01 to one, sets bits 2 and 3 to zero, and leaves bits 4-15
// unchanged.
dev->SetWireInValue(0x01, 0x0003, 0x000F);

// WireIn ports are only updated on the FPGA when UpdateWireIns() is called.
// Here, WireIn ports 0x00 and 0x01 are updated simultaneously.
dev->UpdateWireIns();
```

TriggerIn ports are virtual 16-bit wires that transfer digital one-shot pulses from the host computer to the FPGA. Up to 32 **TriggerIn** ports (with addresses from 0x40 to 0x5F) are available for use with each module. The following C++ code shows how pulses are sent over **TriggerIn** ports.

RHS2000 USB/FPGA Interface: RhythmStim

```
okCFrontPanel *dev;
// Code to open Opal Kelly board not shown here.

// Send one-shot pulse on bit 0 of TriggerIn port 0x40.
dev->ActivateTriggerIn(0x40, 0);

// Now send one-shot pulse on bit 7 of TriggerIn port 0x40.
dev->ActivateTriggerIn(0x40, 7);
```

WireIn 0x00: WireInResetRun TriggerIn 0x41: TrigInSpiStart

WireInResetRun[0]: **reset**

When the Opal Kelly board is first powered up and RhythmStim is uploaded, this **reset** signal should be brought high momentarily to initialize many internal registers and finite state machines. This **reset** signal should then remain low for the remainder of RhythmStim operation. Pulling this signal high resets the sampling rate to its default value of 30 kS/s/channel and clears all command RAM banks.

WireInResetRun[1]: **SPI_run_continuous**

When this bit is set high, data acquisition will run continuously once it is started by pulsing **TrigInSpiStart[0]**. To halt data acquisition immediately, set this bit to zero and set **WireInMaxTimeStep** (WireIns 0x01 and 0x02) to zero. If this bit is set low, data acquisition will only run for a finite number of samples set by **MaxTimeStep**.

WireInResetRun[2]: **DSP_settle**

When this bit is set high, the **LSB of all CONVERT commands sent to on all MOSI lines is set to one**, settling the RHS2116 digital offset removal filters. (See the RHS2116 datasheet for more information on this function.)

WireInResetRun[3]: **amp_settle_mode**

When this bit is set low, **fast artifact recovery** is performed using low frequency cutoff shifting (Register 12 on the RHS2116). This is the recommended method. When this bit is set high, fast artifact recovery is performed using the “fast settle” function (Register 10 on the RHS2116).

WireInResetRun[4]: **charge_recov_mode**

When this bit is set low, **charge recovery** is performed using charge-limited charge recovery drivers (Register 48 on the RHS2116). When this bit is set high, charge recovery is performed using the charge recovery switches (Register 46 on the RHS2116).

WireInResetRun[5]: unused

WireInResetRun[12:6]: **DAC_noise_slice**

The first two DACs are designed to be connected to audio left and right channels. This variable slices out the central +/-16 x **DAC_noise_slice** LSBs of the signals in these two DACs and shifts the remaining signal up or down to zero, improving **audibility** of neural spikes.

WireInResetRun[15:13]: **DAC_gain**

The signals in all eight DACs are scaled by a factor of two raised to the power of **DAC_gain**. A gain of 1, 2, 4, 8, 16, 32, 64, or 128 may be specified in this way.

WireIn 0x01: WireInMaxTimeStepLsb WireIn 0x02: WireInMaxTimeStepMsb

These two 16-bit ports are used to convey a 32-bit unsigned integer **MaxTimeStep** that indicates the **maximum number of time steps (samples) that will run once data acquisition is started** by pulsing **TrigInSpiStart**. If **SPI_run_continuous** (in WireIn address 0x00) is set high, the value in this register is ignored. Setting this register to zero will halt data acquisition, provided **SPI_run_continuous** is set to zero.

RHS2000 USB/FPGA Interface: RhythmStim

WireIn 0x03: WireInDataFreqPll

TriggerIn 0x40: TrigInDcmProg

WireInDataFreqPll[7:0]: “M” multiply parameter for clock frequency synthesizer

WireInDataFreqPll[15:8]: “D” divide parameter for clock frequency synthesizer

These parameters are used to set the RHS2116 amplifier sampling frequency. A 100 MHz reference clock is provided to the FPGA from an off-chip clock generator. The output frequency of a programmable FPGA clock generator (a digital clock manager, or DCM) is given by:

$$\text{FPGA internal clock frequency} = 100 \text{ MHz} \times (M / D) / 2$$

M and D are “multiply” and “divide” integers used in the FPGA’s digital clock manager (DCM) phase-locked loop (PLL) frequency synthesizer, and are subject to the following restrictions:

- M must have a value in the range of 2 to 256.
- D must have a value in the range of 1 to 256.
- The ratio M / D must fall in the range of 0.05 to 3.33

(See pages 85-86 of Xilinx document UG382 “Spartan-6 FPGA Clocking Resources” for more details.)

This variable-frequency clock drives the state machine that controls all SPI communication with the RHS2116 chips. A complete SPI cycle (consisting of one CS pulse and 32 SCLK pulses) takes 140 clock cycles. The SCLK period is 4 clock cycles; the CS pulse is high for 10 clock cycles between commands.

RhythmStim samples all 16 channels and then executes 4 auxiliary commands that can be used to read and write from other registers on the chip. Therefore, a complete cycle that samples from each amplifier channel takes $140 \times (16 + 4) = 140 \times 20 = 2800$ clock cycles. So the per-channel sampling rate of each amplifier is 2800 times slower than the internal FPGA clock frequency.

Based on these design choices, we can use the following values of M and D to generate the following useful amplifier sampling rates for electrophysiological applications.

M	D	FPGA internal clock frequency	per-channel sample rate	per-channel sample period
7	125	2.80 MHz	1.00 kS/s	1000.0 μ s
7	100	3.50 MHz	1.25 kS/s	800.0 μ s
21	250	4.20 MHz	1.50 kS/s	666.7 μ s
14	125	5.60 MHz	2.00 kS/s	500.0 μ s
35	250	7.00 MHz	2.50 kS/s	400.0 μ s
21	125	8.40 MHz	3.00 kS/s	333.3 μ s
14	75	9.33 MHz	3.33 kS/s	300.0 μ s
28	125	11.20 MHz	4.00 kS/s	250.0 μ s
7	25	14.00 MHz	5.00 kS/s	200.0 μ s
7	20	17.50 MHz	6.25 kS/s	160.0 μ s
112	250	22.40 MHz	8.00 kS/s	125.0 μ s
14	25	28.00 MHz	10.00 kS/s	100.0 μ s
7	10	35.00 MHz	12.50 kS/s	80.0 μ s
21	25	42.00 MHz	15.00 kS/s	66.7 μ s
28	25	56.00 MHz	20.00 kS/s	50.0 μ s
35	25	70.00 MHz	25.00 kS/s	40.0 μ s
42	25	84.00 MHz	30.00 kS/s	33.3 μ s

To set a new clock frequency, assert new values for M and D and pulse TrigInDcmProg[0]:

```
okCFrontPanel *dev;  
// Code to open Opal Kelly board not shown here.
```


RHS2000 USB/FPGA Interface: RhythmStim

```
dev->SetWireInValue(0x03, (M << 8) + D); // 0x03 = WireInDataFreqPll
dev->UpdateWireIns();
dev->ActivateTriggerIn(0x40, 0); // 0x40 = TrigInDcmProg
```

If the board is reset, the sample rate will revert to 30 kS/s/channel.

WireIn 0x04: WireInMisoDelay

WireInMisoDelay[3:0]: MISO delay for Port A
WireInMisoDelay[7:4]: MISO delay for Port B
WireInMisoDelay[11:8]: MISO delay for Port C
WireInMisoDelay[15:12]: MISO delay for Port D

These four 4-bit registers set the **sampling delay** applied to MISO1 and MISO2 inputs on each of the four RHS2000 SPI ports to account for cable propagation delays. Each register takes a value between 0-15. If the register is set to zero, MISO1 and MISO2 on that port are sampled on the rising edge of each SCLK pulse. Increasing the register value by one delays MISO sampling by one-quarter of an SCLK period. Each SCLK period is equal to 1/700 of the per-channel sampling period.

For example, if the per-channel amplifier sampling rate is set to 20 kS/s then the per-channel sampling period is 50 μ s. The SCLK period will then be 71.4 ns, so every unit increase in the MISO delay register will delay MISO sampling by 17.9 ns.

In addition to the expected round-trip cable delays, there will also be delays due to the FPGA I/O and the RHS2116 I/O. The Xilinx Spartan-6 FPGA has an LVDS output pin delay of 1.9 ns and an LVDS input pin delay of 1.4 ns. The RHS2116 has a typical I/O delay of 9.0 ns. This total I/O delay (12.3 ns) should be added to any expected cable delays when calculating the optimum values for these registers.

WireIn 0x05: WireInStimCmdMode

WireInStimCmdMode[0]: **stim_cmd_mode**

Setting this bit to one enables automatic **stimulation command mode**, where the four auxiliary command slots are controlled by the FPGA in response to stimulation parameters and stimulation trigger sources that have been configured (see below for details). Setting this bit to zero allows the user to specify arbitrary SPI commands for the four auxiliary command slots.

WireIn 0x06: WireInStimRegAddr

WireIn 0x07: WireInStimRegWord

TriggerIn 0x41: TrigInSpiStart

TriggerIn 0x42: TrigInRamAddrReset

WireInStimRegAddr[3:0]: **StimRegAddress**
WireInStimRegAddr[7:4]: **StimRegChannel**
WireInStimRegAddr[12:8]: **StimRegModule**

WireInStimRegWord[15:0]: **StimProgWord**

TrigInSpiStart[1]: **ResetSequencers**

TrigInRamAddrReset[1]: **ProgramStimReg**

The RhythmStim FPGA code creates 128 independent **Stimulation Sequencer** state machines that automatically control stimulation sequences across all channels on eight RHS2116 chips when **stim_cmd_mode** is set to one. Each Stimulation Sequencer has 14 internal registers that can be programmed using these WireIns and TriggerIn.

To program a state machine register, assert new values for **StimRegAddress**, **StimRegChannel**, **StimRegModule**, and **StimProgWord**, and pulse **TrigInRamAddrReset[1]**:

