

RHD



XEM7310 Interface: Rhythm USB-7310

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Features

- ◆ Open-source Verilog hardware description language (HDL) code configures a Xilinx field-programmable gate array (FPGA) to communicate with multiple RHD digital electrophysiology interface chips
- ◆ Verilog code is written for the commercially-available Opal Kelly XEM7310 module with integrated SuperSpeed USB 3.0 interface
- ◆ Up to 1024 simultaneous amplifier channels supported at sample rates up to 30 kS/s/channel
- ◆ Programmable FPGA clock for RHD interface: sample rates from 1 kS/s/channel to 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 RHD amplifier channels
- ◆ Auxiliary digital I/O: 16 digital input lines and 16 digital output lines supported

Applications

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

Description

To facilitate the development of electrophysiology recording systems using the RHD series of microchips, Intan Technologies provides the following open-source USB/FPGA interface for developers. Designated **Rhythm USB-7310**, the interface consists of Verilog HDL code written for the commercially-available Opal Kelly XEM7310 USB/FPGA interface module and a C++ API. Rhythm USB-7310 configures the Xilinx FPGA on the Opal Kelly module to communicate with up to 16 RHD chips over SPI buses and to stream data from these chips to a host computer over a SuperSpeed USB 3.0 interface.

The Opal Kelly drivers and Rhythm USB-7310 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 Rhythm USB-7310 hardware and software protocols so that developers may quickly link the RHD chips to a host computer of their choice.

Rhythm USB-7310 supports real-time streaming of up to 1024 amplifier channels from multiple RHD chips, auxiliary data from the chips, data from up to eight other ADCs, and signals from 16 digital inputs. All data is synchronized and time-stamped before transmission over a standard USB 3.0 bus to the host computer.

The host computer may configure the Rhythm USB-7310-based module to set the RHD per-channel sampling rate between 1 kS/s and 30 kS/s for a wide variety of electrophysiology recording applications (e.g., neural spikes, EMG, EKG). Custom RHD command sequences may be uploaded to the FPGA for transmission over the SPI buses. Selected amplifier channels may be directly routed to eight optional DACs for analog signal reconstruction or audio monitoring with minimal latency.

Rhythm USB-7310 FPGA I/O Signals

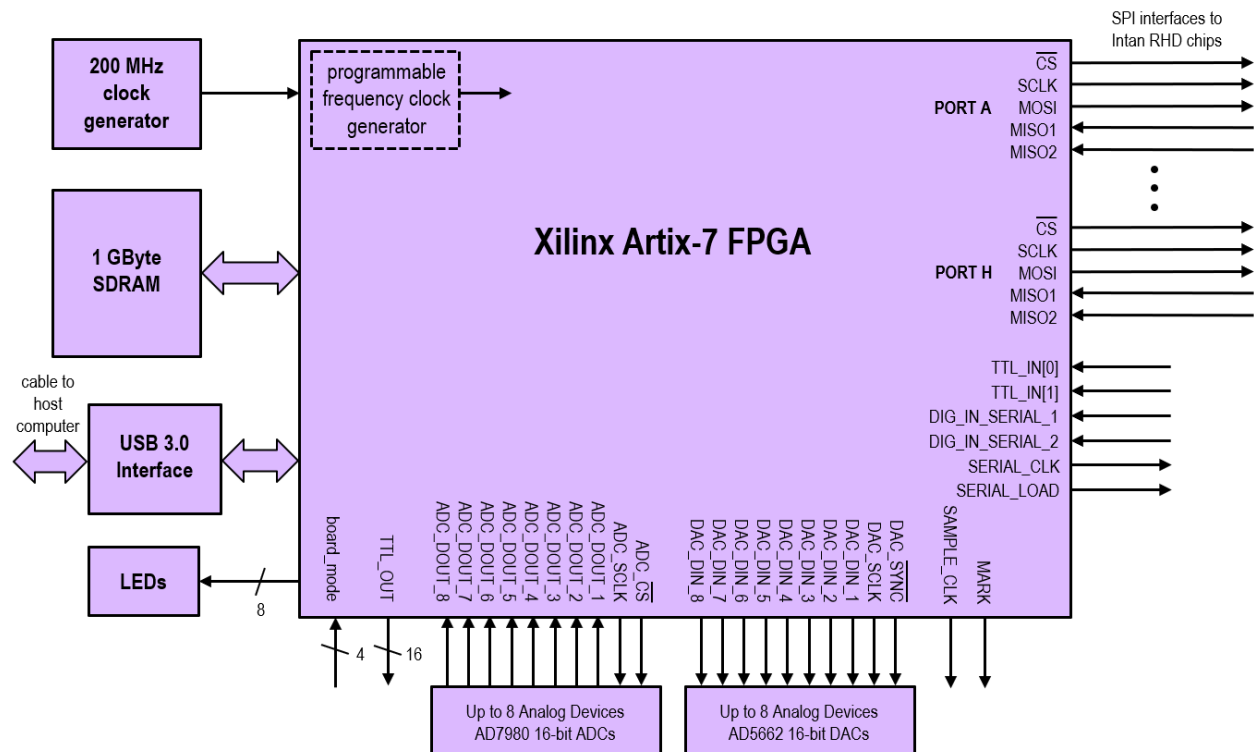
General Description

The Rhythm USB-7310 interface code is designed for the Opal Kelly XEM7310-A75 USB/FPGA module which is a small commercially-available circuit board containing a Xilinx Artix-7 FPGA (XC7A75T-1C), a 1-GByte SDRAM chip, a 200-MHz clock source, I/O connectors, and a USB 3.0 interface chip capable of streaming data to a host computer at rates exceeding 340 MByte/s. (A photo of the board is shown on page 1 of this datasheet. See www.opalkelly.com for detailed information on this module.)

The Artix-7 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 Vivado software. The bitfile must be uploaded to the FPGA through the host computer USB interface 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 XEM7310-A200 USB/FPGA module which is identical to the XEM7310-A75 except for the use of an XC7A200T-1C FPGA which contains approximately three times as many logic gates as the XC7A75T-1C. Developers who wish to add significant amounts of processing at the FPGA level may wish to use this module and recompile the Rhythm USB-7310 Verilog code selecting this larger FPGA as the target.

The diagram below shows the main elements of the XEM7310 board and the I/O signals defined by Rhythm USB-7310.



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RHD SPI Interfaces

Rhythm USB-7310 sets up eight SPI ports (labeled A through H) that can send independent command streams to different sets of RHD chips. Unlike the old USB2 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 RHD chips. LVDS signaling is recommended for operation over long cables.

Each SPI port on the FPGA has three output signals that coordinate communication with RHD chips and send commands: \overline{CS} , SCLK, and MOSI (Master Out, Slave In). The FPGA always acts as the SPI master device, and each RHD chip acts as an SPI slave device. Each SPI port in Rhythm USB-7310 has two MISO (Master In, Slave Out) inputs for receiving data from an RHD chip. This means that each port can be connected to two RHD chips, but both of these chips will receive the same commands. So, for example, the auxiliary digital output pin on the two RHD chips cannot be set to different values. For most applications this is not a serious restriction, and it permits the construction of compact 128-channel recording modules using two RHD2164 chips, for example. Each module requires a 12-conductor cable to support five LVDS SPI signals plus power and ground.

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.) Rhythm USB-7310 allows users to adjust the MISO sampling delay independently on all eight SPI ports to account for cable delays.

Using dual MISO signals on each of eight ports, the FPGA can stream data from up to 16 RHD chips. If 16 RHD2164 chips are used, a total of 1024 amplifier channels may be acquired in real time. The USB 3.0 interface on the Opal Kelly XEM7310 module is capable of reliably streaming data from 1024 channels to a host computer at per-channel sampling rates up to 30 kS/s, even with typical USB protocol overhead and software overhead.

Rhythm USB-7310 sends commands to all RHD chips in a repeating 35-command sequence: every sampling period, the FPGA sends the commands CONVERT(0), CONVERT(1), CONVERT(2), and so on up to CONVERT(31) to sample from all amplifiers on the chip. (If the 16-channel RHD2216 chip is used, the last 16 CONVERT commands produce junk results that can be ignored.) These 32 CONVERT commands are followed by three “auxiliary” commands that may be used to perform a variety of other tasks on an RHD chip, like synthesizing a waveform for electrode impedance testing, reading from the auxiliary inputs, performing ADC calibration, or reading and writing other registers. Under Rhythm USB-7310, the first 32 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 200-MHz clock to the FPGA; this clock is used to run the USB interface logic. Rhythm USB-7310 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 RHD amplifiers can be sampled at per-channel rates varying from 1 kS/s to 30 kS/s.

Other I/O Signals

Rhythm USB-7310 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. Rhythm USB-7310 is designed to support the Analog Devices AD5662 DAC and the Analog Devices AD7980 ADC (**note:** the older Rhythm code for USB2 supported the AD7680 ADC, which has a different command protocol); other DACs and ADCs could be supported by modifying the Verilog code. Rhythm USB-7310 permits the user to select particular RHD amplifier channels to be routed directly to selected DACs through the FPGA, eliminating any USB or host computer latency. 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 RHD amplifiers, and their results are streamed back to the host computer over the USB interface.

Rhythm USB-7310 also supports 16 digital inputs and 16 digital outputs. The digital outputs produce 3.3V signals. The digital inputs have a logic threshold around 1.5V and can safely accept signals up to 5V. Two digital inputs are sampled directly; more can be implemented using 74HC165 shift register integrated circuits (contact Intan Technologies for more information).

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.

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.

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A digital output signal **sample_clk** is provided on FPGA pin B35_L21P as a convenience. This signal is a clock running at the per-channel amplifier sampling rate. The duty cycle of the signal is 1/35. For example, if the board is configured to sample each RHD amplifier channel at 20 kS/s then the period of this clock will be 50 μ s. It will be high for approximately 1.43 μ s, and low the rest of the cycle. (The signal goes high at the falling edge of \overline{CS} that begins the CONVERT(0) command, and it goes low at the falling edge of \overline{CS} that begins the CONVERT(1) command.)

