

RHD2000



USB3/FPGA Interface: Rhythm USB3

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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 RHD2000 digital electrophysiology interface chips
- ◆ Verilog code is written for a commercially-available Opal Kelly XEM6310 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 RHD2000 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 RHD2000 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 RHD2000-based products
- ◆ Starting point for the development of custom interfaces to RHD2000 chips

Description

To facilitate the development of electrophysiology recording systems using the new RHD2000 series of microchips, Intan Technologies provides the following open-source USB/FPGA interface for developers. Designated **Rhythm USB3**, the interface consists of Verilog HDL code written for the commercially-available Opal Kelly XEM6310 USB/FPGA interface module and a C++ API. Rhythm configures the Xilinx FPGA on the Opal Kelly module to communicate with up to 16 RHD2000 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 USB3 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 hardware and software protocols so that developers may quickly link the RHD2000 chips to a host computer of their choice.

Rhythm USB3 supports real-time streaming of up to 1024 amplifier channels from multiple RHD2000 chips, auxiliary data from the chips (e.g., special chip functions such as temperature sensing), 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 USB3-based module to set the RHD2000 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 RHD2000 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.

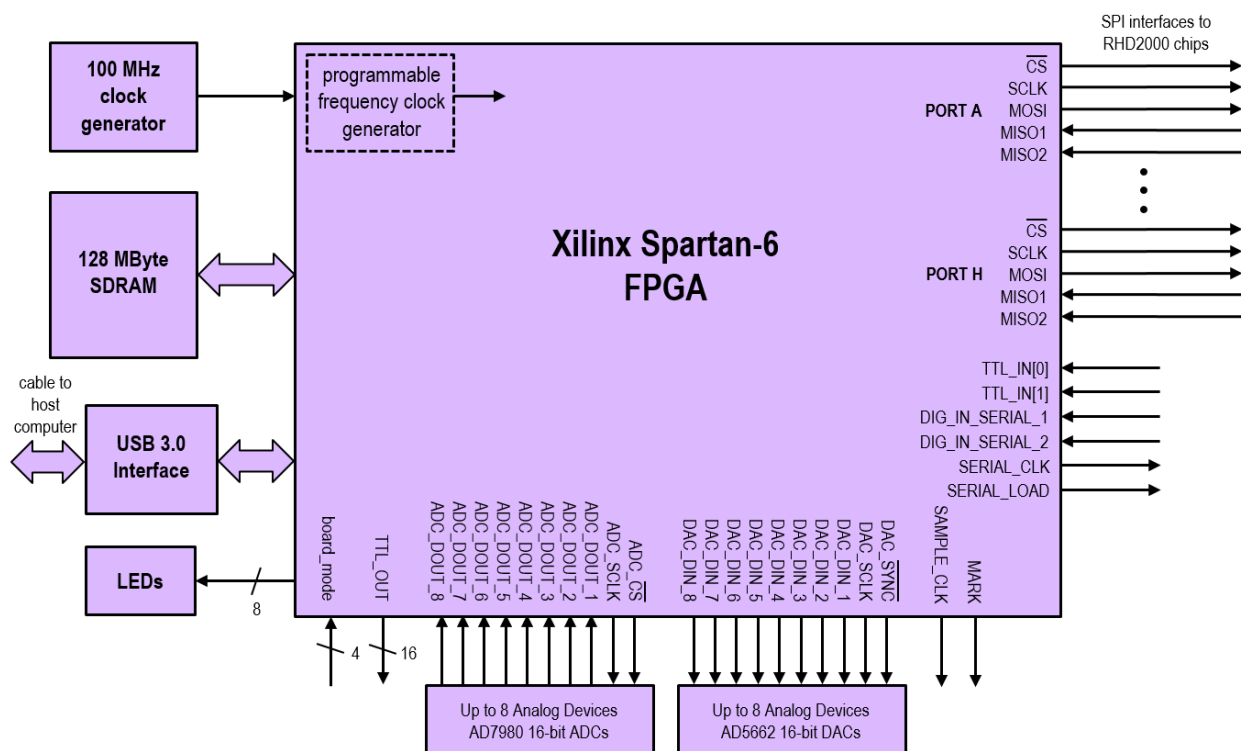
Rhythm USB3 FPGA I/O Signals

General Description

The Rhythm USB3 interface code is designed for the Opal Kelly XEM6310-LX45 USB/FPGA module which is a small commercially-available circuit board containing a Xilinx Spartan-6 FPGA (XC6SLX45-2), a 128-MByte SDRAM chip, a 100-MHz clock source, I/O connectors, and a USB 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 <http://www.opalkelly.com> for detailed information on this module.)