```
okCFrontPanel *dev;
// Code to open Opal Kelly board not shown here.
dev->SetWireInValue(0x06, (module << 8) + (channel << 4) + address);
dev->SetWireInValue(0x07, register_value);
```

RHS2000 USB/FPGA Interface: RhythmStim

```
dev->UpdateWireIns();  
dev->ActivateTriggerIn(0x42, 1);
```

The value of StimRegChannel should be between zero and 15; this corresponds to the channel on an RHS2116 chip. The value of StimRegModule is used to select between RHS2116 chips on the following ports:

StimRegModule	Port
0	Port A, MISO1
1	Port A, MISO2
2	Port B, MISO1
3	Port B, MISO2
4	Port C, MISO1
5	Port C, MISO2
6	Port D, MISO1
7	Port D, MISO2

The 14 registers in each of the 128 Stimulation Sequencer state machines are listed and described below:

Stimulation Sequencer Register Address	Stimulation Sequencer Register Name
0	TriggerParams
1	StimParams
2	EventAmpSettleOn
3	EventAmpSettleOff
4	EventStartStim
5	EventStimPhase2
6	EventStimPhase3
7	EventEndStim
8	EventRepeatStim
9	EventChargeRecovOn
10	EventChargeRecovOff
11	EventAmpSettleOnRepeat
12	EventAmpSettleOffRepeat
13	EventEnd

The functions of each Stimulation Sequencer register are described below:

TriggerParams[4:0]: **TriggerSource**. This 5-bit number selects the signal to be used as the trigger for stimulation pulses. TriggerSource may have the following values:

0-15: Digital In 1-16 ports

16-23: Analog In (ADC) 1-8 ports (logic threshold voltage set by WireIn 0x0F)

24-31: Software triggers (see WireIn 0x12)

TriggerParams[5]: **TriggerOnEdge**. If this bit is set to one, a single stimulation pulse will trigger on the rising or falling edge of the trigger source. If this bit is set to zero, stimulation pulses will be level triggered, and will repeat as long as the trigger signal remains at the level specified by TriggerPolarity (see next item).

TriggerParams[6]: **TriggerPolarity**. If this bit is set to zero, stimulation will trigger on a low or falling-edge signal. If this bit is set to one, stimulation will trigger on a high or rising-edge signal.

TriggerParams[7]: **TriggerEnabled**. This bit must be set to one to enable stimulation on this channel. If this bit is set to zero, all trigger events are ignored and stimulation is disabled on this channel.

RHS2000 USB/FPGA Interface: RhythmStim

StimParams[7:0]: **NumberOfStimPulses**. This 8-bit number should be set to the number of stimulation pulses that a single trigger should elicit **minus one**. So if a single stimulation pulse is desired, this number should be set to zero. If 256 pulses are desired, this number should be set to 255.

StimParams[9:8]: **StimShape**. This 2-bit number determines the shape of the stimulation current pulse. There are three valid values for the Stimulation Sequencer:

0: Biphasic. Current of one polarity followed immediately by current of the opposite polarity.

1: Biphasic with dead zone. Current of one polarity followed by a period of zero current, followed by current of the opposite polarity.

2: Triphasic. Current of one polarity followed immediately by current of the opposite polarity, then followed by current of the first polarity.

StimParams[10]: **NegStimFirst**. If this bit is set to one, the first phase of stimulation current will be negative (i.e., cathodic). If this bit is set to zero, the first phase of stimulation current will be positive (i.e., anodic). Most neural stimulation applications use cathodic-first stimulation.

The remaining “event” registers take 16-bit numbers that specify times relative to the trigger time ($t = 0$), in multiples of amplifier sampling period. For example, if the amplifiers are sampled at 20 kS/s, the sampling period will be 50 μ s, so an event register value of 40 would correspond to a time of 2.0 ms after the trigger.

EventAmpSettleOn: At this time after a trigger event, the amplifier settle circuitry is activated for this channel. If you do not wish to enable the amplifier settle circuitry during a stimulation event, set this event time to be greater than EventEnd.

EventAmpSettleOff: At this time, the amplifier settle circuitry is turned off.

EventStartStim: At this time, the stimulation current is turned on with a polarity controlled by NegStimFirst. The amplitude of this stimulation current should have been previously selected by manually programming Registers 34-35, 64-79, and 96-111 on each RHS2116 chip.

EventStimPhase2: At this time, the stimulation current switches polarity. The amplitude can be different depending on how Registers 64-79 and 96-111 are programmed.

EventStimPhase3: This register is only used if StimShape is set to Triphasic. At this time, the stimulation current switches back to the original polarity.

EventEndStim: At this time, the stimulation current is turned off.

EventRepeatStim: If more than one stimulation pulse was selected (i.e., NumberOfStimPulses > 0), then at this time the sequencer will jump back to $t = 0$ until the desired number of pulses have been delivered.

EventChargeRecovOn: At this time after a trigger event, the charge recovery circuitry is activated for this channel. If you do not wish to enable the charge recovery circuitry during a stimulation event, set this event time to be greater than EventEnd.

EventChargeRecovOff: At this time, the charge recovery circuitry is turned off.

EventAmpSettleOnRepeat and EventAmpSettleOffRepeat: If multiple stimulation pulses have been selected, these registers can be used to turn the amplifier settle circuitry on and off between repeated pulses. These times should always be less than EventRepeatStim. If you wish for the amplifier settle circuitry to remain on continuously during a multiple-pulse train or you wish to avoid using amplifier settle entirely, set these times greater than EventEnd.

EventEnd: This time marks the end of a stimulation event. The Stimulation Sequencer is blind to new trigger events until EventEnd is reached, so this register can be used to set a “refractory period” where re-triggering is disabled for a time after a stimulation pulse has completed. If level-based triggered is selected, this parameter will determine the repetition rate of multiple pulses caused by an extended trigger signal.

The RhythmStim FPGA code also contains eight **Analog Output Sequencers** that can be used to create triggered voltage pulses on any of the Analog Out (DAC) ports. The registers in the Analog Output Sequencers are addressed with values of StimRegModule ranging from 8-15, with StimRegChannel equal to zero. Each state machine has 11 registers that are listed and described below:

RHS2000 USB/FPGA Interface: RhythmStim

Analog Output Register Address	Analog Output Register Name
0	TriggerParams
1	StimParams
4	EventStartStim
5	EventStimPhase2
6	EventStimPhase3
7	EventEndStim
8	EventRepeatStim
9	DACBaseline
10	DACPositive
11	DACNegative
13	EventEnd

TriggerParams and StimParams have the same functions as in the Stimulation Sequencer described above, with the exception that the StimShape variable can take one of four values:

- 0: Biphasic. Voltage of one level followed immediately by voltage of a different level.
- 1: Biphasic with dead zone. Voltage of one level followed by a period of baseline voltage, followed by voltage of a different polarity.
- 2: Triphasic. Voltage of one level followed immediately by voltage of a different polarity, then followed by voltage of the first level.
- 3: Monophasic: Voltage of one level.

EventStartStim, EventStimPhase2, EventStimPhase3, EventEndStim, EventRepeatStim, and EventEnd have analogous functions to the registers of the same name in the Stimulation Sequencer.

DACBaseline is a 16-bit number that sets the default baseline level for the DAC. Similarly, DACPositive sets the positive voltage level and DACNegative sets the negative voltage level. All of these values are unsigned numbers with offsets: a value of 32768 sets the voltage to the middle of the DAC range. A value of zero sets the DAC to its minimum voltage; a value of 65535 sets the DAC to its maximum voltage.

The RhythmStim FPGA code also contains sixteen **Digital Output Sequencers** that can be used to create triggered logic pulses on any of the Digital Out ports. The registers in the Digital Output Sequencers are addressed with StimRegModule equal to 16 and with StimRegChannel set to a value between 0-15 to select Digital Out ports 1-16. Each state machine has 6 registers that are listed and described below:

Digital Output Register Address	Digital Output Register Name
0	TriggerParams
1	StimParams
4	EventStartStim
7	EventEndStim
8	EventRepeatStim
13	EventEnd

TriggerParams, EventStartStim, EventEndStim, EventRepeatStim, and EventEnd have analogous functions to the registers of the same name in the Stimulation Sequencer.

The StimParams register contains only the NumberOfStimPulses variable; there is no StimShape or NegStimFirst variable. All logic pulses are monophasic.

RHS2000 USB/FPGA Interface: RhythmStim

The FPGA code includes provisions that ensure when data acquisition is stopped, all units under Sequencer control are turned off: RHS2116 current stimulators are turned off, DACs are set to their baseline values, and Digital Out channels are set to zero. However, when data acquisition is stopped it is possible that some of the Sequencers could be in the middle of producing multiple output pulses, and when data acquisition is restart (possibly a long time later) the pulses will continue. To avoid this preservation of state, the user can pulse the **ResetSequencers** bit (bit 1 on **TrigInSpiStart**) to reset all multiple pulse counters to zero. It is good practice to pulse this trigger after data acquisition is stopped.

WireIn 0x08: WireInDcAmpConvert

WireInDcAmpConvert[0]: **DcAmpConvertEnable**

This bit controls the **D** flag in the CONVERT commands issued to the RHS2116 chips. Setting it to one causes all attached chips to perform ADC conversions on the DC low-gain amplifiers as well as the AC high-gain amplifiers. See the RHS2116 datasheet for more details.

WireIn 0x09: WireInExtraStates

Setting WireInExtraStates to a value greater than zero extends the number of internal clock cycles that CS is high from ten to ten plus the value of this variable. Under normal operation, this WireIn should be set to zero.

WireIn 0x0A: WireInDacReref

WireInDacReref[4:0]: **DAC_reref_channel_sel**

WireInDacReref[9:5]: **DAC_reref_stream_sel**

WireInDacReref[10]: **DAC_reref_mode**

If **DAC_reref_mode** is set to one, the amplifier channel from stream **DAC_reref_stream_sel** and channel **DAC_reref_channel_sel** is subtracted from all eight amplifier signals that are routed to the DACs. If digital re-referencing is implemented in software, these registers may be used to add real time re-referencing to the DAC outputs.