Power Supply

The total current consumption of the XEM7310 board running Rhythm USB-7310 exceeds the 500 mA USB port limit. It is recommended to power the Opal Kelly XEM7310 board from a 5V DC power supply capable of sourcing sufficient current and having a 2.1mm inner-diameter / 5.5mm outer-diameter connector. Digi-Key (www.digikey.com) offers a medical-rated power supply that mates with the XEM7310 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 1.0V, 1.8V, and 3.3V supplies. See the Opal Kelly documentation for current limits on these supplies.

If RHD 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. RHD 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 four pages are based on information in the Opal Kelly XEM7310 User's Manual.

There are four pins labeled board_mode[0..3] which are configured as inputs. Our RHX data acquisition software requires these pins to be set to 13 (board_mode[3] = 1, board_mode[2] = 1, board_mode[1] = 0, board_mode[0] = 1) to recognize an XEM7310 as an RHD recording controller.

Users may wish to purchase the BRK7010 breakout board which can be connected to the XEM7310 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., B35_L19P and B35_L19N are I/O pin pairs in FPGA Bank 35). An inspection of the **xem7310.xdc** file provided with Rhythm USB-7310 shows that the IOSTANDARD LVDS_25 property is used for LVDS signals, while IOSTANDARD LVCMOS_33 is used for standard CMOS signals.

MC1 I/O Connections – Odd Pins

MC1 Pin	Connection	FPGA Pin	Rhythm USB-7310 Interface Pin Name
1	+VDCIN		+5V
3	+VDCIN		+5V
5	+VDCIN		+5V
7	+1.8VDD		
9	+3.3VDD		VDD
11	+3.3VDD		VDD
13	+3.3VDD		VDD
15	W9	B34_L24P	ADC_CS
17	Y9	B34_L24N	DAC_SCLK
19	R6	B34_L17P	DAC_SYNC
21	T6	B34_L17N	DAC_DIN_8
23	U6	B34_L16P	unused
25	V5	B34_L16N	unused
27	T5	B34_L14P	DAC_DIN_7
29	U5	B34_L14N	DAC_DIN_6
31	AA5	B34_L10P	unused
33	D17	B34_L10N	unused
35	DGND		GND
37	AB7	B34_L20P	DAC_DIN_5
39	AB6	B34_L20N	DAC_DIN_4
41	R3	B34_L3P	unused
43	R2	B34_L3N	unused
45	Y3	B34_L9P	unused
47	AA3	B34_L9N	unused
49	U2	B34_L2P	unused
51	V2	B34_L2N	DAC_DIN_3
53	W2	B34_L4P	DAC_DIN_2
55	DGND		GND
57	Y2	B34_L4N	DAC_DIN_1
59	T1	B34_L1P	ADC_DOUT_2
61	U1	B34_L1N	ADC_DOUT_1
63	AA1	B34_L7P	DIG_IN_SERIAL_2
65	AB1	B34_L7N	DIG_IN_SERIAL_1
67	AB16	B13_L2P	EXP_ID
69	AB17	B13_L2N	EXP_DETECT
71	AA15	B13_L4P	STATUS_LED_3
73	AB15	B13_L4N	STATUS_LED_2
75	Y16	B13_L1P	STATUS_LED_1
77	V4	B34_L12P_MRCC	unused
79	W4	B34_L12N_MRCC	unused

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MC1 I/O Connections – Even Pins

MC1 Pin	Connection	FPGA Pin	Rhythm USB-7310 Interface Pin Name
2	DGND		GND
4	+1.0VDD		
6	+1.0VDD		
8	AB11	SYS_CLK_MC1	
10	M9	XADC_VN	
12	L10	XADC_VP	
14	DGND		GND
16	V9	B34_L21P	ADC_SCLK
18	V8	B34_L21N	TTL_OUT[0]
20	V7	B34_L19P	TTL_OUT[1]
22	W7	B34_L19N	TTL_OUT[2]
24	Y8	B34_L23P	TTL_OUT[3]
26	Y7	B34_L23N	TTL_OUT[4]
28	W6	B34_L15P	TTL_OUT[5]
30	W5	B34_L15N	TTL_OUT[6]
32	R4	B34_L13P	board_mode[0]
34	T4	B34_L13N	board_mode[1]
36	VCCO_MC1		
38	Y4	B34_L11P	board_mode[2]
40	AA4	B34_L11N	board_mode[3]
42	Y6	B34_L18P	TTL_OUT[7]
44	AA6	B34_L18N	TTL_OUT[8]
46	AA8	B34_L22P	TTL_OUT[9]
48	AB8	B34_L22N	TTL_OUT[10]
50	U3	B34_L6P	TTL_OUT[11]
52	V3	B34_L6N	TTL_OUT[12]
54	W1	B34_L5P	TTL_OUT[13]
56	VCCO_MC1		
58	Y1	B34_L5N	TTL_OUT[14]
60	AB3	B34_L8P	TTL_OUT[15]
62	AB2	B34_L8N	ADC_DOUT_8
64	Y13	B13_L5P	ADC_DOUT_7
66	AA14	B13_L5N	ADC_DOUT_6
68	AA13	B13_L3P	ADC_DOUT_5
70	AB13	B13_L3N	ADC_DOUT_4
72	W15	B13_L16P	ADC_DOUT_3
74	W16	B13_L16N	TTL_IN[1]
76	AA16	B13_L1N	TTL_IN[0]
78	DGND		GND
80	DGND		GND

MC2 I/O Connections – Odd Pins

MC2 Pin	Connection	FPGA Pin	Rhythm USB-7310 Interface Pin Name
1	DGND		GND
3	+VCCBAT		
5	FPGA_TCK		
7	FPGA_TMS		
9	FPGA_TDI		
11	SYS_CLK_MC2	AB12	
13	DGND		GND
15	P5	B35_L21P	SAMPLE_CLK
17	P4	B35_L21N	MARK
19	N4	B35_L19P	SERIAL_LOAD
21	N3	B35_L19N	SERIAL_CLK
23	L5	B35_L18P	SPI_LED_H
25	L4	B35_L18N	SPI_LED_G
27	M6	B35_L23P	SPI_LED_F
29	M5	B35_L23N	SPI_LED_E
31	M1	B35_L15P	SPI_LED_D
33	L1	B35_L15N	SPI_LED_C
35	VCCO_MC2		
37	K2	B35_L9P	SPI_LED_B
39	J2	B35_L9N	SPI_LED_A
41	K1	B35_L7P	MISO_H2
43	J1	B35_L7N	MISO_H1
45	H3	B35_L11P	unused
47	G3	B35_L11N	MOSI_H
49	E2	B35_L4P	SCLK_H
51	D2	B35_L4N	\overline{CS}_H
53	F3	B35_L6P	MISO_G2
55	VCCO_MC2		
57	E3	B35_L6N	MISO_G1
59	B1	B35_L1P	unused
61	A1	B35_L1N	MOSI_G
63	K4	B35_L13P	SCLK_G
65	J4	B35_L13N	\overline{CS}_G
67	T16	B13_L17P	MISO_F2
69	U16	B13_L17N	MISO_F1
71	V13	B13_L13P	unused
73	V14	B13_L13N	MOSI_F
75	Y11	B13_L11P	SCLK_F
77	H4	B35_L12P_MRCC	\overline{CS}_F
79	G4	B35_L12N_MRCC	MISO_E2

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MC2 I/O Connections – Even Pins

MC2 Pin	Connection	FPGA Pin	Rhythm USB-7310 Interface Pin Name
2	+3.3VDD		VDD
4	+3.3VDD		VDD
6	+3.3VDD		VDD
8	FPGA_TDO		
10	F4	B35_IO0	
12	L6	B35_IO25	
14	DGND		GND
16	P6	B35_L24P	$\overline{CS_A}$
18	N5	B35_L24N	SCLK_A
20	P2	B35_L22P	MOSI_A
22	N2	B35_L22N	unused
24	R1	B35_L20P	MISO_A1
26	P1	B35_L20N	MISO_A2
28	M3	B35_L16P	$\overline{CS_B}$
30	M2	B35_L16N	SCLK_B
32	K6	B35_L17P	MOSI_B
34	J6	MOSI2_B	unused
36	DGND		GND
38	L3	B35_L14P	MISO_B1
40	K3	B35_L14N	MISO_B2
42	J5	B35_L10P	$\overline{CS_C}$
44	H5	B35_L10N	SCLK_C
46	H2	B35_L8P	MOSI_C
48	G2	B35_L8N	unused
50	G1	B35_L5P	MISO_C1
52	F1	B35_L5N	MISO_C2
54	E1	B35_L3P	$\overline{CS_D}$
56	DGND		GND
58	D1	B35_L3N	SCLK_D
60	C2	B35_L2P	MOSI_D
62	B2	B35_L2N	unused
64	U15	B13_L14P	MISO_D1
66	V15	B13_L14N	MISO_D2
68	T14	B13_L15P	$\overline{CS_E}$
70	T15	B13_L15N	SCLK_E
72	W14	B13_L6P	MOSI_E
74	Y14	B13_L6N	unused
76	Y12	B13_L11N	MISO_E1
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 1 GByte SDRAM chip that can be used for just such a purpose (though only 128 MBytes are used, for consistency with earlier versions of Rhythm). The Rhythm USB-7310 code implements an SDRAM-based FIFO as a circular queue of 16-bit words. Three on-FPGA "mini-FIFOs" regulate the flow of data into and out of the main SDRAM FIFO. The output of the FIFO is connected to a "BTPipeOut" 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 Rhythm USB-7310 FIFO can hold $2^{27} = 134,217,728$ bytes, or $2^{26} = 67,108,864$ 16-bit words. The on-FPGA "mini-FIFOs" add a few hundred 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. 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 Rhythm USB-7310 Verilog code is structured to ensure that data frames are always integer multiples of four 16-bit words.

Communication with the SDRAM chip must be done in 256-bit chunks, so if only 15 16-bit words are written to the FIFO, they will not pass through the SDRAM until a final 16-bit word is written. In order to fully flush the FIFO, it is necessary to always write an integer multiple of 16 16-bit words to the FIFO. The Rhythm USB-7310 Verilog code includes a 4-bit counter that increments with every word written into the FIFO to track how many remainder words are present and writes the necessary number of dummy words when pausing or stopping the flow of data to ensure the last words are included in a full 256-bit chunk.