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

The diagram below shows the main elements on the Opal Kelly XEM6310 board and the I/O signals defined by Rhythm USB3.



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RHD2000 SPI Interfaces

Rhythm USB3 sets up eight SPI ports (labeled A through H) that can send independent command streams to different sets of RHD2000 chips. Unlike the 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 RHD2000 chips. LVDS signaling is recommended for operation over long cables.

Each SPI port on the FPGA has three output signals that coordinate communication with RHD2000 chips and send commands: CS, SCLK, and MOSI (Master Out, Slave In). The FPGA always acts as the SPI master device, and each RHD2000 acts as an SPI slave device. Each SPI port in Rhythm USB3 has two MISO (Master In, Slave Out) inputs for receiving data from an RHD2000 chip. This means that each port can be connected to two RHD2000 chips, but both of these chips will receive the same commands. So, for example, the auxiliary digital output pin on the two RHD2000 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 USB3 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 RHD2000 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 XEM6310 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 USB3 sends commands to all RHD2000 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 RHD2000 chip, like synthesizing a waveform for electrode impedance testing, reading from the auxiliary inputs or temperature sensor, performing ADC calibration, or reading and writing other registers. Under Rhythm USB3, 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 100-MHz clock to the FPGA; this clock is used to run the USB interface logic. Rhythm USB3 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 RHD2000 amplifiers can be sampled at per-channel rates varying from 1 kS/s to 30 kS/s.

Other I/O Signals

Rhythm USB3 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 USB3 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 USB3 permits the user to select particular RHD2000 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 RHD2000 amplifiers, and their results are streamed back to the host computer over the USB interface.

Rhythm USB3 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.

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

A digital output signal **sample_clk** is provided on FPGA pin L51P as a convenience. This signal is a clock running at the per-channel amplifier sampling rate. The duty cycle of the signal is 1/35. For example, if the board is configured to sample each RHD2000 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 CS that begins the CONVERT(0) command, and it goes low at the falling edge of CS that begins the CONVERT(1) command.)

Power Supply

The total current consumption of the XEM6310 board running Rhythm USB3 exceeds the 500 mA USB port limit. It is recommended to power the Opal Kelly XEM6310 board from a 5V DC power supply capable of sourcing sufficient current and having a 2.1mm inner-diameter / 5.5mm outer-diameter connector. Opal Kelly offers a PSS050-25 power supply that provides up to 2.5 A of current. Digi-Key (<http://www.digikey.com>) offers a medical-rated power supply that mates with the XEM6310 board, supplies up to 2.0 A of current, and includes connectors for AC plugs in a variety of countries (part number T1233-P5P-ND).

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

If RHD2000 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. RHD2000 chips may be safely powered at 3.5V, and the excess 0.2 V above the nominal power supply voltage of 3.3V will make up for some of the IR losses incurred over long cables with thin power wires.

I/O Pin Locations

The I/O pin tables on the following two pages are based on information in the Opal Kelly XEM6310 User's Manual.

Users may wish to purchase the BRK6110 breakout board which can be connected to the XEM6310 module, and which brings the I/O pins out to convenient 2mm-pitch headers.

FPGA pin names come in pairs of positive and negative signals that can be used as LVDS pairs (e.g., L34P_1 and L34N_1 are I/O pin pairs in FPGA Bank 1). An inspection of the **xem6310.ucf** file provided with Rhythm USB3 shows that the IOSTANDARD="LVDS_33" flag is used for LVDS signals, while IOSTANDARD="LVCMOS33" is used for standard CMOS signals. If the Rhythm USB3 code is modified to include additional LVDS signals, it is important to note that LVDS outputs can only be instantiated on Bank 0 of this FPGA (i.e., pin names ending in "_0").

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

Note that JP1 is equivalent to JP3 in the XEM6010 USB 2.0 board.