WireIn 0x0B: unused

WireIn 0x0C: WireInAuxEnable

WireInAuxEnable[0]: AuxEnablePortA1

WireInAuxEnable[1]: AuxEnablePortA2

WireInAuxEnable[2]: AuxEnablePortB1

WireInAuxEnable[3]: AuxEnablePortB2

WireInAuxEnable[4]: AuxEnablePortC1

WireInAuxEnable[5]: AuxEnablePortC2

WireInAuxEnable[6]: AuxEnablePortD1

WireInAuxEnable[7]: AuxEnablePortD2

These eight bits control whether auxiliary command sequences uploaded to the FPGA are sent to chips connected to SPI Ports A-D, MOSI 1 and 2, when **stim_cmd_mode** is set to zero. When any of these bits are set to zero, the selected SPI Ports are sent dummy commands (reading from ROM register 255) instead of commands in the auxiliary command list. This “masking” capability allows users to program the registers of one RHS2116 chip without overwriting the registers of other connected chips.

WireIn 0x0D: WireInGlobalSettleSelect

WireInGlobalSettleSelect[0]: SettleWholeHeadstageA

WireInGlobalSettleSelect[1]: SettleWholeHeadstageB

WireInGlobalSettleSelect[2]: SettleWholeHeadstageC

RHS2000 USB/FPGA Interface: RhythmStim

WireInGlobalSettleSelect[3]: SettleWholeHeadstageD

WireInGlobalSettleSelect[4]: SettleAllHeadstages

Since stimulation on one channel can create recording artifacts on nearby channels due to capacitive coupling in headstages, connectors, and/or electrode arrays, it is often useful to perform fast artifact recovery (i.e., amplifier settling) across an entire headstage. If any of the first four bits of this WireIn are set to one, activation of amplifier settling on any channel on a port (A-D) will activate amplifier settling on **all** channels on that port. The fifth bit performs the same function globally for all ports.

WireIn 0x0E: unused

WireIn 0x0F: WireInAdcThreshold

This 16-bit number sets the voltage level used as a logic threshold for Analog In (ADC) channels that are used as triggers for the Stimulation Sequencers, Analog Output Sequencers, or Digital Output Sequencers (see above). This variable uses an unsigned offset representation, so that a value of 32768 represents the midpoint of the ADC's conversion range.

WireIn 0x10: WireInSerialDigitalInCntl

WireInSerialDigitalInCntl[0]: **serial_CLK_manual**

WireInSerialDigitalInCntl[1]: **serial_LOAD_manual**

These bits control two 16-to-1 digital multiplexer shift registers that read digital inputs and configuration switch settings. The output of these shift registers are conveyed via WireOut 0x26. These signals are controlled in the readDigitalInManual() and readDigitalInExp() methods in rhs2000evalboard.cpp.

WireIn 0x11: WireInLedDisplay

WireInLedDisplay[7:0]: These bits control the **eight red LEDs** on the Opal Kelly board. Setting bits to one turns LEDs on.

WireInLedDisplay[15:8]: These bits control the **FPGA pins SPI_LED_A through SPI_LED_F**, and can be used to implement SPI port status indicator LEDs.

WireIn 0x12: WireInManualTriggers

WireInManualTriggers[7:0]: These bits provide eight software-controlled trigger sources that can be selected by any of the Stimulation Sequencers, Analog Output Sequencers, or Digital Output Sequencers (see above).

WireIn 0x13: WireInTtlOutMode

WireInTtlOutMode[7:0]: Setting these bits to one causes Digital Out ports 1-8 to be controlled by the FPGA threshold comparators. Setting these bits to zero causes the corresponding Digital Out ports to be controlled by Digital Output Sequencers, if they are enabled. (Digital Out ports 9-16 are always controlled by Digital Output Sequencers.)

DataStreamSel	Data Stream
0	Port A, MISO1
1	Port A, MISO2
2	Port B, MISO1
3	Port B, MISO2
4	Port C, MISO1
5	Port C, MISO2

RHS2000 USB/FPGA Interface: RhythmStim

6	Port D, MISO1
7	Port D, MISO2

WireIn 0x14: WireInDataStreamEn

WireInDataStreamEn[0]: DataStreamEnA1
WireInDataStreamEn[1]: DataStreamEnA2
WireInDataStreamEn[2]: DataStreamEnB1
WireInDataStreamEn[3]: DataStreamEnB2
WireInDataStreamEn[4]: DataStreamEnC1
WireInDataStreamEn[5]: DataStreamEnC2
WireInDataStreamEn[6]: DataStreamEnD1
WireInDataStreamEn[7]: DataStreamEnD2

Setting one of these bits to one enables a particular data stream from SPI port A-D, MISO 1 or 2, so that its data is sent over the USB interface to the host computer. Setting the bit to zero disables the stream, reducing USB bandwidth and FIFO usage.

Any changes made to these bits do not take effect while data acquisition is running. Data acquisition must be stopped and restarted to enable or disable data streams, so that the size of a data frame never changes during active acquisition.

WireIn 0x15: unused

WireIn 0x16: WireInDacSource1
WireIn 0x17: WireInDacSource2
WireIn 0x18: WireInDacSource3
WireIn 0x19: WireInDacSource4
WireIn 0x1A: WireInDacSource5
WireIn 0x1B: WireInDacSource6
WireIn 0x1C: WireInDacSource7
WireIn 0x1D: WireInDacSource8

WireInDacSourceX[4:0]: DacSourceChannelX
WireInDacSourceX[8:5]: DacSourceStreamX
WireInDacSourceX[9]: DacSourceEnableX

These registers route selected amplifier signals to the eight DACs that RhythmStim supports. For each DAC, the user may select an amplifier channel (0-15) and a data stream (see table below). To enable the DAC, the **DacSourceEnable** bit must be set high. If **DacSourceStream** is set to 8, the DAC will be controlled directly by the host computer via **WireInDacManual**; the **DacSourceChannel** parameter is ignored in this case.

DacSourceStream	Data Stream Routed to DAC
0	Port A, MISO1
1	Port A, MISO2
2	Port B, MISO1
3	Port B, MISO2
4	Port C, MISO1
5	Port C, MISO2
6	Port D, MISO1
7	Port D, MISO2
8	DAC Manual Input
10-15	all zeros

RHS2000 USB/FPGA Interface: RhythmStim

WireIn 0x1E: WireInDacManual

This WireIn is used to control DACs directly when their DacSourceStream parameter is set to 8 (see table above). Typically, this WireIn can only be updated around 1,000 times per second in compiled C++ software, so it cannot be used to synthesize high-frequency waveforms.

WireIn 0x1F: WireInMultiUse

WireInMultiUse is used in concert with TriggerIn signals to program other registers in the FPGA. (See below.)

TrigIn 0x43: TrigInDacThresh

TrigInDacThresh[0]: SetDac1ThresholdLevel
TrigInDacThresh[1]: SetDac2ThresholdLevel
TrigInDacThresh[2]: SetDac3ThresholdLevel
TrigInDacThresh[3]: SetDac4ThresholdLevel
TrigInDacThresh[4]: SetDac5ThresholdLevel
TrigInDacThresh[5]: SetDac6ThresholdLevel
TrigInDacThresh[6]: SetDac7ThresholdLevel
TrigInDacThresh[7]: SetDac8ThresholdLevel

TrigInDacThresh[8]: SetDac1ThresholdPolarity
TrigInDacThresh[9]: SetDac2ThresholdPolarity
TrigInDacThresh[10]: SetDac3ThresholdPolarity
TrigInDacThresh[11]: SetDac4ThresholdPolarity
TrigInDacThresh[12]: SetDac5ThresholdPolarity
TrigInDacThresh[13]: SetDac6ThresholdPolarity
TrigInDacThresh[14]: SetDac7ThresholdPolarity
TrigInDacThresh[15]: SetDac8ThresholdPolarity

RhythmStim includes on-FPGA threshold comparators that produce low-latency digital signals indicating if each waveform routed to one of the eight DACs exceeded user-programmed levels. The bits in this TrigIn are used to program DAC threshold levels and polarities. To program a DAC threshold level, apply the desired value to **WireInMultiUse** and pulse one of the bottom eight bits in **TrigInDacThresh**.

To program a DAC threshold polarity, apply either a zero or one to **WireInMultiUse** and pulse one of the top eight bits in **TrigInDacThresh**. A polarity value of zero will cause the corresponding digital output to go high when the signal routed to that DAC equals or falls below the DAC threshold level. A polarity value of one will cause the digital output to go high when the signal routed to that DAC equals or rises above the DAC threshold level.

TrigIn 0x44: TrigInDacHpf

TrigInDacHpf[0]: EnableDacHighpassFilter
TrigInDacHpf[1]: SetDacHighpassFilterCutoff

RhythmStim includes on-FPGA first-order high-pass filters that can be applied to the eight amplifier signals routed to the DACs and threshold comparators (see above). These high-pass filters can be used to remove low-frequency local field potentials (LFPs) from wideband neural signals before detecting spikes using the programmable comparators. The bits in this TrigIn are used to enable the high-pass filters and to program their cutoff frequency.

To enable or disable the high-pass filters, apply a one or zero, respectively, to **WireInMultiUse** and pulse **TrigInDacHpf[0]**. To set the filter cutoff frequency, apply the filter coefficient to **WireInMultiUse** and pulse **TrigInDacHpf[1]**.

The filter coefficient is a 16-bit unsigned integer that is calculated as follows:

$$\text{Filter coefficient} = 65536 \cdot [1 - \exp(-2\pi \cdot f_{\text{cutoff}}/f_{\text{sample}})]$$

RHS2000 USB/FPGA Interface: RhythmStim

Note that the filter coefficient depends on the amplifier sampling frequency, so if this is changed, the filter coefficient should be updated appropriately.

TrigIn 0x45: TrigInAuxCmdLength

TrigInAuxCmdLength[0]: MaxAuxCmdIndex1
TrigInAuxCmdLength[1]: MaxAuxCmdIndex2
TrigInAuxCmdLength[2]: MaxAuxCmdIndex3
TrigInAuxCmdLength[3]: MaxAuxCmdIndex4
TrigInAuxCmdLength[4]: LoopAuxCmdIndex1
TrigInAuxCmdLength[5]: LoopAuxCmdIndex2
TrigInAuxCmdLength[6]: LoopAuxCmdIndex3
TrigInAuxCmdLength[7]: LoopAuxCmdIndex4

For each auxiliary command slot (**auxcmd1**, **auxcmd2**, **auxcmd3**, and **auxcmd4**), the user must specify the length of the command sequence. This **command sequence length** is the same for all SPI Ports and MOSI lines. When data acquisition is started, all auxiliary command sequences start at the beginning of their selected RAM banks and increment to the next command every sampling period. When the command index reaches the specified command sequence length, the command index resets to a **command loop index**. In many cases, the command loop index will be set to zero so that the entire command sequence repeats in its entirety. However, the command loop index may be set to a number greater than zero so that the first part of the command sequence is executed only once, and a later sequence is executed in a loop.

The RhythmStim FPGA code includes four 8192 x 32 bit RAM banks used to store commands for the four auxiliary command slots **auxcmd1**, **auxcmd2**, **auxcmd3**, and **auxcmd4**. The command sequence length for each auxiliary command slot is set by writing a number between 0 and 8191 to **WireInMultiUse** and pulsing one of the bits 0-3 of **TrigInAuxCmdLength**. The command loop index for each slot is set by writing a number between 0 and 8191 to **WireInMultiUse** and pulsing one of the bits 4-7 of **TrigInAuxCmdLength**.

For example, to set a command sequence length of eight (which will execute **nine** commands: indices 0-8) and a command loop index of zero, both for **auxcmd2**:

```
okCFrontPanel *dev;
// Code to open Opal Kelly board not shown here.
dev->SetWireInValue(0x1F, 8); // 0x1F = WireInMultiUse
dev->UpdateWireIns();
dev->ActivateTriggerIn(0x45, 1); // trigger write to MaxAuxCmdIndex2
dev->SetWireInValue(0x1F, 0); // 0x1F = WireInMultiUse
dev->UpdateWireIns();
dev->ActivateTriggerIn(0x45, 5); // trigger write to LoopAuxCmdIndex2
```

USB Software Endpoints: PipeIn Ports

PipeIn ports are virtual 8-bit buses that stream data bytes synchronously from the host computer to the FPGA. Up to 32 PipeIn ports (with addresses from 0x80 to 0x9F) are available for use with each Opal Kelly module. The following C++ code shows how data is streamed over PipeIn ports.

```
okCFrontPanel *dev;
// Code to open Opal Kelly board not shown here.

// Allocate buffer to store 64 kBytes.
unsigned char usbBuffer[65536];

// Write 64 kBytes from buffer to PipeIn.
long numBytesToWrite = 65536;
dev->WriteToPipeIn(0x80, numBytesToWrite, usbBuffer);
```

See the Opal Kelly FrontPanel User's Manual for more information on PipeIn endpoints.

Pipeln 0x80: PipelnAuxCmd1Msw
Pipeln 0x81: PipelnAuxCmd1Lsw
Pipeln 0x82: PipelnAuxCmd2Msw
Pipeln 0x83: PipelnAuxCmd2Lsw
Pipeln 0x84: PipelnAuxCmd3Msw
Pipeln 0x85: PipelnAuxCmd3Lsw
Pipeln 0x86: PipelnAuxCmd4Msw
Pipeln 0x87: PipelnAuxCmd4Lsw

TrigIn 0x42: TrigInRamAddrReset

These Pipelns are used to upload auxiliary command sequences from the host computer to the FPGA. Each of these Pipelns is backed by an 8192 x 16 bit RAM block on the FPGA, so up to 16384 bytes can be uploaded after the RAM blocks are reset by pulsing TrigInRamAddrReset[0]. Each command word is 32 bits wide, and there are two different Pipelns for each auxiliary command slot to receive the most significant word (MSW) and least significant word (LSW) of each command. Since Pipelns fundamentally transfer 8-bit bytes, the least significant byte of each word should be sent first.

Example writing commands to the auxcmd1 slot:

```
okCFrontPanel *dev;
// Code to open Opal Kelly board and start SPI operation not shown here.

// Allocate buffers to command word lists.
unsigned int commandList[8192];
unsigned char commandBufferMsw[16384];
unsigned char commandBufferLsw[16384];
int i, numCmds;

// ...Assume that commandList has now been filled in with numCmds commands.

// Now break apart commands into bytes:
for (i = 0; i < numCmds; i++) {
    commandBufferLsw[2*i] = (unsigned char)(commandList[i] & 0x000000ff) >> 0;
    commandBufferLsw[2*i + 1] = (unsigned char)(commandList[i] & 0x0000ff00) >> 8;
    commandBufferMsw[2*i] = (unsigned char)(commandList[i] & 0x00ff0000) >> 16;
    commandBufferMsw[2*i + 1] = (unsigned char)(commandList[i] & 0xff000000) >> 24;
}

// Reset RAM address pointer to zero.
dev->ActivateTriggerIn(0x42, 0); // 0x42 = TrigInRamAddrReset
// Write bytes to auxcmd1 MSW PipeIn from buffer.
dev->WriteToPipeIn(0x80, 2*numCmds, commandBufferMsw); // 0x80 = PipeInAuxCmd1Msw
// Reset RAM address pointer to zero again.
dev->ActivateTriggerIn(0x42, 0); // 0x42 = TrigInRamAddrReset
// Write bytes to auxcmd1 LSW PipeIn from buffer.
dev->WriteToPipeIn(0x81, 2*numCmds, commandBufferLsw); // 0x81 = PipeInAuxCmd1Lsw
```

USB Software Endpoints: WireOut Ports

WireOut ports are virtual 16-bit wires that transfer data asynchronously from the FPGA to the host computer. Up to 32 WireOut ports (with addresses from 0x20 to 0x3F) are available for use with each Opal Kelly module. The following C++ code shows how data is received from WireOut ports.

```
okCFrontPanel *dev;
// Code to open Opal Kelly board not shown here.