The Rhythm USB-7310 interface is capable of transmitting up to 32 simultaneous **data streams**. In Rhythm USB-7310, a data stream is defined as the SPI output of one MISO line from an RHD chip. The 32 data streams correspond to the 32 MISO inputs (and DDR inputs) to the FPGA in Ports A through H. Unless 16-channel RHD2216 chips are used, each data stream conveys 32 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 0xD7A22AAA38132A53 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.

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

16-bit MISO result 1 from data stream 2 (if data stream 2 is enabled)

...

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

16-bit MISO result 2 from data stream 1 (if data stream 1 is enabled)

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

...

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

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...

16-bit MISO result 35 from data stream 1 (if data stream 1 is enabled)

16-bit MISO result 35 from data stream 2 (if data stream 2 is enabled)

...

16-bit MISO result 35 from data stream 32 (if data stream 32 is enabled)

Between zero and three 16-bit filler word (all zeros)

16-bit AD7980 ADC 1 result

16-bit AD7980 ADC 2 result

16-bit AD7980 ADC 3 result

16-bit AD7980 ADC 4 result

16-bit AD7980 ADC 5 result

16-bit AD7980 ADC 6 result

16-bit AD7980 ADC 7 result

16-bit AD7980 ADC 8 result

16-bit TTL input result

16-bit TTL output current value

The all-zero filler words are inserted to ensure 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 $(35 \cdot N + 16 + N \bmod 4)$ words or $2 \cdot (35 \cdot N + 16 + N \bmod 4)$ bytes, where N is the number of data streams that are enabled. The Opal Kelly USB-7310 interface sends data in bytes. In Rhythm USB-7310, 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 ($N = 1$) will have a data frame 104 bytes in length. Running at the maximum rate of 30 kS/s, the data rate will be 3.12 MByte/s. At this rate, the FIFO can hold up to 43.0 seconds of data. A 1024-channel system ($N = 32$) will have a data frame 2272 bytes in length. Running at the maximum rate of 30 kS/s, the data rate will be 68.16 MByte/s. At this rate, the FIFO can hold up to 1.9 seconds of data. These calculations demonstrate that the FIFO has sufficient capacity to handle typical brief operating system pauses during USB data transfers.

The Opal Kelly USB-7310 interface can easily handle 68.16 MByte/s data rates, provided a reasonably fast host computer is used. A Dell XPS 8930 Windows 10 PC purchased in 2020 with a 3.0 GHz Intel i7-9700 processor is capable of running at this rate with an Opal Kelly XEM7310 board and multi-threaded C++ software.

The bulk of each data frame consists of MISO results received from the SPI interface from each RHD chip. These MISO results are numbered 1 through 35, and correspond to the 35 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(31)

auxiliary command 1

auxiliary command 2

auxiliary command 3

It is important to remember that the RHD uses a pipelined communication protocol; each command sent over the MOSI line generates a 16-bit result that is transmitted over the MISO line two commands later (see the “SPI Command Words” section of the RHD datasheet for details). The FPGA introduces another one-command pipeline delay in the received MISO results, so **every MISO result received through the Rhythm USB-7310 FPGA corresponds to the MOSI command sent three steps earlier**. Thus “MISO result 1” is the result of the “auxiliary command 1” from the previous sampling period; “MISO result 4” corresponds to the “CONVERT(0)” command from the current sampling period; and “MISO result 35” corresponds to the “CONVERT(31)” command from the current sampling period. To see the result of the three auxiliary commands at the end of a sampling period, the next data frame must be read.

Programming Auxiliary Command Sequences

Each RHD SPI port (A through H) can send a different set of commands in the three auxiliary command slots described above, which we will abbreviate as **auxcmd1**, **auxcmd2**, and **auxcmd3**. Sequences of auxiliary commands can be uploaded into on-FPGA RAM banks that each hold up to 1024 commands. These command sequences will be transmitted over the MOSI line from each port. The FPGA contains multiple RAM banks that may be pre-loaded with different command sequences which can then be switched rapidly to select different operations.

A concrete example will make things clearer: Let's assume that we always use the **auxcmd1** slot for updating the RHD on-chip DAC used to generate waveforms for electrode impedance testing (i.e., **Zcheck DAC** in Register 6). 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 1024 or fewer commands. Each command slot has 16 RAM banks associated with it that can be rapidly selected as the command source. We could generate command sequences corresponding to sine waves at 16 different frequencies (one of these would probably be a "flat-line" DC waveform to be used when impedance testing is disabled) and upload these to the 16 different **auxcmd1** RAM banks shortly after the FPGA booted up. This would allow us to rapidly switch between impedance testing frequencies without having to upload new command sequences.

Similarly, we could always use the **auxcmd2** slot for sampling the auxiliary inputs to the RHD ADC. We could put together a list of commands to perform these functions and load it into one of the 16 RAM banks associated with the **auxcmd2** slot. Since only one of these commands is executed every sampling period, these sensors would be sampled at a slower rate than the RHD amplifiers, but this is acceptable for most applications.

We could use the **auxcmd3** slot to initialize all the other registers on the chip (e.g., to set amplifier bandwidth), to perform ADC calibration once, and to perform other miscellaneous tasks. Again, there are 16 on-FPGA RAM banks associated with the **auxcmd3** slot in case it is necessary to send different commands to SPI ports A through H.

For each auxiliary command slot (**auxcmd1**, **auxcmd2**, and **auxcmd3**), the user must specify the length of the command sequence. This **command sequence length** is the same for Ports A through H. 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 and to run ADC calibration only once at the beginning of data acquisition.

Any changes made in the selection of RAM bank to be used for a particular command slot, or changes 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.

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 **BTPipeOut** endpoints transfer information from the FPGA to the host computer. Opal Kelly makes all drivers and API software available for download with the purchase of an XEM board. In the sections below, we list all the Opal Kelly endpoints used by Rhythm USB-7310, and we provide sample C++ code for communicating over these endpoints to a Rhythm USB-7310-powered XEM7310 board.

Opening and Initializing the Opal Kelly Board

The following C++ code shows how an Opal Kelly XEM7310 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 **ConfigRHDController_7310.bit** bitfile contains the compiled Rhythm USB-7310 Verilog code provided by Intan Technologies. After this bitfile is uploaded to the XEM7310 board, it behaves as the Rhythm USB-7310 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 XEM7310 PLL to default configuration to produce 200 MHz FPGA clock.
dev->LoadDefaultPLLConfiguration();

// Upload Rhythm USB-7310 bitfile which is compiled from Rhythm USB-7310 Verilog code.
dev->ConfigureFPGA("ConfigRHDController_7310.bit");
```

USB Software Endpoints: WireIn and TriggerIn Ports

USB-7310 WireIn ports are virtual 32-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 0x12345678.
dev->SetWireInValue(0x00, 0x12345678);

// 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 4-31
// unchanged.
dev->SetWireInValue(0x01, 0x00000003, 0x0000000F);

// 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 32-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.

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```
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: TrignSpiStart

WireInResetRun[0]: **reset**

When the Opal Kelly board is first powered up and Rhythm USB-7310 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 Rhythm USB-7310 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 **TrignSpiStart[0]**. To halt data acquisition immediately, set this bit to zero and set **WireInMaxTimeStep** (WireIn 0x01) 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 on all MOSI lines is set to one, settling the RHD digital offset removal filters. (See the RHD datasheet for more information on this function.)

WireInResetRun[3]: **TTL_out_mode**

When this bit is set high, the lower eight bits of the digital output lines (TTL_OUT[0] – TTL_OUT[7]) are put under control of FPGA-implemented threshold comparators that provide logic high signals if waveforms routed to the ADCs exceed user-programmed thresholds. (See **TrignDacConfig** below for more information.) The upper eight bits of the digital output lines (TTL_OUT[8] – TTL_OUT[15]) are controlled by the most significant byte of **WireInTtlOut**.

When this bit is set low, all 16 digital output lines are controlled by **WireInTtlOut**.

WireInResetRun[5:4]: 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.

WireInResetRun[16]: **pipeout_block_throttle_override**

This bit controls a restriction on the minimum data chunk that can be transferred over the USB3 interface. It should be set to zero for normal operation. It is set to one briefly by the flush() function in rhxcontroller.cpp in order to clear all remaining data out of the FIFO.

WireIn 0x01: WireInMaxTimeStep

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This port conveys 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.

WireIn 0x02: 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 0x21. These signals are controlled in the `getNumSPIPorts()` method in `rhxcontroller.cpp`.

WireIn 0x03: WireInDataFreqPll

TriggerIn 0x40: TrigInConfig

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 RHD amplifier sampling frequency. A 200 MHz reference clock is provided to the FPGA from an off-chip clock generator. The output frequency of a programmable FPGA clock generator (a multi-mode clock manager, or MMCM) is given by:

$$\text{FPGA internal clock frequency} = 200 \text{ MHz} \times (M / D) / 4$$

M and D are “multiply” and “divide” integers used in the FPGA’s MMCM 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.)

For compatibility with software that also communicates with the original version of Rhythm USB3 and its digital clock manager (DCM), the above M,D calculation is used. However, the Artix-7 FPGA that is used for the 7310 interface actually controls the output frequency with a different equation, detailed on page 72 of Xilinx document UG472 “7 series FPGAs Clocking Resources User Guide”. Rhythm USB-7310 expects the original Rhythm USB3 M,D values and translates them into the M,D,O values used by the 7-series FPGAs.

This variable-frequency clock drives the state machine that controls all SPI communication with the RHD chips. A complete SPI cycle (consisting of one \overline{CS} pulse and 16 SCLK pulses) takes 80 clock cycles. The SCLK period is 4 clock cycles; the \overline{CS} pulse is high for 14 clock cycles between commands.

Rhythm USB-7310 samples all 32 channels and then executes 3 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 $80 \times (32 + 3) = 80 \times 35 = 2800$ 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

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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 **TrigInConfig[0]**:

```
okCFrontPanel* dev;
// Code to open Opal Kelly board not shown here.
dev->SetWireInValue(0x03, (M << 8) + D); // 0x03 = WireInDataFreqPll
dev->UpdateWireIns();
dev->ActivateTriggerIn(0x40, 0); // 0x40 = TrigInConfig
```

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
WireInMisoDelay[19:16]: MISO delay for Port E
WireInMisoDelay[23:20]: MISO delay for Port F
WireInMisoDelay[27:24]: MISO delay for Port G
WireInMisoDelay[31:28]: MISO delay for Port H

These eight 4-bit registers set the sampling delay applied to MISO1 and MISO2 inputs on each of the eight RHD 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 RHD I/O. The Xilinx Artix-7 FPGA has input and output pin delays of several nanoseconds. The RHD has a typical I/O delay of 9.0 ns. This total I/O delay, plus any delays added by additional circuitry (e.g., isolation buffers) should be added to any expected cable delays when calculating the optimum values for these registers.

WireIn 0x05: WireInCmdRamAddr

WireIn 0x06: WireInCmdRamBank

WireIn 0x07: WireInCmdRamData

TrigIn 0x40: TrigInConfig

These registers are used to upload auxiliary command sequences to RAM banks on the FPGA. To load a command into a particular RAM bank, the following sequence must be executed:

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Use **WireCmdRamAddr** to select an address in the range of 0-1023.

Use **WireInCmdRamBank** to select a RAM bank in the range of 0-15.

Use **WireInCmdRamData** to set the 16-bit MOSI command to be programmed.

Pulse **TrigInConfig[1]** to program the MOSI command to the selected RAM bank and address for **auxcmd1**. Pulse **TrigInConfig[2]** for **auxcmd2**. Pulse **TrigInConfig[3]** for **auxcmd3**.

Repeat this process to program command sequences into the 16 x 3 RAM banks on the FPGA. Each RAM bank can hold up to 1024 commands.

The following example shows how to program the command WRITE(6, 128) to address 7 of RAM bank 3 in the **auxcmd2** slot:

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

unsigned int command = 0x8780; // WRITE(6, 128) command.

dev->SetWireInValue(0x05, 7); // Set address to 7.
dev->SetWireInValue(0x06, 3); // Set RAM bank to 3.
dev->SetWireInValue(0x07, command); // Set command to be programmed.
dev->UpdateWireIns();
dev->ActivateTriggerIn(0x40, 2); // Load in RAM for auxcmd2.
```

WireIn 0x08: WireInAuxCmdBank1

WireInAuxCmdBank1[3:0]: AuxCmdBank1A
WireInAuxCmdBank1[7:4]: AuxCmdBank1B
WireInAuxCmdBank1[11:8]: AuxCmdBank1C
WireInAuxCmdBank1[15:12]: AuxCmdBank1D
WireInAuxCmdBank1[19:16]: AuxCmdBank1E
WireInAuxCmdBank1[23:20]: AuxCmdBank1F
WireInAuxCmdBank1[27:24]: AuxCmdBank1G
WireInAuxCmdBank1[31:28]: AuxCmdBank1H

Each one of these four-bit registers is used to select the RAM bank (0-15) that will be used to send MOSI commands to each port in the **auxcmd1** auxiliary command slot.

WireIn 0x09: WireInAuxCmdBank2

WireInAuxCmdBank2[3:0]: AuxCmdBank2A
WireInAuxCmdBank2[7:4]: AuxCmdBank2B
WireInAuxCmdBank2[11:8]: AuxCmdBank2C
WireInAuxCmdBank2[15:12]: AuxCmdBank2D
WireInAuxCmdBank2[19:16]: AuxCmdBank2E
WireInAuxCmdBank2[23:20]: AuxCmdBank2F
WireInAuxCmdBank2[27:24]: AuxCmdBank2G
WireInAuxCmdBank2[31:28]: AuxCmdBank2H

Each one of these four-bit registers is used to select the RAM bank (0-15) that will be used to send MOSI commands to each port in the **auxcmd2** auxiliary command slot.

WireIn 0x0A: WireInAuxCmdBank3

WireInAuxCmdBank3[3:0]: AuxCmdBank3A
WireInAuxCmdBank3[7:4]: AuxCmdBank3B
WireInAuxCmdBank3[11:8]: AuxCmdBank3C
WireInAuxCmdBank3[15:12]: AuxCmdBank3D

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WireInAuxCmdBank3[19:16]: AuxCmdBank3E
WireInAuxCmdBank3[23:20]: AuxCmdBank3F
WireInAuxCmdBank3[27:24]: AuxCmdBank3G
WireInAuxCmdBank3[31:28]: AuxCmdBank3H

Each one of these four-bit registers is used to select the RAM bank (0-15) that will be used to send MOSI commands to each port in the **auxcmd3** auxiliary command slot.

WireIn 0x0B: WireInAuxCmdLength

WireInAuxCmdLength[9:0]: AuxCmdLength1
WireInAuxCmdLength[19:10]: AuxCmdLength2
WireInAuxCmdLength[29:20]: AuxCmdLength3

Each one of these registers should be set to a number **AuxCmdLength** between 0 and 1023, indicating the index of the last valid command in the selected RAM banks for **auxcmd1**, **auxcmd2**, and **auxcmd3**, respectively. For example, if a RAM bank contains 128 commands that should repeat, set the register value to 127. Note that command lengths must be the same for SPI Ports A through H.

WireIn 0x0C: WireInAuxCmdLoop

WireInAuxCmdLoop[9:0]: AuxCmdLoop1
WireInAuxCmdLoop[19:10]: AuxCmdLoop2
WireInAuxCmdLoop[29:20]: AuxCmdLoop3

Each one of these registers should be set to a number **AuxCmdLoop** between 0 and 1023, indicating the auxiliary command RAM address that is jumped to after the command index reaches **AuxCmdLength** for **auxcmd1**, **auxcmd2**, and **auxcmd3**, respectively. To create a simple list of repeating commands, **AuxCmdLoop** should be set to zero. To create a list of 50 commands where the first 10 commands execute only once and the next 40 command repeat in a loop, set **AuxCmdLoop** to 9 and **AuxCmdLength** to 49.

WireIn 0x0D: WireInLedDisplay

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

WireIn 0x0E: 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.

WireIns 0x0F, 0x10, 0x11, 0x12, and 0x13: unused

These four-bit registers are used to select the data source for each of 32 data streams Rhythm USB-7310 uses to send data over the USB interface to the host computer. The data streams for each setting of **DataStreamSel** are listed in the table below. The last eight rows with the "DDR" designation support 64-channel RHD2164 chips that use double data rate (DDR) SPI to transfer MISO data on both the rising and falling edges of SCLK. The traditional data streams sample MISO on the rising edges of SCLK, plus any delay defined by **WireInMisoDelay**. The DDR data streams sample MISO on the falling edges of SCLK, plus any delay defined by **WireInMisoDelay**.

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WireIn 0x14: WireInDataStreamEn

Setting one of these 32 bits to one enables a particular data stream, 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.

DataStreamEn bit	Data Stream
0	Port A, MISO1
1	Port A, MISO1 DDR
2	Port A, MISO2
3	Port A, MISO2 DDR
4	Port B, MISO1
5	Port B, MISO1 DDR
6	Port B, MISO2
7	Port B, MISO2 DDR
8	Port C, MISO1
9	Port C, MISO1 DDR
10	Port C, MISO2
11	Port C, MISO2 DDR
12	Port D, MISO1
13	Port D, MISO1 DDR
14	Port D, MISO2
15	Port D, MISO2 DDR
16	Port E, MISO1
17	Port E, MISO1 DDR
18	Port E, MISO2
19	Port E, MISO2 DDR
20	Port F, MISO1
21	Port F, MISO1 DDR
22	Port F, MISO2
23	Port F, MISO2 DDR
24	Port G, MISO1
25	Port G, MISO1 DDR
26	Port G, MISO2
27	Port G, MISO2 DDR
28	Port H, MISO1
29	Port H, MISO1 DDR
30	Port H, MISO2
31	Port H, MISO2 DDR

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: WireInTtlOut

WireInTtlOut[15:0]: TtlOut

This register sets the 16 TTL output pins defined by Rhythm USB-7310. (If **TTL_out_mode** is set to one, the lower eight TTL output pins are controlled by the FPGA threshold comparators.)

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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[10:5]: DacSourceStreamX
WireInDacSourceX[11]: DacSourceEnableX

These registers route selected amplifier signals to the eight DACs that Rhythm USB-7310 supports. For each DAC, the user may select an amplifier channel (0-31) and a data stream (nominally 0-31). To enable the DAC, the **DacSourceEnable** bit must be set high. If **DacSourceStream** is set to 32, the DAC will be controlled directly by the host computer via **WireInDacManual**; the **DacSourceChannel** parameter is ignored in this case.

WireIn 0x1E: WireInDacManual

WireInDacManual[15:0]: DacManual

This WireIn is used to control DACs directly when their DacSourceStream parameter is set to 32 (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 0x40: TrigInConfig

TrigInConfig[4]: EnableDacHighpassFilter
TrigInConfig [5]: SetDacHighpassFilterCutoff

Rhythm USB-7310 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 **TrigInConfig[4]**. To set the filter cutoff frequency, apply the filter coefficient to **WireInMultiUse** and pulse **TrigInConfig[5]**.

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

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

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

TrigInConfig [6]: EnableExternalFastSettle
TrigInConfig [7]: SetExternalFastSettleChannel

Rhythm USB-7310 includes real-time control of the “fast settle” function on all connected RHD chips. Enabling fast settle effectively blanks the amplifiers and prevents them from saturating during exposure to large transient input signals (e.g., due to nearby stimulation). To enable or disable real-time control of the fast settle function, apply a one or zero, respectively, to **WireInMultiUse** and pulse **TrigInConfig[6]**. To select the TTL digital input used for fast settle control, apply a number between 0 and 15 to

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WireInMultiUse and pulse **TrigInConfig[7]**. There is a latency of 4-5 amplifier sampling periods from the digital input changing to the fast settle function turning on or off.

TrigInConfig[8]: SetSpiPortLeds

Eight LEDs can be connected to the Rhythm USB-7310 FPGA as general-purpose indicators. For example, they can be illuminated when an RHD chip is detected on a particular SPI port. To set these eight bits, apply a value between 0 and 255 to **WireInMultiUse** and pulse **TrigInConfig[8]**.

TrigInConfig[9]: SetUSB3BlockSize

TrigInConfig[10]: SetDdrBlockSize

These triggers are used to set parameters for SuperSpeed USB-7310 data transfer. The variables USB3BlockSize and DdrBlockSize are set by placing a value on **WireInMultiUse** and pulsing these trigger lines. For optimal data transfer, it is recommended to set USB3BlockSize to 256 (the actual USB block size will be four times this value) and DdrBlockSize to 32.