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JP2 I/O Connections

JP2 Pin	Connection	FPGA Pin	Rhythm USB3 Interface Pin Name
1	DGND		GND
3	VBATT		
5	JTAG_TCK		
7	JTAG_TMS		
9	JTAG_TDI		
11	U12	L22N_2	
13	DGND		GND
15	G16	L9P_1	SAMPLE_CLK
17	G17	L9N_1	MARK
19	H19	L34P_1	SERIAL_LOAD
21	H18	L34N_1	SERIAL_CLK
23	F16	L10P_1	SPI_LED_H
25	F17	L10N_1	SPI_LED_G
27	J17	L36P_1	SPI_LED_F
29	K17	L36N_1	SPI_LED_E
31	K16	L21P_1	SPI_LED_D
33	J16	L21N_1	SPI_LED_C
35	+VCCO1		
37	V21	L52P_1	SPI_LED_B
39	V22	L52N_1	SPI_LED_A
41	T21	L50P_1	MISO_H2
43	T22	L50N_1	MISO_H1
45	P21	L48P_1	unused
47	P22	L48N_1	MOSI_H
49	M21	L46P_1	SCLK_H
51	M22	L46N_1	$\overline{\text{CS}}_H$
53	L20	L45P_1	MISO_G2
55	+VCCO1		
57	L22	L45N_1	MISO_G1
59	H21	L41P_1	unused
61	H22	L41N_1	MOSI_G
63	F21	L37P_1	SCLK_G
65	F22	L37N_1	$\overline{\text{CS}}_G$
67	D21	L31P_1	MISO_F2
69	D22	L31N_1	MISO_F1
71	B21	L19P_1	unused
73	B22	L19N_1	MOSI_F
75	A21	L20N_1	SCLK_F
77	J20	L43P_1	$\overline{\text{CS}}_F$
79	J22	L43N_1	MISO_E2

JP2 Pin	Connection	FPGA Pin	Rhythm USB3 Interface Pin Name
2	+3.3VDD		VDD
4	+3.3VDD		VDD
6	+3.3VDD		VDD
8	JTAG_TDO		
10	VREF_1		
12	RFUSE		
14	DGND		GND
16	G19	L33P_1	$\overline{\text{CS}}_A$
18	F20	L33N_1	SCLK_A
20	H20	L38P_1	MOSI_A
22	J19	L38N_1	unused
24	D19	L29P_1	MISO_A1
26	D20	L29N_1	MISO_A2
28	F18	L30P_1	$\overline{\text{CS}}_B$
30	F19	L30N_1	SCLK_B
32	M16	L58P_1	MOSI_B
34	L15	L58N_1	unused
36	DGND		GND
38	K20	L40P_1	MISO_B1
40	K19	L40N_1	MISO_B2
42	U20	L51P_1	$\overline{\text{CS}}_C$
44	U22	L51N_1	SCLK_C
46	R20	L49P_1	MOSI_C
48	R22	L49N_1	unused
50	N20	L47P_1	MISO_C1
52	N22	L47N_1	MISO_C2
54	M20	L42P_1	$\overline{\text{CS}}_D$
56	DGND		GND
58	L19	L42N_1	SCLK_D
60	K21	L44P_1	MOSI_D
62	K22	L44N_1	unused
64	G20	L39P_1	MISO_D1
66	G22	L39N_1	MISO_D2
68	E20	L35P_1	$\overline{\text{CS}}_E$
70	E22	L35N_1	SCLK_E
72	C20	L32P_1	MOSI_E
74	C22	L32N_1	unused
76	A20	L20P_1	MISO_E1
78	DGND		GND
80	DGND		GND