// We must first execute UpdateWireOuts to refresh WireOut values on host computer.
dev->UpdateWireOuts();

// Read from WireOut 0x20 endpoint.
unsigned int fromFpga;
```


RHS2000 USB/FPGA Interface: RhythmStim

```
fromFpga = dev->GetWireOutValue(0x20);
```

WireOut 0x20: WireOutNumWordsLsb

WireOut 0x21: WireOutNumWordsMsb

These two 16-bit ports are used to transfer a 32-bit unsigned integer **NumWords** that indicates the total number of 16-bit words contained in the USB FIFO on the Opal Kelly board. Before executing a **ReadFromPipeOut** command, the host computer should first read this number to ensure that sufficient data is present in the FIFO buffer. Otherwise, underflow will occur and corrupted data will be transferred to the computer. (Note that **NumWords** reports the number of 16-bit **words** in the FIFO, while **ReadFromPipeOut** operates at the **byte** level.) These ports should also be monitored to prevent buffer overflow. The FIFO can hold a bit over $2^{26} = 67,108,864$ words, but in practice it should never be allowed to get close to its maximum capacity.

WireOut 0x22: WireOutSpiRunning

WireOutSpiRunning[0]: **SpiRunning**

This bit is high while data acquisition is running and low when it has stopped.

WireOutSpiRunning[15:1]: unused

WireOut 0x23: WireOutTtlIn

This register returns the values of the 16 TTL input pins defined by RhythmStim. (These pins are only sampled synchronously and updated when the RHS2116 SPI commands are running.)

WireOut 0x24: WireOutDataClkLocked

WireOutDataClkLocked[0]: **DataClkLocked**

This bit goes high when the digital clock manager has successfully stabilized to a new frequency. When **WireInDataFreqPll** is changed and **DcmProgTrigger** is pulsed, it can take several milliseconds for the new clock frequency to stabilize. This pin should be monitored after frequency changes, and no data acquisition should be performed until this bit goes high.

WireOutDataClkLocked[1]: **DcmProgDone**

When **WireInDataFreqPll** is changed and **DcmProgTrigger** is pulsed, it can take several milliseconds before the digital clock manager is ready to be changed to yet another frequency. After any frequency changes this pin should be monitored, and no more frequency changes should be attempted until this bit goes high.

WireOutDataClkLocked[15:2]: unused

WireOut 0x25: WireOutBoardMode

WireOutBoardMode[3:0]: **BoardMode**

BoardMode is a 4-bit value set by direct inputs to the FPGA. These pins are typically connected to DIP switches that are set to identify different types of boards.

WireOut 0x3E: WireOutBoardId

This WireOut returns a constant value of 800 (decimal), identifying the board as a RhythmStim-compatible device.

WireOut 0x3F: WireOutBoardVersion

This WireOut returns a constant value, identifying the version of RhythmStim running on the board.

USB Software Endpoints: PipeOut Ports

PipeOut ports are virtual 8-bit buses that stream data bytes synchronously from the FPGA to the host computer. Up to 32 PipeOut ports (with addresses from 0xA0 to 0xBF) are available for use with each Opal Kelly module. The following C++ code shows how data is streamed over PipeOut ports.

```
okCFrontPanel *dev;
// Code to open Opal Kelly board not shown here.

// Allocate buffer to store 64 kBytes.
unsigned char usbBuffer[65536];

// Read 64 kBytes from PipeOut 0xA0 into buffer.
long numBytesRead, numBytesToRead;
numBytesToRead = 65536;
numBytesRead = dev->ReadFromPipeOut(0xA0, numBytesToRead, usbBuffer);
// Note: numBytesRead will be negative if read failed.

// 16-bit words are sent least-significant-byte first.
unsigned int firstWord;
firstWord = (usbBuffer[1] << 8) | usbBuffer[0];
```

In order to minimize communication overhead and achieve maximum USB transfer speeds, Opal Kelly recommends reading from PipeOuts in relatively large data blocks. Reading at least 5 milliseconds of accumulated amplifier data from the board at a time will provide adequate USB data rates in most cases. See the Opal Kelly FrontPanel User's Manual for more information.

PipeOut 0xA0: PipeOutData

This PipeOut is used to stream data from all RHS2116 chips (and several additional data sources) through the FPGA to the host computer. The PipeOut is backed by a large FIFO implemented using the 128 MByte SDRAM on the Opal Kelly board. This FIFO module allows continuously-streaming data (e.g., from multiple RHS2116 chips) to be transferred smoothly over a USB interface to a computer that will grab the data in bursts, and may be unresponsive for a brief time due to multitasking or other operating system overhead.

There is no mechanism in this FIFO to protect against underflow. That is, if the computer tries to read more data than the FIFO is currently holding, the FIFO will just repeat the last word after it runs out of data. To prevent underflow, it is essential for the host to monitor the value of **NumWords** (WireOut 0x20 and 0x21) and never attempt to read more words than the FIFO contains.

Example:

```
okCFrontPanel *dev;
// Code to open Opal Kelly board and start SPI operation not shown here.

// Allocate buffer to store data.
unsigned char usbBuffer[BUFFERSIZE];

// Wait until enough data is available in the FIFO...
unsigned int numWordsAvailable = 0;
while (numWordsAvailable < BUFFERSIZE / 2) {
    dev->UpdateWireOuts();
    numWordsAvailable = 65536 * dev->GetWireOutValue(0x21) +
                        dev->GetWireOutValue(0x20);
}

// Remember, NumWords (WireOut 0x20 and 0x21) returns the number of 16-bit words in
// the FIFO, but ReadFromPipeOut() operates on bytes. Factor of two difference!

// Read bytes from PipeOut 0xA0 into buffer.
```

RHS2000 USB/FPGA Interface: RhythmStim