TrigIn 0x41: TrigInSpiStart

See WireIn 0x00 description above.

TrigIn 0x42: TrigInDacConfig

TrigInDacConfig[0]: SetDac1ThresholdLevel

TrigInDacConfig [1]: SetDac2ThresholdLevel

TrigInDacConfig [2]: SetDac3ThresholdLevel

TrigInDacConfig [3]: SetDac4ThresholdLevel

TrigInDacConfig [4]: SetDac5ThresholdLevel

TrigInDacConfig [5]: SetDac6ThresholdLevel

TrigInDacConfig [6]: SetDac7ThresholdLevel

TrigInDacConfig [7]: SetDac8ThresholdLevel

TrigInDacConfig [8]: SetDac1ThresholdPolarity

TrigInDacConfig [9]: SetDac2ThresholdPolarity

TrigInDacConfig [10]: SetDac3ThresholdPolarity

TrigInDacConfig [11]: SetDac4ThresholdPolarity

TrigInDacConfig [12]: SetDac5ThresholdPolarity

TrigInDacConfig [13]: SetDac6ThresholdPolarity

TrigInDacConfig [14]: SetDac7ThresholdPolarity

TrigInDacConfig [15]: SetDac8ThresholdPolarity

Rhythm USB-7310 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 **TrigInDacConfig**.

To program a DAC threshold polarity, apply either a zero or one to **WireInMultiUse** and pulse one of the top eight bits in **TrigInDacConfig**. 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.

TrigInDacConfig [16]: EnableExternalDigOutPortA

TrigInDacConfig [17]: EnableExternalDigOutPortB

TrigInDacConfig [18]: EnableExternalDigOutPortC

TrigInDacConfig [19]: EnableExternalDigOutPortD

TrigInDacConfig [20]: EnableExternalDigOutPortE

TrigInDacConfig [21]: EnableExternalDigOutPortF

TrigInDacConfig [22]: EnableExternalDigOutPortG

TrigInDacConfig [23]: EnableExternalDigOutPortH

TrigInDacConfig [24]: SetExternalDigOutChannelPortA

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TrigInDacConfig [25]: SetExternalDigOutChannelPortB
TrigInDacConfig [26]: SetExternalDigOutChannelPortC
TrigInDacConfig [27]: SetExternalDigOutChannelPortD
TrigInDacConfig [28]: SetExternalDigOutChannelPortE
TrigInDacConfig [29]: SetExternalDigOutChannelPortF
TrigInDacConfig [30]: SetExternalDigOutChannelPortG
TrigInDacConfig [31]: SetExternalDigOutChannelPortH

Rhythm USB-7310 includes real-time control of the auxiliary digital output pin (**auxout**) on each RHD chip connected to the FPGA. To enable or disable real-time control of auxiliary digital output pins on Ports A through H, apply a one or zero to **WireInMultiUse** and pulse one of **TrigInDacConfig[16-23]**. To select the TTL digital input used for auxiliary digital output control, apply a number between 0 and 15 to **WireInMultiUse** and pulse one of **TrigInDacConfig[24-31]**. There is a latency of 4-5 amplifier sampling periods from the digital input changing to the **auxout** pin on the RHD chip turning on or off.

USB Software Endpoints: WireOut Ports

USB-7310 WireOut ports are virtual 32-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;  
fromFpga = dev->GetWireOutValue(0x20);
```

WireOut 0x20: WireOutNumWords

This port is 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 slightly over $2^{26} = 67,108,864$ words, but in practice it should never be allowed to get close to its maximum capacity.

WireOut 0x21: WireOutSerialDigitalIn

WireOutSerialDigitalIn[0]: **TtInSerial**
WireOutSerialDigitalIn[1]: **TtInSerialExp**
WireOutSerialDigitalIn[2]: **ExpanderDetect**
WireOutSerialDigitalIn[3]: **ExpanderId1**

TtInSerial and **TtInSerialExp** are used to sense the output of two 16-to-1 digital multiplexer shift registers controlled by **WireIn 0x02**. **ExpanderDetect** and **ExpanderId1** are used to sense the presence of an optional I/O Expander module.

WireOut 0x22: WireOutSpiRunning

WireOutSpiRunning[0]: **SpiRunning**

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

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WireOut 0x23: WireOutTtlIn

WireOutTtlIn[15:0]: **TtlIn**

This register returns the values of the 16 TTL input pins defined by Rhythm USB-7310. (These pins are only sampled synchronously and updated when the RHD amplifiers 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.

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 0x26 – 0x3D: unused

WireOut 0x3E: WireOutBoardId

This WireOut returns a constant value of 700 (decimal).

WireOut 0x3F: WireOutBoardVersion

This WireOut returns a constant value, identifying the version of Rhythm USB-7310 running on the board (currently 1).

USB Software Endpoints: BTPipeOut Ports

USB-7310 BTPipeOut ports are virtual 8-bit buses (“block throttled” pipe outs) that stream data bytes synchronously from the FPGA to the host computer. Up to 32 BTPipeOut 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 BTPipeOut 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;
const int USB3_BLOCK_SIZE = 1024;
numBytesToRead = 65536;
```

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```
numBytesRead = dev->ReadFromBlockPipeOut(0xA0, USB3_BLOCK_SIZE, 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 BTPipeOuts in relatively large data blocks. Reading approximately 30 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.

BTPipeOut 0xA0: PipeOutData

This BTPipeOut is used to stream data from all RHD chips (and several additional data sources) through the FPGA to the host computer. The BTPipeOut is backed by a large FIFO implemented using the 1 GByte SDRAM (of which 128 MBytes are used) on the Opal Kelly board. This FIFO module allows continuously-streaming data (e.g., from multiple RHD 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 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 = dev->GetWireOutValue(0x20);
}