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JP1 I/O Connections

JP1 Pin	Connection	FPGA Pin	Rhythm USB3 Interface Pin Name
1	+VDC		+5V
3	+VDC		+5V
5	+VDC		+5V
7	+1.8VDD		
9	+3.3VDD		VDD
11	+3.3VDD		VDD
13	+3.3VDD		VDD
15	W20	L60P_1	ADC_CNV
17	W22	L60N_1	DAC_SCLK
19	U19	L70P_1	DAC_SYNC
21	V20	L70N_1	DAC_DIN_8
23	C5	L2P_0	LVDS_1+
25	A5	L2N_0	LVDS_1-
27	D14	L49P_0	DAC_DIN_7
29	C14	L49N_0	DAC_DIN_6
31	E16	L66P_0	LVDS_2+
33	D17	L66N_0	LVDS_2-
35	DGND		GND
37	D7	L32P_0	DAC_DIN_5
39	D8	L32N_0	DAC_DIN_4
41	L17	L61P_1	LVDS_3+
43	K18	L61N_1	LVDS_3-
45	D6	L3P_0	LVDS_4+
47	C6	L3N_0	LVDS_4-
49	A3	L1P_0	unused
51	A4	L1N_0	DAC_DIN_3
53	B8	L6P_0	DAC_DIN_2
55	DGND		GND
57	A8	L6N_0	DAC_DIN_1
59	B10	L34P_0	ADC_DOUT_2
61	A10	L34N_0	ADC_DOUT_1
63	C13	L38P_0	DIG_IN_SERIAL_2
65	A13	L38N_0	DIG_IN_SERIAL_1
67	C15	L51P_0	EXP_ID
69	A15	L51N_0	EXP_DETECT
71	C17	L64P_0	STATUS_LED_3
73	A17	L64N_0	STATUS_LED_2
75	A18	L65N_0	STATUS_LED_1
77	C11	L35P_0	LVDS_5+
79	A11	L35N_0	LVDS_5-

JP1 Pin	Connection	FPGA Pin	Rhythm USB3 Interface Pin Name
2	DGND		GND
4	+1.2VDD		
6	+1.2VDD		
8	T14	L23P_2	
10	Y9	L43P_2	
12	AB9	L43N_2	
14	DGND		GND
16	T19	L74P_1	ADC_SCLK
18	T20	L74N_1	TTL_OUT[0]
20	P17	L72P_1	TTL_OUT[1]
22	N16	L72N_1	TTL_OUT[2]
24	M17	L71P_1	TTL_OUT[3]
26	M18	L71N_1	TTL_OUT[4]
28	P18	L73P_1	TTL_OUT[5]
30	R19	L73N_1	TTL_OUT[6]
32	D9	L7P_0	board_mode[0]
34	C8	L7N_0	board_mode[1]
36	+VCCO0		
38	D10	L33P_0	board_mode[2]
40	C10	L33N_0	board_mode[3]
42	D11	L36P_0	TTL_OUT[7]
44	C12	L36N_0	TTL_OUT[8]
46	D15	L62P_0	TTL_OUT[9]
48	C16	L62N_0	TTL_OUT[10]
50	B6	L4P_0	TTL_OUT[11]
52	A6	L4N_0	TTL_OUT[12]
54	C7	L5P_0	TTL_OUT[13]
56	+VCCO0		
58	A7	L5N_0	TTL_OUT[14]
60	C9	L8P_0	TTL_OUT[15]
62	A9	L8N_0	ADC_DOUT_8
64	B12	L37P_0	ADC_DOUT_7
66	A12	L37N_0	ADC_DOUT_6
68	B14	L50P_0	ADC_DOUT_5
70	A14	L50N_0	ADC_DOUT_4
72	B16	L63P_0	ADC_DOUT_3
74	A16	L63N_0	TTL_IN[1]
76	B18	L65P_0	TTL_IN[0]
78	DGND		GND
80	DGND		GND

General Description of Interface Operation

Host Computer Interface

Most electrophysiology recording applications require that data is sampled at a steady rate for long periods of time. To interface this steady stream of data with a host computer that uses a modern, multitasking operating system requires a hardware FIFO (First In, First Out) buffer to store data during brief intervals while the computer is busy performing other tasks. Luckily, the Opal Kelly board includes a 128 MByte SDRAM chip that can be used for just such a purpose. The Rhythm USB3 code implements an SDRAM-based FIFO as a circular queue of 16-bit words. Two on-FPGA 4 kByte "mini-FIFOs" regulate the flow of data into and out of the main SDRAM FIFO. The output of the FIFO is connected to a "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 capacity of the FIFO is dominated by the 128-Mbyte SDRAM. This can hold $2^{27} = 134,217,728$ bytes, or $2^{26} = 67,108,864$ 16-bit words. The on-FPGA "mini-FIFOs" add a couple of thousand more words to this total, but it is good practice never to allow the FIFO to get more than 75% full in case the computer OS hangs for a moment.