```
long numBytesRead;  
numBytesRead = dev->ReadFromPipeOut(0xA0, BUFFERSIZE, usbBuffer);
```

RhythmStim Verilog Code Description

Verilog Source Code

The RhythmStim interface is described by a set of Verilog files that may be compiled into a bitfile using the free Xilinx ISE WebPack software. While Intan Technologies provides a pre-compiled bitfile, developers may wish to modify the RhythmStim code for custom applications. The primary Verilog files are described below.

main.v: This is the top-level RhythmStim Verilog code that defines all FPGA I/O, executes the main state machine running all SPI I/O with the RHS2116 chips, and defines connections to all other modules in the Verilog files listed below.

SDRAM_FIFO.v: This code makes use of the off-FPGA 128-MByte SDRAM to implement a large FIFO buffer. This Verilog file uses a number of other miscellaneous Verilog files to implement the SDRAM controller. Many of these files were derived from the Opal Kelly RamTest Verilog example.

variable_freq_clk_generator.v: This module sets up the programmable-frequency clock used to run the RHS2116 chips at user-selectable sampling rates.

MISO_phase_selector.v: This small module implements the user-programmable delay in sampling MISO SPI lines to compensate for signal propagation delay on long cables.

RAM_bank.v and **RAM_block.v:** These files use on-FPGA memory to implement multiple 8192-word RAM banks for storing auxiliary command sequences.

DAC_output_scalable_HPF.v: This module implements a serial interface to an optional off-board Analog Devices AD5662 16-bit DAC, as well as variable gain, noise slicing, high-pass filtering, and threshold comparator functions.

ADC_input.v: This module implements a serial interface to an optional off-board Analog Devices AD7980 16-bit ADC.

stim_sequencer.v: This module implements a state machine that generates stimulation control bits for 16 RHS2116 stimulator channels. A variety of stimulation waveforms (biphasic, biphasic with dead zone, and triphasic), trigger methods (edge triggered, level triggered), and pulse train options are supported.

analog_out_sequencer.v: This module implements a state machine that generates voltage pulses signals for a 16-bit DAC. A variety of stimulation waveforms (biphasic, biphasic with dead zone, triphasic, and monophasic), trigger methods (edge triggered, level triggered), and pulse train options are supported.

digout_sequencer.v: This module implements a state machine that generates digital pulses for 16 digital outputs. A variety of trigger methods (edge triggered, level triggered) and pulse train options are supported.

okLibrary.v: This Verilog file provided by Opal Kelly implements the communication endpoints (e.g., WireIns, PipeOuts) in the FPGA. It should not be modified.

xem6010.ucf: This file defines the location (i.e., pin number) and characteristics of all FPGA I/O signals.

main.bit: This is the bitfile that is generated by compiling all the above Verilog files with Xilinx ISE WebPack. This file should be copied into the directory containing the C++ executable file that opens and configures the Opal Kelly board.

RHS2000 USB/FPGA Interface: RhythmStim

Main State Machine Description

The heart of the RhythmStim code, in **main.v**, is a finite state machine that cycles through a pattern of 140 repeating states. These 140 states execute a single SPI cycle. (Refer to the RHS2116 datasheet for more information on the SPI communication protocol.)

Each SCLK period consists of four states labeled **ms_clkX_a** through **ms_clkX_d**, where X advances from 1 to 32. After 32 complete SCLK cycles, there are an additional two states (**ms_clk33_a** and **ms_clk33_b**) to create a delay between the falling edge of the last SCLK pulse and the rising edge of CS. The CS signal is held high for 10 states labeled **ms_cs_a** through **ms_cs_j**. After all 140 states have completed, the variable **channel** is incremented. If **channel** exceeds 19, it is reset to 0. This variable tracks the repeating series of 20 commands send on the MOSI line (16 CONVERT commands for each amplifier channel and four auxiliary commands).

Data is transferred to the FIFO (and thence to the USB interface) during particular states of this main state machine. One 16-bit word can be transferred to the FIFO during each state.

- The 64-bit header magic number is sent during states **ms_clk1_b** through **ms_clk2_a** only when channel = 0.
- The timestamp is sent during states **ms_clk2_b** and **ms_clk2_c** only when channel = 0.
- Data streams 1-8 are sent during states **ms_clk2_d** through **ms_clk6_c**.
- The state of all on-chip stimulators (including stimulator on/off, polarity, amplifier settle on/off, and charge recovery on/off) are sent during states **ms_clk6_d** through **ms_clk14_c**.
- States **ms_clk14_d** through **ms_clk30_c** could be used to send more data streams in the future.
- States **ms_clk30_d** through **ms_clk32_c** are used to send data from the eight optional DACs only when channel = 19.
- States **ms_clk32_d** through **ms_cs_e** are used to send data from the eight optional ADCs only when channel = 19.
- State **ms_cs_f** is used to send the 16 TTL inputs only when channel = 19.
- State **ms_cs_g** is used to send the current value of the 16 TTL outputs only when channel = 19.

RhythmStim C++ API

Intan Technologies provides a basic, open-source C++ application programming interface (API) for controlling the RhythmStim FPGA interface described above. The API consists of three C++ classes: **Rhs2000EvalBoard**, **Rhs2000Registers**, and **Rhs2000DataBlock**. These classes are defined in *.cpp and *.h files named **rhs2000evalboard**, **rhs2000registers**, and **rhs2000datablock**. Additionally, any application must include the Opal Kelly API files **okFrontPanelDLL.cpp** and **okFrontPanelDLL.h**.

The RhythmStim API is written using standard C++ and uses the **string**, **vector**, and **queue** classes from the C++ Standard Template Library (STL).

The public member functions of each class in the RhythmStim API are described below.

Rhs2000EvalBoard Class Reference

This class provides access to and control of the Opal Kelly XEM6010 USB/FPGA interface board running the RhythmStim interface Verilog code. Only one instance of the **Rhs2000EvalBoard** object is needed to control a RhythmStim-based FPGA interface.

The public member functions of the **Rhs2000EvalBoard** class are listed below.

Rhs2000EvalBoard()

Constructor.

int open()

Finds an Opal Kelly XEM6010-LX45 board attached to a USB port and opens it. Returns 1 if successful. Returns -1 if Opal Kelly FrontPanel DLL cannot be loaded. Returns -2 if an XEM6010 board is not found.

bool uploadFpgaBitFile(string filename)

Uploads the RhythmStim configuration file (i.e., bitfile) to the Xilinx FPGA on the open Opal Kelly board. Returns true if successful.

void initialize()

Initializes RhythmStim FPGA registers to default values.

void resetBoard()

Resets the FPGA. This clears all auxiliary command RAM banks, clears the USB FIFO, and resets the per-channel sampling rate to its default value of 30.0 kS/s/channel.

bool setSampleRate(AMPLIFIER_SAMPLE_RATE newSampleRate)

Sets the per-channel sampling rate of the RHS2116 chips connected to the RhythmStim FPGA. Returns false if an unsupported sampling rate is requested. Sample rates are given using the **AMPLIFIER_SAMPLE_RATE** enumeration; defined values are:

SampleRate1000Hz
SampleRate1250Hz
SampleRate1500Hz
SampleRate2000Hz
SampleRate2500Hz

SampleRate3000Hz
SampleRate3333Hz
SampleRate4000Hz
SampleRate5000Hz
SampleRate6250Hz
SampleRate8000Hz
SampleRate10000Hz
SampleRate12500Hz
SampleRate15000Hz
SampleRate20000Hz
SampleRate25000Hz
SampleRate30000Hz

double getSampleRate()

Returns the current per-channel sampling rate (in Hz) as a floating-point number.

AmplifierSampleRate getSampleRateEnum()

Returns the current per-channel sampling rate as an **AmplifierSampleRate** enumeration.

void uploadCommandList(const **vector<int>** &commandList, **AuxCmdSlot** auxCommandSlot)

Uploads a command list (generated by an instance of the **Rhs2000Registers** class) to a particular auxiliary command slot on the FPGA. Command slots are given using the **AuxCmdSlot** enumeration; defined values are:

AuxCmd1
AuxCmd2
AuxCmd3
AuxCmd4

void printCommandList(const **vector<int>** &commandList)

Prints a command list (generated by an instance of the **Rhs2000Registers** class) to the console in readable form, for diagnostic purposes.

void selectAuxCommandLength(**AuxCmdSlot** auxCommandSlot, **int** loopIndex, **int** endIndex)

Specifies a command sequence end point (endIndex = 0-8191) and command loop index (loopIndex = 0-8191) for a particular auxiliary command slot (AuxCmd1, AuxCmd2, AuxCmd3, or AuxCmd4).

void setContinuousRunMode(**bool** continuousMode);

Sets the FPGA to run continuously once started (if continuousMode is set to true) or to run until maxTimeStep is reached (if continuousMode is set to false).

void setMaxTimeStep(**unsigned int** maxTimeStep)

Sets maxTimeStep for cases where continuousMode = false.

RHS2000 USB/FPGA Interface: RhythmStim

void run()

Starts SPI data acquisition.

bool isRunning()

Returns true if the FPGA is currently running SPI data acquisition.

unsigned int numWordsInFifo()

Returns the number of 16-bit words in the USB FIFO. The user should never attempt to read more data than the FIFO currently contains, as it is not protected against underflow.

unsigned int fifoCapacityInWords()

Returns the number of 16-bit words in the USB SDRAM FIFO can hold (67,108,864). The FIFO can actually hold a few thousand words more than this due to the on-FPGA mini-FIFOs used to interface with the SDRAM, but this function provides a conservative estimate of maximum FIFO capacity.

void setStimCmdMode(bool enabled)

Enables or disables automatic stimulation command mode in the FPGA. Affects all RHS2116 chips connected. If automatic stimulation command mode is enabled, all auxiliary commands uploaded to the FPGA are ignored, and the four extra command slots during each sampling period are used to set stimulation parameters (i.e., turning stimulators on/off, setting stimulation polarity, activating amplifier settling for fast artifact recovery, and activating charge recovery) that are controlled by the Stimulation Sequencer state machines.

void programStimReg(int stream, int channel, StimRegister reg, int value)

Programs a value to a particular Stimulation Sequencer state machine on the FPGA. Also works for Analog Output Sequencers and Digital Output Sequencers with stream > 7. See description under **WireInStimRegAddr** and **WireInStimRegWord** above for details on the operation of the Sequencers. The desired Sequencer register must be specified using the **StimRegister** enumeration; defined values are:

- TriggerParams
- StimParams
- EventAmpSettleOn
- EventAmpSettleOff
- EventStartStim
- EventStimPhase2
- EventStimPhase3
- EventEndStim
- EventChargeRecovOn
- EventChargeRecovOff
- EventAmpSettleOnRepeat
- EventAmpSettleOffRepeat
- EventEnd
- DacBaseline
- DacPositive
- DacNegative

RHS2000 USB/FPGA Interface: RhythmStim