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

// Read bytes from BTPipeOut 0xA0 into buffer.
long numBytesRead;
const int USB3_BLOCK_SIZE = 1024;
numBytesRead = dev->ReadFromBlockPipeOut(0xA0, USB3_BLOCK_SIZE, BUFFERSIZE,
                                         usbBuffer);
```

Rhythm USB-7310 Verilog Code Description

Verilog Source Code

The Rhythm USB-7310 interface is described by a set of Verilog files that may be compiled into a bitfile using the free Xilinx Vivado software. While Intan Technologies provides a pre-compiled bitfile, developers may wish to modify the Rhythm USB-7310 code for custom applications. The primary Verilog files are described below.

main.v: This is the top-level Rhythm USB-7310 Verilog code that defines all FPGA I/O, executes the main state machine running all SPI I/O with the RHD chips, and defines connections to all other modules in the Verilog files listed below.

SDRAM_FIFO.v: This code makes use of 128 MBytes of the off-FPGA 1 GByte 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 RHD 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 1024-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.

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

xem7310.xdc: 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 the Xilinx Vivado software. This file should be renamed to ConfigRHDController_7310.bit and copied into the directory containing the C++ executable file that opens and configures the Opal Kelly board.

Rhythm USB-7310 C++ API

Intan Technologies provides a basic, open-source C++ application programming interface (API) for controlling the Rhythm USB-7310 FPGA interface described above. The API consists of three C++ classes: **RHXController**, **RHXRegisters**, and **RHXDataBlock**. These classes are defined in *.cpp and *.h files named **rhxcontroller**, **rhxregisters**, and **rhxdatablock**. Additionally, any application must link to the Opal Kelly library file **okFrontPanel.lib**.

The Rhythm USB-7310 API is written using standard C++ and uses the **string**, **vector**, **cmath**, **mutex**, and **deque** classes from the C++ Standard Template Library (STL).

The public member functions of each class in the Rhythm USB-7310 API are described below.

RHXController Class Reference

This class provides access to and control of the Opal Kelly XEM7310 USB/FPGA interface board running the Rhythm USB-7310 interface Verilog code. Only one instance of the **RHXController** object is needed to control a Rhythm USB-7310-based FPGA interface. Methods in this class are designed to be thread-safe using a **mutex** (mutual exclusion) variable to ensure this.

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

RHXController()

Constructor.

~RHXController()

Destructor.

bool isSynthetic()

Returns if this controller is synthetic (used for demonstration purposes when Intan hardware may not be present). Returns false if this **RHXController** represents a real Opal Kelly XEM7310-A75 board.

bool isPlayback()

Returns if this controller represents a playback controller (used for data playback purposes when new data acquisition is not desired). Returns false if this **RHXController** represents a real Opal Kelly XEM7310-A75 board.

AcquisitionMode acquisitionMode()

Returns the mode that this controller is running in. Acquisition modes are given using the **AcquisitionMode** enumeration; defined values are:

LiveMode
SyntheticMode
PlaybackMode

Returns **LiveMode** if this **RHXController** represents a real Opal Kelly XEM7310-A75 board.

vector<string> listAvailableDeviceSerials()

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Lists all available Opal Kelly devices currently connected to this computer. Returns a vector of strings containing each device's serial number.

int open(const string &boardSerialNumber)

Finds an Opal Kelly XEM7310-A75 board attached to a USB port with the given serial number and opens it. Returns 1 if successful. Returns -2 if an XEM7310 board is not found.

int open()

Finds the first Opal Kelly board attached to a USB port and opens it. Returns 1 if successful. Returns -2 if an Opal Kelly board is not found. Note that this doesn't necessarily open a XEM7310 board, so if any other Opal Kelly boards are connected, the above function to open a specific board should be used instead.

bool uploadFpgaBitFile(const string &filename)

Uploads the Rhythm USB-7310 configuration file (i.e., bitfile) to the Xilinx FPGA on the open Opal Kelly board. Returns true if successful.

void initialize()

Initializes Rhythm USB-7310 FPGA registers to default values.

static void resetBoard(okCFrontPanel* dev_)

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. The static version of this method also requires a pointer to the **okCFrontPanel** device.

void resetFpga()

Performs a low-level reset of the FPGA. This can be called when closing an application to make sure everything has stopped.

bool setSampleRate(AMPLIFIER_SAMPLE_RATE newSampleRate)

Sets the per-channel sampling rate of the RHD chips connected to the Rhythm USB-7310 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

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SampleRate12500Hz
SampleRate15000Hz
SampleRate20000Hz
SampleRate25000Hz
SampleRate30000Hz

double getSampleRate()

static double getSampleRate(**AmplifierSampleRate** sampleRate_)

Returns the current (non-static) or provided **AmplifierSampleRate** enumeration (static) as a per-channel sampling rate (in Hz) floating-point number.

AmplifierSampleRate getSampleRateEnum()

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

static string getSampleRateString(**AmplifierSampleRate** sampleRate_)

Returns the provided **AmplifierSampleRate** enumeration as a human-readable string, from “1 kHz” to “30 kHz”.

static AmplifierSampleRate nearestSampleRate(**double** rate, **double** percentTolerance= 1.0)

Returns the nearest supported sample rate to the desired rate, within the given tolerance, as an **AmplifierSampleRate** enumeration.

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

Uploads a command list (generated by an instance of the **RHXRegisters** class) to a particular auxiliary command slot and RAM bank (0-15) on the FPGA. Command slots are given using the **AuxCmdSlot** enumeration; defined values are:

AuxCmd1
AuxCmd2
AuxCmd3
AuxCmd4 (not compatible with RHD XEM7310 Interface)

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

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

int findConnectedChips(**vector<ChipType>** &chipType, **vector<int>** &portIndex, **vector<int>** &commandStream, **vector<int>** &numChannelsOnPort, **bool** synthMaxChannels = false)

Scan all SPI ports to find all connected RHD amplifier chips. Read the chip ID from on-chip ROM register to determine the number of amplifier channels on each port. This process is repeated at all possible MISO delays in the FPGA to determine the optimum MISO delay for each port to compensate for variable cable length.

This function returns three vectors of length `maxNumDataStreams()`: `chipType` (the type of chip connected to each data stream); `portIndex` (the SPI port number [A=1, B=2,...] associated with each data stream); and `commandStream` (the stream index for sending commands to the FPGA for a particular read stream index). This function also returns a vector of length `maxNumSPIPorts()`: `numChannelsOnPort` (the total number of amplifier channels on each port).

RHD XEM7310 Interface: Rhythm USB-7310

This function normally returns 1. A value of -1 or -2 can be returned under certain conditions if a USB Interface Board is being used, but for the RHD XEM7310 Interface this function will always return 1.

The `synthMaxChannels` argument is only used for synthetic controllers, and should always be left false by default for real RHD XEM7310 boards.

The type of chip is specified using the `ChipType` enumeration; defined values are:

- NoChip
- RHD2132Chip
- RHD2216Chip
- RHD2164Chip
- RHS2116Chip (not compatible with RHD XEM7310 Interface)
- RHD2164MISOBChip

void selectAuxCommandBank(BoardPort port, AuxCmdSlot auxCommandSlot, int bank)

Selects an auxiliary command slot (`AuxCmd1`, `AuxCmd2`, or `AuxCmd3`) and bank (0-15) for a particular SPI port. The SPI port is specified using the `BoardPort` enumeration; defined values are:

- PortA
- PortB
- PortC
- PortD
- PortE
- PortF
- PortG
- PortH

void selectAuxCommandBankAllPorts(AuxCmdSlot auxCommandSlot, int bank)

Selects an auxiliary command slot (`AuxCmd1`, `AuxCmd2`, or `AuxCmd3`) and bank (0-15) for all SPI ports.

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

Specifies a command sequence end point (`endIndex` = 0-1023) and command loop index (`loopIndex` = 0-1023) for a particular auxiliary command slot (`AuxCmd1`, `AuxCmd2`, or `AuxCmd3`).

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.

void run()

Starts SPI data acquisition.

bool isRunning()

RHD XEM7310 Interface: Rhythm USB-7310

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

unsigned int `getNumWordsInFifo()`

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 `getLastNumWordsInFifo()`

Returns the most recently measured number of 16-bit words in the USB FIFO. Does not directly read this value from the USB port, and so may be out of date, but does not have to wait on other USB access to finish in order to execute.

unsigned int `getLastNumWordsInFifo(bool &hasBeenUpdated)`

Returns the most recently measured number of 16-bit words in the USB FIFO. Does not directly read this value from the USB port, and so may be out of date, but does not have to wait on other USB access to finish in order to execute. The boolean variable **hasBeenUpdated** is set to indicate if this value has been updated since the last time this function was called.

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 hundred 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 `setCableDelay(BoardPort port, int delay)`

Sets the delay for sampling the MISO line on a particular SPI port (PortA through PortH), 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 through PortH), 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 through PortH) based on the length of the cable between the FPGA and the RHD 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.

RHD XEM7310 Interface: Rhythm USB-7310

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 RHD.)

void enableDataStream(int stream, bool enabled)

Enables (if enabled is true) or disables (if enabled is false) one of the 32 available USB data streams (0-31). The data streams are assigned the following numbers:

stream	Data Stream
0	Port A, MISO1
1	Port A, MISO1 DDR
2	Port A, MISO2
3	Port A, MISO2 DDR
4	Port B, MISO1
5	Port B, MISO1 DDR
6	Port B, MISO2
7	Port B, MISO2 DDR
8	Port C, MISO1
9	Port C, MISO1 DDR
10	Port C, MISO2
11	Port C, MISO2 DDR
12	Port D, MISO1
13	Port D, MISO1 DDR
14	Port D, MISO2
15	Port D, MISO2 DDR
16	Port E, MISO1
17	Port E, MISO1 DDR
18	Port E, MISO2
19	Port E, MISO2 DDR
20	Port F, MISO1
21	Port F, MISO1 DDR
22	Port F, MISO2
23	Port F, MISO2 DDR
24	Port G, MISO1
25	Port G, MISO1 DDR
26	Port G, MISO2
27	Port G, MISO2 DDR
28	Port H, MISO1
29	Port H, MISO1 DDR
30	Port H, MISO2
31	Port H, MISO2 DDR

int getNumEnabledDataStreams()

Returns the total number of enabled USB data streams.

RHD XEM7310 Interface: Rhythm USB-7310

ControllerType getType()

Returns the type of this controller. This should always return **ControllerRecordUSB3** for the RHD XEM7310 interface. The type is specified using the **ControllerType** enumeration; defined values are:

ControllerRecordUSB2 (not compatible with RHD XEM7310 Interface)
ControllerRecordUSB3
ControllerStimRecord (not compatible with RHD XEM7310 Interface)

int maxNumDataStreams()

static int maxNumDataStreams(**ControllerType** type_)

Returns the total number of data streams for this controller's type (non-static) or a controller of the given type (static). This returns 32 for the RHD XEM7310 interface. The type of controller is specified with the **ControllerType** enumeration, defined above.

int maxNumSPIPorts()

static int maxNumSPIPorts(**ControllerType** type_)

Returns the maximum number of SPI ports for this controller's type (non-static) or a controller of the given type (static). This returns 8 for the RHD XEM7310 interface. The type of controller is specified with the **ControllerType** enumeration, defined above.

int boardMode()

static int boardMode(**ControllerType** type_)

Returns the board mode for this controller's type (non-static) or a controller of the given type (static). This returns 13 for the RHD XEM7310 interface. Note that this doesn't actually read the FPGA's digital input pins set on the physical controller (this is done through the **getBoardMode()** method) and instead just reports the software variable associated with this controller.

static int numAnalogIO(**ControllerType** type_, **bool** expanderConnected_)

Returns the number of Analog Inputs/Outputs for a controller of the given type. For the RHD XEM7310 interface, this will return 8 if an I/O expander is connected, otherwise this will return 2.

static int numDigitalIO(**ControllerType** type_, **bool** expanderConnected_)

Returns the number of Digital Inputs/Outputs for a controller of the given type. For the RHD XEM7310 interface, this will return 16 if an I/O expander is connected, otherwise this will return 2.

static string getAnalogInputChannelName(**ControllerType** type_, **int** channel_)

Returns the name of the specified Analog Input channel for the given type. For the RHD XEM7310 interface, this will return "ANALOG-IN-1" to "ANALOG-IN-8".

static string getAnalogOutputChannelName(**ControllerType** type_, **int** channel_)

Returns the name of the specified Analog Output channel for the given type. For the RHD XEM7310 interface, this will return "ANALOG-OUT-1" to "ANALOG-OUT-8".

static string getDigitalInputChannelName(**ControllerType** type_, **int** channel_)

RHD XEM7310 Interface: Rhythm USB-7310

Returns the name of the specified Digital Input channel for the given type. For the RHD XEM7310 interface, this will return "DIGITAL-IN-01" to "DIGITAL-IN-16".

static string getDigitalOutputChannelName(ControllerType type_, int channel_)

Returns the name of the specified Digital Output channel for the given type. For the RHD XEM7310 interface, this will return "DIGITAL-OUT-01" to "DIGITAL-OUT-16".

static string getAnalogIOChannelNumber(ControllerType type_, int channel_)

Returns the number of the specified Analog I/O channel for the given type. For the RHD XEM7310 interface, this will return "1" to "8".

static string getDigitalIOChannelNumber(ControllerType type_, int channel_)

Returns the number of the specified Digital I/O channel for the given type. For the RHD XEM7310 interface, this will return "01" to "16".

static string getBoardTypeString(ControllerType type_)

Returns the type of the controller as a string. For the RHD XEM7310 interface, this will return "ControllerRecordUSB3".

void clearTtlOut()

Sets all 16 bits of the digital TTL output lines on the FPGA to zero.

void setTtlOut(const int* ttlOutArray)

Sets the 16 bits of the digital TTL output lines on the FPGA high or low according to an integer array. The length-16 array ttlOutArray should contain values of 0 or 1.