In order to completely "clean out" the FIFO after pausing or stopping the flow of data into it, it is necessary to always write an integer multiple of **four** 16-bit words to the FIFO. The SDRAM chip reads data only in 64-bit chunks, so if there are one, two, or three 16-bit words of data remaining in the input mini-FIFO, they will not be read into the SDRAM (and passed to the output mini-FIFO and thence the USB bus) after the flow of data from the source has stopped. The Rhythm USB3 Verilog code is structured to ensure that data frames are always integer multiples of four 16-bit words.

The Rhythm USB3 interface is capable of transmitting up to 32 simultaneous **data streams**. In Rhythm USB3, a data stream is defined as the SPI output of one MISO line from an RHD2000 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)

...

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)

...

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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 USB3 interface sends data in bytes. In Rhythm USB3, 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 USB3 interface can easily handle 68.16 MByte/s data rates, provided a reasonably fast host computer is used. A Dell Precision T1700 Windows 7 PC purchased in 2014 with a 3.1 GHz Xeon processor is capable of running at this rate with an Opal Kelly XEM6310 board and multi-threaded C++ software.

The bulk of each data frame consists of MISO results received from the SPI interface from each RHD2000 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 RHD2000 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 RHD2000 datasheet for details). The FPGA introduces another one-command pipeline delay in the received MISO results, so **every MISO result received through the Rhythm USB3 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.

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Programming Auxiliary Command Sequences

Each RHD2000 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 RHD2000 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 temperature sensor, the supply voltage sensor, and maybe the auxiliary inputs to the RHD2000 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 RHD2000 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 **PipeOut** 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 USB3, and we provide sample C++ code for communicating over these endpoints to a Rhythm USB3-powered XEM6310 board.

Opening and Initializing the Opal Kelly Board

The following C++ code shows how an Opal Kelly XEM6310 board is opened and initialized. Additional code should be added to check for errors and other exceptions (e.g., board not connected, multiple boards connected). The **main.bit** bitfile contains the compiled Rhythm USB3 Verilog code provided by Intan Technologies. After this bitfile is uploaded to the XEM6310 board, it behaves as the Rhythm USB3 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 XEM6310 PLL to default configuration to produce 100 MHz FPGA clock.
dev->LoadDefaultPLLConfiguration();