void configureStimTrigger(int stream, int channel, int triggerSource, bool triggerEnabled, bool edgeTriggered, bool triggerOnLow)

Configures a stimulation trigger for a Sequencer state machine. This function calls programStimReg and programs the **TriggerParams** register of a particular Sequencer.

void configureStimPulses(int stream, int channel, int numPulses, StimShape shape, bool negStimFirst)

Configures stimulation pulse parameters for a Sequencer state machine. This function calls programStimReg and programs the **StimParams** register of a particular Sequencer. The desired stimulation shape must be specified using the **StimShape** enumeration; defined values are:

Biphasic
BiphasicWithInterphaseDelay
Triphasic
Monophasic

Not all stimulation shapes are valid with all types of Sequencers. See description under WireIns **WireInStimRegAddr** and **WireInStimRegWord** above for details on the operation of the Sequencers.

void resetSequencers()

This function resets all Sequencer state machines on the FPGA. This is typically called after data acquisition is stopped. It is possible that a Sequencer could be in the middle of playing out a long pulse train (e.g., 100 stimulation pulses). If this function is not called, the pulse train will resume after data acquisition is restarted.

void setAnalogInTriggerThreshold(double voltageThreshold)

Sets the voltage threshold to be used for digital triggering from Analog In (ADC) ports. This function assumes additional circuitry has been added to the 16-bit ADCs to extend their input range to ± 10.24 V.

void setManualStimTrigger(int trigger, bool triggerOn)

Sets the state of the manual (software) stimulation triggers 0-7 that can be used to trigger stimulation events.

void enableAuxCommandsOnOneStream(int stream)

Assuming that automatic stimulation command mode has been disabled, this function allows the user to select one specific RHS2116 chip (stream 0-7) to receive auxiliary commands that have been uploaded to the FPGA. All other chips receive dummy commands (reading from ROM Register 255) during the auxiliary command slots. This allows the user to program chips independently (e.g., to set stimulation amplitudes differently on different chips).

void enableAuxCommandsOnAllStreams()

Assuming that automatic stimulation command mode has been disabled, this function sets all connected RHS2116 chips to receive the same auxiliary commands that have been uploaded in the auxcmd1 – auxcmd4 slots on the FPGA.

void setGlobalSettlePolicy(bool settleWholeHeadstageA, bool settleWholeHeadstageB, bool settleWholeHeadstageC, bool settleWholeHeadstageD, bool settleAllHeadstages)

Since stimulation on one channel can create recording artifacts on nearby channels due to capacitive coupling in headstages, connectors, and/or electrode arrays, it is often useful to perform fast artifact recovery (i.e., amplifier settling) across an entire headstage. This function configures **WireInGlobalSettleSelect** (see above) to enable various modes of global amplifier settling.

RHS2000 USB/FPGA Interface: RhythmStim

void setAmpSettleMode(**bool** useFastSettle)

Selects the amplifier settle (fast artifact recovery) mode for all connected RHS2116 chips. If useFastSettle is true, the traditional fast settle method is used. If useFastSettle is false, the low frequency cutoff select method is used (recommended).

void setChargeRecovery(**bool** useSwitch)

Selects the charge recovery mode for all connected RHS2116 chips. If useSwitch is true, the charge recovery switches are used. If useSwitch is false, the current-limited charge recovery drivers are used.

void setCableDelay(**BoardPort** port, **int** delay)

Sets the delay for sampling the MISO line on a particular SPI port (PortA, PortB, PortC, or PortD), in integer clock steps, where each clock step is 1/2800 of a per-channel sampling period. Cable delay should be updated after any changes are made to the sampling rate, since cable delay calculations are based on the clock period.

Most users will probably find it more convenient to use **setCableLengthMeters** or **setCableLengthFeet** instead of using **setCableDelay** directly.

int getCableDelay(**BoardPort** port)

void getCableDelay(**vector**<**int**> &delays)

Returns the last delay set on a particular SPI port (PortA, PortB, PortC, or PortD), or all ports, in integer clock steps.

void setCableLengthMeters(**BoardPort** port, **double** lengthInMeters)

void setCableLengthFeet(**BoardPort** port, **double** lengthInFeet)

Sets the delay for sampling the MISO line on a particular SPI port (PortA, PortB, PortC, or PortD) based on the length of the cable between the FPGA and the RHS2116 chip (in meters or feet). Cable delay should be updated after any changes are made to the sampling rate, since cable delay calculations are based on the clock period.

double estimateCableLengthMeters(**int** delay)

double estimateCableLengthFeet(**int** delay)

Based on a delay setting used in **setCableDelay**, these functions return the estimated cable length corresponding to this setting.

void setDspSettle(**bool** enabled);

Turns on or off the DSP settle function in the FPGA. (This only executes when CONVERT commands are executed by the RHS2116.)

void enableDataStream(**int** stream, **bool** enabled)

Enables (if enabled is true) or disables (if enabled is false) one of the eight available USB data streams (0-7).

int getNumEnabledDataStreams()

Returns the total number of enabled USB data streams.

RHS2000 USB/FPGA Interface: RhythmStim

void getTtlIn(int ttlInArray[])

Reads the 16 bits of the digital TTL input lines on the FPGA into a length-16 integer array. The TTL inputs are only sampled when SPI ports are running.

void setDacManual(int value)

Sets the manual AD5662 DAC control (DacManual) WireIn to value (0-65536). DAC values are only updated when SPI ports are running.

void setLedDisplay(int ledArray[])

Sets the eight red LEDs on the Opal Kelly XEM6010 board according to a length-8 integer array.

void enableDac(int dacChannel, bool enabled)

Enables (if enabled is true) or disables (if enabled is false) AD5662 DACs connected to the FPGA.

void setDacGain(int gain)

Scales the digital signals to all eight AD5662 DACs by a factor of 2^{gain} , where gain is between 0 and 7.

void setAudioNoiseSuppress(int noiseSuppress)

Sets the noise slicing region for DAC channels 1 and 2 (i.e., audio left and right) to $\pm 16 \times \text{noiseSuppress}$ LSBs, where noiseSuppress is between 0 and 127. This improves the audibility of weak neural spikes in noisy waveforms.

void selectDacDataStream(int dacChannel, int stream)

void selectDacDataChannel(int dacChannel, int dataChannel)

Assigns a particular data stream (0-7) and amplifier channel (0-15) to an AD5662 DAC channel (0-7). Setting stream to 8 selects the DacManual source.

void enableDacHighpassFilter(bool enable)

Enables (if enabled is true) or disables (if enabled is false) the first-order high-pass filters implemented in the FPGA on all eight DAC/comparator channels. These filters may be used to remove low-frequency local field potential (LFP) signals from neural signals to facilitate spike detection while still recording the complete wideband data.

void setDacHighpassFilter(double cutoff)

Sets a cutoff frequency (in Hz) for first-order high-pass filters implemented in the FPGA on all eight DAC/comparator channels.

void setDacThreshold(int dacChannel, int threshold, bool trigPolarity)

Sets a threshold level (0-65535) and trigger polarity for a low-latency FPGA threshold comparator on a DAC channel (0-7). The threshold parameter corresponds to the RHS2116 chip ADC output value, where the 'zero' level is 32768 and the step size is $0.195 \mu\text{V}$. If the trigger polarity is set to true, RHS2116 signals equaling or rising above the threshold produce a high digital output. If the trigger polarity is set to false, RHS2116 signals equaling or falling below the threshold produce a high digital output. If the corresponding DAC is disabled, the digital output will always be low.

RHS2000 USB/FPGA Interface: RhythmStim

To enable the comparator output signals on TTL outputs 0-7, the **setTtlMode** function must be used (see below).

void setTtlOutMode(bool mode1, bool mode2, bool mode3, bool mode4, bool mode5, bool mode6, bool mode7, bool mode8)

Sets the TTL digital output mode of the FPGA for digital out ports 1-8. If mode is set false, the digital output pin is controlled by the Digital Output Sequencer. If mode is set true, the output is controlled by the low-latency threshold comparator connected to the waveform routed to the corresponding DAC. Digital out ports 9-16 are always controlled by Digital Output Sequencers.

void flush()

Flush all remaining data out of the FIFO. (This function should only be called when SPI data acquisition has been stopped.)

bool readDataBlock(Rhs2000DataBlock *dataBlock)

Reads a data block from the USB interface and stores the data into an **Rhs2000DataBlock** object dataBlock. Returns true if data block was available.

long readDataBlocksRaw(int numBlocks, unsigned char *buffer)

Reads certain number of USB data blocks, if the specified number is available, and writes the raw bytes to a buffer. Returns the total number of bytes read.

bool readDataBlocks(int numBlocks, queue<Rhs2000DataBlock> &dataQueue)

Reads a specified number of data blocks from the USB interface and appends them to a queue. Returns true if the requested number of data blocks were available.

int queueToFile(queue<Rhs2000DataBlock> &dataQueue, ofstream &saveOut)

Writes the contents of a data block queue to a binary output stream. Returns number of data blocks appended to queue.

int getBoardMode()

Reads four digital input pins on the FPGA (see **JP3 I/O Connections** section) and returns this as an integer. These pins will typically be hard-wired either high or low to encode a 4-bit number that identifies particular properties of the interface board.

Rhs2000Registers Class Reference

This class creates and manages a data structure representing the internal RAM registers on a RHS2116 chip, and generates command lists to configure the chip and perform other functions. Changing the value of variables within an instance of this class does not directly affect a RHS2116 chip connected to the FPGA; rather, a command list must be generated from this class and then downloaded to the FPGA board using **Rhs2000EvalBoard::uploadCommandList**. Typically, one instance of **Rhs2000Registers** will be created for each RHS2116 chip attached to the RhythmStim interface. However, if all chips will receive the same MOSI commands, then only one instance of **Rhs2000Registers** is required.

The public member functions of the **Rhs2000Registers** class are listed below.

RHS2000 USB/FPGA Interface: RhythmStim

Rhs2000Registers(double sampleRate, StimStepSize stimStep)

Constructor. Sets RHS2116 register variables to default values. The desired stimulation step size must be specified using the **StimStepSize** enumeration; defined values are:

StimStepSize10nA
StimStepSize20nA
StimStepSize50nA
StimStepSize100nA
StimStepSize200nA
StimStepSize500nA
StimStepSize1uA
StimStepSize2uA