void setAllDacsToZero();

Set all DACs to midline value (zero). DAC values are only updated 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(const int* ledArray)

Sets the eight red LEDs on the Opal Kelly XEM7310 board according to a length-8 integer array.

void setSpiLedDisplay(const int* ledArray)

Sets the eight red LEDs on the front panel SPI ports according to a length-8 integer array.

void enableDac(int dacChannel, bool enabled)

RHD XEM7310 Interface: Rhythm USB-7310

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 (0-31) and amplifier channel (0-31) to an AD5662 DAC channel (0-7). Setting stream to 32 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 RHD chip ADC output value, where the 'zero' level is 32768 and the step size is 0.195 μV . If the trigger polarity is set to true, RHD signals equaling or rising above the threshold produce a high digital output. If the trigger polarity is set to false, RHD 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.

void enableExternalFastSettle(bool enable)

Enables or disables real-time control of amplifier fast settle from an external digital input.

void setExternalFastSettleChannel(int channel)

Selects external TTL digital input channel (0-15) used to control amplifier fast settle function.

void enableExternalDigOut(BoardPort port, bool enable)

Enables or disables real-time control of auxiliary digital output pin (**auxout**) on RHD chips on a selected SPI port from an external digital input.

void setExternalDigOutChannel(BoardPort port, int channel)

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Selects external TTL digital input channel (0-15) used to control the auxiliary digital output pin (**auxout**) on RHD chips on a selected SPI port.

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(RHXDataBlock* dataBlock)

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

long readDataBlocksRaw(int numBlocks, uint8_t* 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, deque<RHXDataBlock*> &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(deque<RHXDataBlock*> &dataQueue, ofstream &saveOut)

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

static int getBoardMode(okCFrontPanel* dev_)

int getBoardMode()

Reads four digital input pins on the FPGA (see **MC1 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. The static version of this method also requires a pointer to the **okCFrontPanel** device. This is typically used to read the board mode from the Controller and set an internal software variable, which is then reported with the **boardMode()** method.

int getNumSPIPorts(bool &expanderBoardDetected)

static int getNumSPIPorts(okCFrontPanel* dev_, bool isUSB3, bool &expanderBoardDetected, bool isRHS7310)

Using external digital shift registers on the controller motherboard, detects the number of SPI ports (typically four or eight) and returns this as an integer. Sets **expanderBoardConnected** if the FPGA detects an I/O Expander. The static version of this method also requires a pointer to the **okCFrontPanel** device and boolean input **isRHS7310** which should always be set false for the RHD XEM7130 Interface.

void enableDacReref(bool enabled)

Enables or disables DAC re-referencing, where a selected amplifier channel is subtracted from all DACs in real time.

void setDacRerefSource(int stream, int channel)

Selects an amplifier channel from a particular data stream to be subtracted from all DAC signals.

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StreamChannelPair streamChannelFromWaveName(const string &waveName)

Returns the stream and channel number within that stream required to access an amplifier or auxiliary analog input specified by the string waveName.

Amplifier channels are specified as follows: "A-000", "C-127", "H-031", etc. The first letter is a port designation (A-H in the 1024-channel Recording Controller; A-D in the 512-channel Recording Controller), followed by a hyphen, followed by a three-digit channel number ranging from 000-127 in RHD systems.

Auxiliary input channels are specified as follows: "A-AUX1", "C-AUX6", "H-AUX2", etc. The first letter is a port designation, followed by a hyphen, followed by "AUX" and a number ranging from 1-6. Auxiliary waveNames return a valid stream number, but channel = -1 since three auxiliary inputs share the same channel.

StreamChannelPair is a struct containing { int stream; int channel; } Invalid waveNames return **stream** = -1, **channel** = -1.

int pipeReadError()

Returns the Opal Kelly error code (see okFrontPanel.h for details) when a read from a BTPipeOut fails, often attributed to connection or interference problems on USB.

RHXRegisters Class Reference

This class creates and manages a data structure representing the internal RAM registers on an RHD 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 an RHD chip connected to the FPGA; rather, a command list must be generated from this class and then downloaded to the FPGA board using **RHXController::uploadCommandList**. Typically, one instance of **RHXRegisters** will be created for each RHD chip attached to the Rhythm USB-7310 interface. However, if all chips will receive the same MOSI commands, then only one instance of **RHXRegisters** is required.

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

RHXRegisters(ControllerType type_, double sampleRate_, StimStepSize stimStep_ = StimStepSize500nA)

Constructor. Sets RHD register variables to default values. stimStep_ is unused by the RHD XEM7310 Interface (only used for Stim controllers), and can be left at the default value.

void setFastSettle(bool enabled)

Enables or disables amplifier fast settle function.

void setDigOutLow(DigOut pin = DigOut1)

void setDigOutHigh(DigOut pin = DigOut1)

void setDigiOutHiZ(DigOut pin = DigOut1)

Sets the auxiliary digital output variable to indicate a low, high, or high impedance (HiZ) output. RHD chips only have a single output pin, so only the default value of **DigOut1** should be used for the RHD XEM7310 Interface.

void enableAux1(bool enabled)

void enableAux2(bool enabled)

void enableAux3(bool enabled)

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Enables or disables ADC auxiliary inputs 1, 2, and 3.

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.

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

void setZcheckPolarity(ZcheckPolarity polarity)

Selects impedance testing of positive or negative amplifier inputs (RHD2216 only), specified using the **ZcheckPolarity** enumeration; defined values are:

ZcheckPositiveInput
ZcheckNegativeInput

int setZcheckChannel(int channel)

Selects the amplifier channel (0-63) for impedance testing.

void setAmpPowered(int channel, bool powered)

void powerUpAllAmps()

void powerDownAllAmps()

Powers up or down selected amplifiers on RHD chip.

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int getRegisterValue(**int** reg)

Returns the value of a selected RHD RAM register (0-21), based on the current register variables in the class instance.

double setUpperBandwidth(**double** upperBandwidth)

double setLowerBandwidth(**double** lowerBandwidth, **int** select = 0)

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. For RHD chips, the default value of select = 0 should be used.

unsigned int createRHXCommand(**RHXCommandType** commandType)

unsigned int createRHXCommand(**RHXCommandType** commandType, **unsigned int** arg1)

unsigned int createRHXCommand(**RHXCommandType** commandType, **unsigned int** arg1, **unsigned int** arg2)

Returns a 16-bit MOSI command based on the **RHXCommandType** enumeration; defined values are:

- RHXCommandConvert**
- RHXCommandCalibrate**
- RHXCommandCalClear**
- RHXCommandRegWrite**
- RHXCommandRegRead**
- RHXCommandComplianceReset** (RHS only)

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. A fourth overload of this method that includes parameters “unsigned int uFlag” and “unsigned int mFlag” should only be used with RHS chips, and can be ignored with an RHD XEM7310 interface.

int createCommandListRHDRRegisterConfig(**vector<unsigned int>** &commandList, **bool** calibrate, **int** numCommands)

Creates a list of numCommands commands to program most RAM registers on an RHD chip, read those values back to confirm programming, read ROM registers, and (if calibrate == true) run ADC calibration. Returns the length of the command list; numCommands must be 60 or greater.

int createCommandListRHDSampleAuxIns(**vector<unsigned int>** &commandList, **bool** calibrate, **int** numCommands)

Creates a list of numCommands commands to sample auxiliary ADC inputs 1-3 at 1/4 the amplifier sampling rate. The reading of a ROM register is interleaved to allow for data frame alignment. Return the length of the command list; numCommands should be evenly divisible by four.

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

Creates a list of up to 1024 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 createCommandListRHUpdateDigOut(**vector<unsigned int>** &commandList, **int** numCommands)

Creates a list of numCommands commands to update Register 3 (controlling the auxiliary digital output pin) every sampling period. This function returns the length of the command list.

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

Creates a list of dummy commands with a specific command. Returns the length of the command list (which should be n).

vector<double> getDspFreqTable()

static vector<double> getDspFreqTable(double sampleRate_)

Returns a size-16 vector containing all possible cutoff frequencies for the on-chip DSP offset removal filter (a one-pole highpass filter). The static function requires the system's sample rate as an input parameter.

int maxCommandLength()

static int maxCommandLength(ControllerType type)

Returns size of on-FPGA auxiliary command RAM banks. For all RHD interfaces, this returns 1024.

int maxNumChannelsPerChip()

static int maxNumChannelsPerChip(ControllerType type)

Returns maximum number of amplifier channels per chip. For all RHD interfaces, this returns 64.

RHXDataBlock Class Reference

This class creates a data structure storing 128 data samples from a Rhythm USB-7310 FPGA interface controlling up to 16 RHD chips. Typically, instances of **RHXDataBlock** 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 **RHXDataBlock** class are listed below.

RHXDataBlock(ControllerType type_, int numDataStreams_)

RHXDataBlock(const RHXDataBlock &obj)

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

~RHXDataBlock()

Destructor.

int samplesPerDataBlock()

static int samplesPerDataBlock(ControllerType type_)

Returns the number of samples in a single data block, which is always 128.

static unsigned int dataBlockSizeInWords(ControllerType type_, int numDataStreams_)

unsigned int dataBlockSizeInWords()

Returns the size of a USB data block (in 16-bit words) when numDataStreams data streams (0-32) are enabled.

void fillFromUsbBuffer(uint8_t* usbBuffer, int blockIndex)

Fills the data block with raw data from the n^{th} data block in a USB input buffer in an **RHXController** 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 RHX registers from a selected USB data stream (0-31) to the console. This function assumes that the command string generated by **RHXRegisters::createCommandListRHDRegisterConfig** has been uploaded to the **AuxCmd3** slot.

static bool checkUsbHeader(const uint8_t* usbBuffer, int index, ControllerType type_)

bool checkUsbHeader(const uint8_t* usbBuffer, int index)

Checks the first 64 bits of USB header against the fixed Rhythm USB-7310 "magic number" to verify proper data synchrony.

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).

uint32_t timeStamp(int t)

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Returns the timestamp at index *t* (0-127) of this data block.

int amplifierData(int stream, int channel, int t)

Returns a single sample of amplifier data from the specified channel (0-31) on the specific stream (0-31), corresponding to the timestamp at index *t* (0-127) of this data block.

int auxiliaryData(int stream, int channel, int t)

Returns a single sample of auxiliary data from the specified channel (0-2) on the specific stream (0-31), corresponding to the timestamp at index *t* (0-127) of this data block.

int boardAdcData(int channel, int t)

Returns a single sample of Analog Input data from the specified on-board ADC channel (0-7), corresponding to the timestamp at index *t* (0-127) of this data block.

int ttlIn(int channel, int t)

Returns a single sample of TTL Input data from the specified on-board Digital Input channel (0-15), corresponding to the timestamp at index *t* (0-127) of this data block. Values are 1 (TTL high) or 0 (TTL low).

int ttlOut(int channel, int t)

Returns a single sample of TTL Output data from the specified on-board Digital Output channel (0-15), corresponding to the timestamp at index *t* (0-127) of this data block. Values are 1 (TTL high) or 0 (TTL low).

static int blocksFor30Hz(AMPLIFIER_SAMPLE_RATE rate)

Returns the number of RHX data blocks that should be read over the USB interface each time for an approximate USB read rate of 30 Hz.

static int maxChannelsPerStream()

Returns the maximum number of amplifier channels that can be present per data stream. For all RHD interfaces, this returns 32.

static int channelsPerStream(CONTROLLER_TYPE type_)

int channelsPerStream()

Returns the number of amplifier channels that are present per data stream. For all RHD interfaces, this returns 32.

static int numAuxChannels(CONTROLLER_TYPE type_)

int numAuxChannels()

Returns the number of auxiliary channels that are present per data stream. For all RHD interfaces, this returns 3.

int getChipID(int stream, int auxCmdSlot, int ®ister59Value)

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Returns this chip's ID (-1 for no chip, 1 for RHD2132, 2 for RHD2216, 4 for RHD2164, 1000 for RHD2164MISOB). This assumes that a command list created by `RHXRegisters::createCommandListRHDRegisterConfig` has been uploaded and run, and the resulting `RHXDataBlock` read first.

`static uint64_t headerMagicNumber(ControllerType type_)`

`uint64_t headerMagicNumber()`

Returns the RHD header magic number. For the RHD XEM7310 interface, this is 0xd7a22aaa38132a53.

Example Usage

A simple `main.cpp` C++ program presented below opens an Opal Kelly XEM7310 board, configures it with the Rhythm USB-7310 FPGA configuration bitfile (`ConfigRHDController_7310.bit`), and sets the clock generator for a 20 kS/s/channel sampling rate. The MISO sampling delay is set for a 3-foot cable. The program then modifies the default values of the RHD registers, generates command sequences for the three auxiliary command slots, and uploads these commands to the FPGA RAM banks. Two versions of the `AuxCmd3` sequence are created: one runs the ADC calibration, and this is executed once in a 128-sample SPI run. Register data from this brief run is read over the USB interface, and displayed on the console to confirm RHD register settings.

The other version of the `AuxCmd3` sequence does not execute ADC calibration, so this RAM bank is used for the next acquisition, which is a one-second run. Complete data from the one-second acquisition is then saved in binary format to a file on disk.