// Upload Rhythm USB3 bitfile which is compiled from Rhythm USB3 Verilog code.
dev->ConfigureFPGA("main.bit");
```

USB Software Endpoints: WireIn and TriggerIn Ports

USB3 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: TriglSpiStart

WireInResetRun[0]: **reset**

When the Opal Kelly board is first powered up and Rhythm USB3 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 USB3 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 **TriglSpiStart[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 to on all MOSI lines is set to one, settling the RHD2000 digital offset removal filters. (See the RHD2000 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 **TriglDacConfig** 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 rhd2000evalboardusb3.cpp in order to clear all remaining data out of the FIFO.

WireIn 0x01: WireInMaxTimeStep

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 **TriglSpiStart**. If **SPI_run_continuous** (in WireIn address 0x00) is set high, the

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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 readDigitalInManual() and readDigitalInExp() methods in rhd2000evalboardusb3.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 RHD2000 amplifier sampling frequency. A 100 MHz reference clock is provided to the FPGA from an off-chip clock generator. The output frequency of a programmable FPGA clock generator (a digital clock manager, or DCM) is given by:

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

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

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

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

This variable-frequency clock drives the state machine that controls all SPI communication with the RHD2000 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 USB3 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
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

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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 RHD2000 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 RHD2000 I/O. The Xilinx Spartan-6 FPGA has input and output pin delays of several nanoseconds. The RHD2000 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:

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.

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Pulse **TrignConfig[1]** to program the MOSI command to the selected RAM bank and address for **auxcmd1**. Pulse **TrignConfig[2]** for **auxcmd2**. Pulse **TrignConfig[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
WireInAuxCmdBank3[19:16]: AuxCmdBank3E
WireInAuxCmdBank3[23:20]: AuxCmdBank3F
WireInAuxCmdBank3[27:24]: AuxCmdBank3G
WireInAuxCmdBank3[31:28]: AuxCmdBank3H

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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 USB3 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**.

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.

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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 USB3. (If **TTL_out_mode** is set to one, the lower eight TTL output pins are controlled by the FPGA threshold comparators.)

WireIn 0x16: WireInDacSource1

WireIn 0x17: WireInDacSource2

WireIn 0x18: WireInDacSource3

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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 USB3 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 USB3 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 USB3 includes real-time control of the “fast settle” function on all connected RHD2000 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 **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

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Eight LEDs can be connected to the Rhythm USB3 FPGA as general-purpose indicators. For example, they can be illuminated when an RHD2000 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 USB3 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 USB3 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

TrigInDacConfig [25]: SetExternalDigOutChannelPortB

TrigInDacConfig [26]: SetExternalDigOutChannelPortC

TrigInDacConfig [27]: SetExternalDigOutChannelPortD

TrigInDacConfig [28]: SetExternalDigOutChannelPortE

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TrigInDacConfig [29]: SetExternalDigOutChannelPortF
TrigInDacConfig [30]: SetExternalDigOutChannelPortG
TrigInDacConfig [31]: SetExternalDigOutChannelPortH

Rhythm USB3 includes real-time control of the auxiliary digital output pin (**auxout**) on each RHD2000 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 RHD2000 chip turning on or off.

USB Software Endpoints: WireOut Ports

USB3 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 a bit over $2^{26} = 67,108,864$ words, but in practice it should never be allowed to get close to its maximum capacity.

WireOut 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.

WireOut 0x23: WireOutTtIn

WireOutTtIn[15:0]: **TtIn**

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This register returns the values of the 16 TTL input pins defined by Rhythm USB3. (These pins are only sampled synchronously and updated when the RHD2000 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 USB3 running on the board (currently 1).

USB Software Endpoints: BTPipeOut Ports

USB3 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;
numBytesRead = dev->ReadFromBlockPipeOut(0xA0, USB3_BLOCK_SIZE, numBytesToRead,
                                          usbBuffer);
// Note: numBytesRead will be negative if read failed.
```