StimStepSize5uA
StimStepSize10uA

void defineSampleRate(double newSampleRate)

Defines RHS2116 per-channel sampling rate so that certain sample-rate-dependent registers are set correctly. (This function does not change the sampling rate of the FPGA; for this, use **Rhs2000EvalBoard::setSampleRate**.)

void setDigOutLow(DigOut pin)

void setDigOutHigh(DigOut pin)

void setDigiOutHiZ(DigOut pin)

Sets an auxiliary digital output variable to indicate a low, high, or high impedance (HiZ) output for a digital output pin specified by the **DigOut** enumeration; defined values are:

DigOut1
DigOut2
DigOutOD

void enableDsp(bool enabled)

Enables or disables DSP offset removal filter.

double setDspCutoffFreq(double newDspCutoffFreq)

Sets the DSP offset removal filter cutoff frequency as closely to the requested newDspCutoffFreq (in Hz) as possible; returns the actual cutoff frequency (in Hz).

double getDspCutoffFreq()

Returns the current value of the DSP offset removal cutoff frequency (in Hz).

void enableZcheck(bool enabled)

Enables or disables impedance checking mode.

void setZcheckDacPower(bool enabled)

Powers up or down impedance testing DAC.

RHS2000 USB/FPGA Interface: RhythmStim

void setZcheckScale(ZcheckCs scale)

Selects the series capacitor C_s used to convert the voltage waveform generated by the on-chip DAC into an AC current waveform that stimulates a selected electrode for impedance testing. The capacitor is specified using the **ZcheckCs** enumeration; defined values are:

ZcheckCs100fF
ZcheckCs1pF
ZcheckCs10pF

int setZcheckChannel(int channel)

Selects the amplifier channel (0-15) for impedance testing.

void setAmpPowered(int channel, bool powered)

void powerUpAllAmps()

void powerDownAllAmps()

Powers up or down selected AC-coupled high-gain amplifiers on RHS2116 chip.

void setDCAmpPowered(int channel, bool powered)

void powerUpAllDCAmps()

void powerDownAllDCAmps()

Powers up or down selected DC-coupled low-gain amplifiers on RHS2116 chip.

void setStimEnable(bool enable)

Enables or disables stimulation globally on the entire chip by setting appropriate values for Registers 32 and 33.

void setStimStepSize(StimStepSize step)

Sets the stimulation current DAC step size for the entire chip. See Constructor description above for list of valid step sizes.

double stimStepSizeToDouble(StimStepSize step)

Returns the numerical value (in amps) of a stimulation step size enumeration parameter. See Constructor description above for list of valid step sizes.

int setPosStimMagnitude(int channel, int magnitude, int trim)

int setNegStimMagnitude(int channel, int magnitude, int trim)

Sets the positive or negative stimulation magnitude (0 to 255, in DAC steps) and trim value (-128 to +127) for a particular stimulator channel (0-15). Returns -1 if any input parameters are out of range; otherwise returns 0.

void setChargeRecoveryCurrentLimit(ChargeRecoveryCurrentLimit limit)

Sets the charge recovery current limit globally. The currentLimit parameter is set by the **ChargeRecoveryCurrentLimit** enumeration; defined values are:

RHS2000 USB/FPGA Interface: RhythmStim

CurrentLimit1nA
CurrentLimit2nA
CurrentLimit5nA
CurrentLimit10nA
CurrentLimit20nA
CurrentLimit50nA
CurrentLimit100nA
CurrentLimit200nA
CurrentLimit500nA
CurrentLimit1uA

double chargeRecoveryCurrentLimitToDouble(**ChargeRecoveryCurrentLimit** limit)

Returns the numerical value (in amps) of a charge recovery current limit enumeration parameter. See above for list of valid limits.

double setChargeRecoveryTargetVoltage(**double** vTarget)

Sets the target voltage for current-limited charge recovery. The parameter vTarget should specify a voltage in the range of -1.225 to +1.215 (with units of volts). Returns the actual value of the target voltage (limited by DAC resolution).

int getRegisterValue(**int** reg)

Returns the value of a selected RHS2116 RAM register (0-250), based on the current register variables in the class instance.

double setUpperBandwidth(**double** upperBandwidth)

double setLowerBandwidth(**double** lowerBandwidth, **int** select)

Sets the on-chip RH1, RH2, and RL DAC values appropriately to set a particular amplifier bandwidth (in Hz). Returns an estimate of the actual bandwidth achieved. If select = 1, the "A version" of the lower bandwidth is set; this is the version used in normal recording. If select = 0, the "B version" of the lower bandwidth is set; this is the version used to recover from stimulation artifacts if fast artifact recovery is performed using low frequency cutoff shifting.

unsigned int createRhs2000Command(**Rhs2000CommandType** commandType)

unsigned int createRhs2000Command(**Rhs2000CommandType** commandType, **unsigned int** arg1)

unsigned int createRhs2000Command(**Rhs2000CommandType** commandType, **unsigned int** arg1, **unsigned int** arg2)

unsigned int createRhs2000Command(**Rhs2000CommandType** commandType, **unsigned int** arg1, **unsigned int** arg2, **unsigned int** uFlag, **unsigned int** mFlag)

Returns a 32-bit MOSI command based on the **Rhs2000CommandType** enumeration; defined values are:

Rhs2000CommandConvert
Rhs2000CommandCalibrate
Rhs2000CommandCalClear
Rhs2000CommandRegWrite
Rhs2000CommandRegRead
Rhs2000CommandComplianceReset

CONVERT and READ commands use arg1 to specify a register or channel; WRITE commands use arg1 and arg2 to specify a register and value, respectively. The optional arguments uFlag and mFlag should have a value of 0 or 1. Setting these to 1 asserts the U or M flags to update all triggered registers or clear the compliance monitor register, respectively. (See the "SPI Command Words" section of the RHS2116 chip datasheet for more details.)

RHS2000 USB/FPGA Interface: RhythmStim

int createCommandListRegisterConfig(vector<unsigned int> &commandList, bool updateStimParams)

Creates a list of 128 commands to program most RAM registers on an RHS2116 chip, read those values back to confirm programming, read ROM registers, and (if updateStimParams = true) update stimulation amplitudes (Registers 64-79 and 96-111) and other charge-recovery parameters (Registers 34-37). Returns the length of the command list.

int createCommandListRegisterRead(vector<unsigned int> &commandList)

Creates a list of 128 commands to read all registers from an RHS2116 chip without change any values. Returns the length of the command list.

int createCommandListZcheckDac(vector<unsigned int> &commandList, double frequency, double amplitude)

Creates a list of up to 8192 commands to generate a sine wave of particular frequency (in Hz) and amplitude (in DAC steps, 0-128) using the on-chip impedance testing voltage DAC. If frequency is set to zero, a DC baseline waveform is created, which can be used when impedance testing is disabled to minimize on-chip noise. This function returns the length of the command list.

int createCommandListDummy(vector<unsigned int> &commandList, int n)

Creates a list of n dummy commands (reading from ROM Register 255). Returns the length of the command list (which should equal n).

int createCommandListDummy(vector<unsigned int> &commandList, int n, unsigned int cmd)

Creates a list of n dummy commands using a specific command word cmd. Returns the length of the command list (which should equal n).

int createCommandListSingleRegisterConfig(vector<unsigned int> &commandList, int reg)

Creates a list of 128 commands to update a single RAM register reg. Returns the length of the command list.

int createCommandListSetStimMagnitudes(vector<unsigned int> &commandList, int channel, int posMag, int posTrim, int negMag, int negTrim)

Creates a list of 128 commands to set the positive and negative stimulation magnitude and trim parameters for a single channel. Returns the length of the command list.

int createCommandConfigChargeRecovery(vector<unsigned int> &commandList, ChargeRecoveryCurrentLimit currentLimit, double targetVoltage)

Creates a list of 128 commands to set the charge recovery current limit and target voltage. Returns the length of the command list. The parameter targetVoltage should fall within the range of -1.225 to +1.215 (units: volts).

Rhs2000DataBlock Class Reference

This class creates a data structure storing SAMPLES_PER_DATA_BLOCK data samples from a RhythmStim FPGA interface controlling up to eight RHS2116 chips. (A #define statement in `rhs2000datablock.h` currently sets SAMPLES_PER_DATA_BLOCK to 128.) Typically, instances of `Rhs2000DataBlock` will be created dynamically as data becomes available over the USB interface and appended to a queue that will be used to stream the data to disk or to a GUI display.

The public member functions of the `Rhs2000DataBlock` class are listed below.

`Rhs2000DataBlock(int numDataStreams)`

Constructor. Allocates memory for a data block supporting the specified number of data streams.

`unsigned int getSamplesPerDataBlock()`

Returns the SAMPLES_PER_DATA_BLOCK, which is set to 128.

`unsigned int calculateDataBlockSizeInWords(int numDataStreams)`

Returns the size of a USB data block (in 16-bit words) when numDataStreams data streams are enabled.

`void fillFromUsbBuffer(unsigned char usbBuffer[], int blockIndex, int numDataStreams)`

Fills the data block with raw data from the n^{th} data block in a USB input buffer in an `Rhs2000EvalBoard` object. Setting blockIndex to 0 selects the first data block in the buffer, setting blockIndex to 1 selects the second data block, etc.

`void print(int stream)`

Prints the contents of RHS2116 registers from a selected USB data stream (0-7) to the console. This function assumes that the command string generated by `Rhs2000Registers::createCommandListRegisterConfig` has been uploaded to the AuxCmd1 slot.

`void write(ofstream &saveOut, int numDataStreams)`

Writes the contents of a data block object to a binary output stream in little endian format (i.e., least significant byte first).

`bool checkUsbHeader(unsigned char usbBuffer[], int index)`

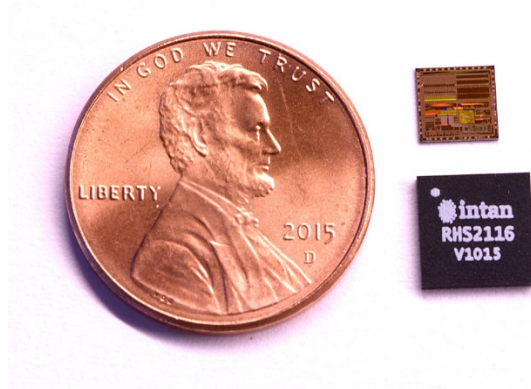
Checks the first 64 bits of USB header against the fixed RhythmStim “magic number” to verify proper data synchrony.

RHS2000 USB/FPGA Interface: RhythmStim

Contact Information

This datasheet is meant to acquaint engineers and scientists with the RhythmStim USB/FPGA interface code developed at Intan Technologies. We value feedback from potential end users. We can discuss your specific needs and suggest a solution tailored to your applications.

For more information, contact Intan Technologies at:



www.intantech.com
info@intantech.com

© 2017-2019 Intan Technologies, LLC

Information furnished by Intan Technologies is believed to be accurate and reliable. However, no responsibility is assumed by Intan Technologies for its use, nor for any infringements of patents or other rights of third parties that may result from its use. Specifications subject to change without notice. Intan Technologies assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using Intan Technologies components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

Intan Technologies' products are not authorized for use as critical components in life support devices or systems. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.