```
#include <iostream>
#include <fstream>
#include <vector>
#include <queue>

using namespace std;

#include "okFrontPanel.h"
#include "rhxcontroller.h"
#include "rhxregisters.h"
#include "rhxdatablock.h"

int main(int argc, char* argv[])
{
    // Create RHX Controller with 20 kHz per-amplifier sampling rate.
    RHXController *rhxController = new RHXController(ControllerRecordUSB3,
                                                    SampleRate20000Hz);

    // Open the first detected Opal Kelly device, load Rhythm USB-7310 bitfile.
    vector<string> availableDevices = rhxController->listAvailableDeviceSerials();
    rhxController->open(availableDevices[0]);

    // Load Rhythm USB-7310 bitfile and initialize
    rhxController->uploadFpgaBitfile("ConfigRHDController_7310.bit");
    rhxController->initialize();
    rhxController->enableDataStream(0, true);

    // We can set the MISO sampling delay which is dependent on the sample rate.
    // We assume a 3-foot cable.
    rhxController->setCableLengthFeet(PortA, 3.0);

    // Let's turn one LED on to indicate that the program is running.
    int ledArray[8] = {1, 0, 0, 0, 0, 0, 0, 0};
    rhxController->setLedDisplay(ledArray);

    // Set up an RHX register object.
    RHXRegisters *chipRegisters = new RHXRegisters(rhxController->getType(),
                                                    rhxController->getSampleRate());

    // Create command lists to be uploaded to auxiliary command slots.
    int commandSequenceLength;
    vector<unsigned int> commandList;

    // First, let's create a command list for the AuxCmd1 slot. This command
    // sequence will create a 1 kHz, full-scale sine wave for impedance testing.
    commandSequenceLength = chipRegisters->createCommandListZcheckDac(commandList,
        1000.0, 128.0);
    rhxController->uploadCommandList(commandList, RHXController::AuxCmd1);
```

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```
rhxController->selectAuxCommandLength(RHXController::AuxCmd1, 0,
    commandSequenceLength - 1);

rhxController->selectAuxCommandBank(PortA, RHXController::AuxCmd1, 0);
// rhxController->printCommandList(commandList); // optionally, print command list

// Next, we'll create a command list for the AuxCmd2 slot. This command sequence
// will sample auxiliary ADC inputs.
commandSequenceLength =
    chipRegisters->createCommandListRHDSampleAuxIns(commandList, 128);
rhxController->uploadCommandList(commandList, RHXController::AuxCmd2);
rhxController->selectAuxCommandLength(RHXController::AuxCmd2, 0,
    commandSequenceLength - 1);
rhxController->selectAuxCommandBank(PortA, RHXController::AuxCmd2, 0);
// rhxController->printCommandList(commandList); // optionally, print command list

// For the AuxCmd3 slot, we will create two command sequences. Both sequences
// will configure and read back the RHD chip registers, but one sequence will
// also run ADC calibration.

// Before generating register configuration command sequences, set amplifier
// bandwidth parameters.

double dspCutoffFreq;
dspCutoffFreq = chipRegisters->setDspCutoffFreq(10.0); // 10 Hz DSP cutoff
cout << "Actual DSP cutoff frequency: " << dspCutoffFreq << " Hz" << endl;

chipRegisters->setLowerBandwidth(1.0); // 1.0 Hz lower bandwidth
chipRegisters->setUpperBandwidth(7500.0); // 7.5 kHz upper bandwidth

commandSequenceLength =
    chipRegisters->createCommandListRHDRegisterConfig(commandList, false, 128);
// Upload version with no ADC calibration to AuxCmd3 RAM Bank 0.
rhxController->uploadCommandList(commandList, RHXController::AuxCmd3, 0);

chipRegisters->createCommandListRHDRegisterConfig(commandList, true, 128);
// Upload version with ADC calibration to AuxCmd3 RAM Bank 1.
rhxController->uploadCommandList(commandList, RHXController::AuxCmd3, 1);
rhxController->selectAuxCommandLength(RHXController::AuxCmd3, 0,
    commandSequenceLength - 1);
// Select RAM Bank 1 for AuxCmd3 initially, so the ADC is calibrated.
rhxController->selectAuxCommandBank(PortA, RHXController::AuxCmd3, 1);
// rhxController->printCommandList(commandList); // optionally, print command list

// Since our longest command sequence is 128 commands, let's just run the SPI
// interface for 128 samples.
rhxController->setMaxTimeStep(128);
rhxController->setContinuousRunMode(false);

// Start SPI interface.
rhxController->run();
// Wait for the 128-sample run to complete.
while (rhxController->isRunning()) { }

// Read the resulting single data block from the USB interface.
RHXDataBlock *dataBlock =
    new RHXDataBlock(rhxController->getType(),
        rhxController->getNumEnabledDataStreams());
rhxController->readDataBlock(dataBlock);

// Display register contents from data stream 0.
dataBlock->print(0);
```

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```
// Now that ADC calibration has been performed, we switch to the command sequence
// that does not execute ADC calibration.
rhxCtrl->selectAuxCommandBank(PortA, RHXController::AuxCmd3, 0);

// Let's save one second of data to a binary file on disk.
ofstream saveOut;
saveOut.open("binary_save_file.dat", ios::binary | ios::out);

deque<RHXDataBlock*> dataQueue;

// Run for one second.
rhxCtrl->setMaxTimeStep(20000);
rhxCtrl->run();

bool usbDataRead;
do {
    usbDataRead = rhxCtrl->readDataBlocks(1, dataQueue);
    if (dataQueue.size() >= 50) { // save 50 data blocks at a time
        rhxCtrl->queueToFile(dataQueue, saveOut);
    }
} while (usbDataRead || rhxCtrl->isRunning());

rhxCtrl->queueToFile(dataQueue, saveOut);

saveOut.close();

// Turn off LED.
ledArray[0] = 0;
rhxCtrl->setLedDisplay(ledArray);

delete dataBlock;
delete chipRegisters;
delete rhxCtrl;

return 0;
}
```

An elaborated version of this `main.cpp` program file is included with the Rhythm USB-7310 API distribution files.

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Reading binary data into MATLAB

The C++ program above saves data from a single data stream to a binary output file. The following MATLAB code reads a saved file for the case where only one data stream is active:

```
fid = fopen(filename, 'r');

s = dir(filename);
filesize = s.bytes;

% allocate space to read the entire file
data = zeros(filesize, 1, 'uint8');

% read the entire file
data = fread(fid, filesize, 'uint8=>uint8');
fclose(fid);

% convert the remaining data from bytes to 2-byte unsigned integers
data = typecast(data, 'uint16');
swapbytes(data);

% convert uint16 datatype to double datatype
data = double(data);

L = length(data);

data = reshape(data, 46, L/46);

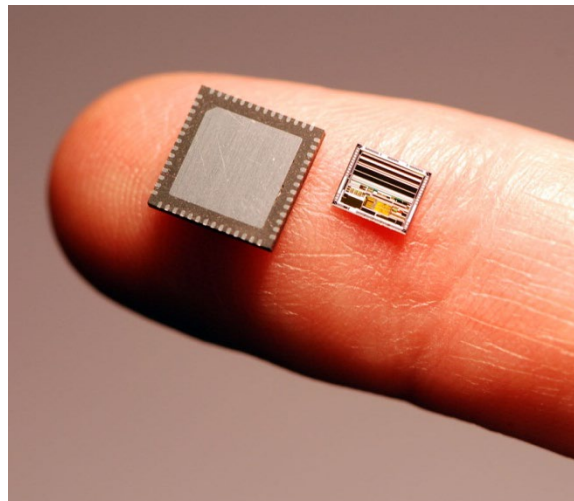
timestamp = data(1,:);
amplifier_data = data(2:33,:);
auxiliary_data = data(34:36,:);
boardADC_data = data(37:44,:);
TTLin = data(45,:);
TTLout = data(46,:);
```

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Contact Information

This datasheet is meant to acquaint engineers and scientists with the Rhythm USB-7310 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:



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