RHD2000 USB3/FPGA Interface: Rhythm USB3

```
// 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 RHD2000 chips (and several additional data sources) through the FPGA to the host computer. The BTPipeOut is backed by a large FIFO implemented using the 128 MByte SDRAM on the Opal Kelly board. This FIFO module allows continuously-streaming data (e.g., from multiple RHD2000 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 USB3 Verilog Code Description

Verilog Source Code

The Rhythm USB3 interface is described by a set of Verilog files that may be compiled into a bitfile using the free Xilinx ISE WebPack software. While Intan Technologies provides a pre-compiled bitfile, developers may wish to modify the Rhythm code for custom applications. The primary Verilog files are described below.

main.v: This is the top-level Rhythm USB3 Verilog code that defines all FPGA I/O, executes the main state machine running all SPI I/O with the RHD2000 chips, and defines connections to all other modules in the Verilog files listed below.

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

variable_freq_clk_generator.v: This module sets up the programmable-frequency clock used to run the RHD2000 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.

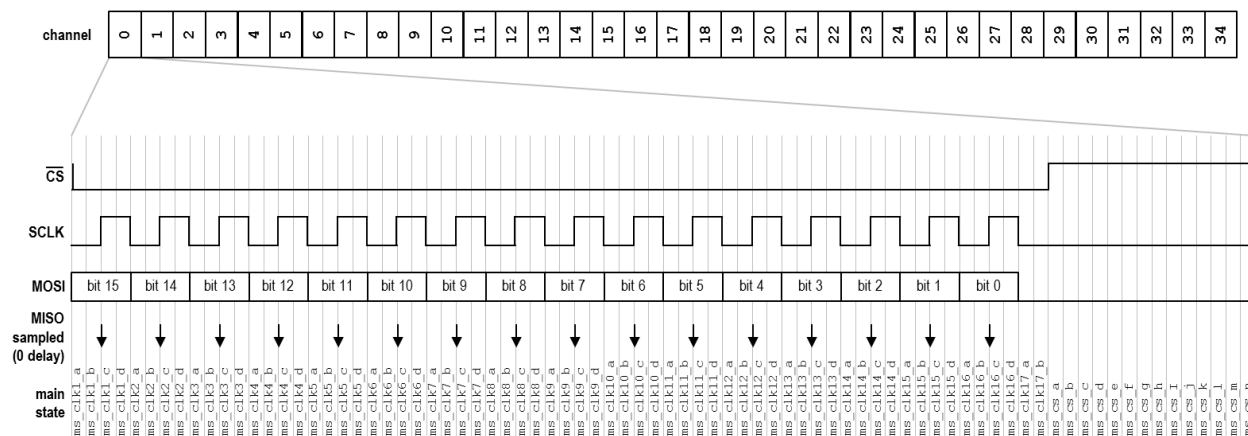
xem6310.ucf: This file defines the location (i.e., pin number) and characteristics of all FPGA I/O signals.

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

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Main State Machine Description

The heart of the Rhythm USB3 code is a finite state machine that cycles through a pattern of 80 repeating states. These 80 states execute a single SPI cycle and are illustrated in the diagram below. (Refer to the RHD2000 datasheet for more information on the SPI communication protocol.)



Each SCLK period consists of four states labeled ms_clkX_a through ms_clkX_d , where X advances from 1 to 16. After 16 complete SCLK cycles, there are an additional two states (ms_clk17_a and ms_clk17_b) to create a delay between the falling edge of the last SCLK pulse and the rising edge of \overline{CS} . The \overline{CS} signal is held high for 14 states labeled ms_cs_a through ms_cs_n . After all 80 states have completed, the variable **channel** is incremented. If **channel** exceeds 34, it is reset to 0. This variable tracks the repeating series of 35 commands send on the MOSI line (32 CONVERT commands for each amplifier channel and three auxiliary commands).

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

- The 64-bit header magic number is sent during states ms_clk1_b through ms_clk2_a only when channel = 0.
- The timestamp is sent during states ms_clk2_b and ms_clk2_c only when channel = 0.
- Data streams 1-32 are sent during states ms_clk2_d through ms_clk10_c .
- States ms_clk17_a , ms_clk17_b , and ms_cs_a are used to send up to three filler words only when channel = 34. These filler words ensure that each data frame consists of an integer multiple of four 16-bit words to satisfy FIFO constraints.
- States ms_cs_b through ms_cs_i are used to send data from the eight optional AD7980 ADCs only when channel = 34.
- State ms_cs_j is used to send the 16 TTL inputs only when channel = 34.
- State ms_cs_k is used to send the current value of the 16 TTL outputs only when channel = 34. This information may be useful to users who wish to reconstruct exact timings based on TTL output events.

Rhythm USB3 C++ API

Intan Technologies provides a basic, open-source C++ application programming interface (API) for controlling the Rhythm USB3 FPGA interface described above. The API consists of three C++ classes: **Rhd2000EvalBoardUsb3**, **Rhd2000RegistersUsb3**, and **Rhd2000DataBlockUsb3**. These classes are defined in *.cpp and *.h files named **rhd2000evalboardusb3**, **rhd2000registersusb3**, and **rhd2000datablockusb3**. Additionally, any application must include the Opal Kelly API files **okFrontPanelDLL.cpp** and **okFrontPanelDLL.h**.

The Rhythm USB3 API is written using standard C++ and uses the **string**, **vector**, **cmath**, **mutex**, and **queue** classes from the C++ Standard Template Library (STL).

The public member functions of each class in the Rhythm USB3 API are described below.

Rhd2000EvalBoardUsb3 Class Reference

This class provides access to and control of the Opal Kelly XEM6310 USB/FPGA interface board running the Rhythm USB3 interface Verilog code. Only one instance of the **Rhd2000EvalBoardUsb3** object is needed to control a Rhythm USB3-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 **Rhd2000EvalBoardUsb3** class are listed below.

Rhd2000EvalBoardUsb3()

Constructor.

int open()

Finds an Opal Kelly XEM6310-LX45 board attached to a USB port and opens it. Returns 1 if successful. Returns -1 if Opal Kelly FrontPanel DLL cannot be loaded. Returns -2 if an XEM6310 board is not found.

bool uploadFpgaBitFile(string filename)

Uploads the Rhythm USB3 configuration file (i.e., bitfile) to the Xilinx FPGA on the open Opal Kelly board. Returns true if successful.

void initialize()

Initializes Rhythm USB3 FPGA registers to default values.

void resetBoard()

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

void reseFpga()

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

RHD2000 USB3/FPGA Interface: Rhythm USB3

bool setSampleRate(**AmplifierSampleRate** newSampleRate)

Sets the per-channel sampling rate of the RHD2000 chips connected to the Rhythm USB3 FPGA. Returns false if an unsupported sampling rate is requested. Sample rates are given using the **AmplifierSampleRate** enumeration; defined values are:

```
SampleRate1000Hz  
SampleRate1250Hz  
SampleRate1500Hz  
SampleRate2000Hz  
SampleRate2500Hz  
SampleRate3000Hz  
SampleRate3333Hz  
SampleRate4000Hz  
SampleRate5000Hz  
SampleRate6250Hz  
SampleRate8000Hz  
SampleRate10000Hz  
SampleRate12500Hz  
SampleRate15000Hz  
SampleRate20000Hz  
SampleRate25000Hz  
SampleRate30000Hz
```

double getSampleRate()

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

AmplifierSampleRate getSampleRateEnum()

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

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

Uploads a command list (generated by an instance of the **Rhd2000RegistersUsb3** 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
```

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

Prints a command list (generated by an instance of the **Rhd2000RegistersUsb3** class) to the console in readable form, for diagnostic purposes.

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
```

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PortE
PortF
PortG
PortH

void selectAuxCommandLength(int auxCommandSlot, AuxCmdSlot 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()

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 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.

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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 RHD2000 chip (in meters or feet). Cable delay should be updated after any changes are made to the sampling rate, since cable delay calculations are based on the clock period.

double estimateCableLengthMeters(int delay)

double estimateCableLengthFeet(int delay)

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

void setDspSettle(bool enabled);

Turns on or off the DSP settle function in the FPGA. (This only executes when CONVERT commands are executed by the RHD2000.)

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

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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.

void clearTtlOut()

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

void setTtlOut(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 getTtlIn(int ttlInArray[])

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

void setDacManual(int value)

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

void setLedDisplay(int ledArray[])

Sets the eight red LEDs on the Opal Kelly XEM6310 board according to a length-8 integer array.

RHD2000 USB3/FPGA Interface: Rhythm USB3

void enableDac(int dacChannel, bool enabled)

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

void setDacGain(int gain)

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

void setAudioNoiseSuppress(int noiseSuppress)

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

void selectDacDataStream(int dacChannel, int stream)

void selectDacDataChannel(int dacChannel, int dataChannel)

Assigns a particular data stream (0-31) 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 RHD2000 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, RHD2000 signals equaling or rising above the threshold produce a high digital output. If the trigger polarity is set to false, RHD2000 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.

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

void setTtlMode(int mode)

Sets the TTL digital output mode of the FPGA. If mode is set to zero, all 16 TTL digital output pins are controlled manually using `setTtlOut`. If mode is set to one, the upper eight TTL outputs are controlled manually, while the lower eight TTL outputs are controlled by low-latency threshold comparators connected to the eight waveforms routed to the DACs.

void enableExternalFastSettle(bool enable)

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

RHD2000 USB3/FPGA Interface: Rhythm USB3

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 RHD2000 chips on a selected SPI port from an external digital input.

void setExternalDigOutChannel(BoardPort port, int channel)

Selects external TTL digital input channel (0-15) used to control the auxiliary digital output pin (**auxout**) on RHD2000 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(Rhd2000DataBlockUsb3 *dataBlock)

Reads a data block from the USB interface and stores the data into an **Rhd2000DataBlockUsb3** object dataBlock. Returns true if data block was available.

long readDataBlocksRaw(int numBlocks, unsigned char *buffer)

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

bool readDataBlocks(int numBlocks, queue<Rhd2000DataBlockUsb3> &dataQueue)

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

int queueToFile(queue<Rhd2000DataBlockUsb3> &dataQueue, ofstream &saveOut)

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

int getBoardMode()

Reads four digital input pins on the FPGA (see **JP1 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.

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.

Rhd2000RegistersUsb3 Class Reference

This class creates and manages a data structure representing the internal RAM registers on a RHD2000 chip, and generates command lists to configure the chip and perform other functions. Changing the value of variables within an instance of this class does not directly affect a RHD2000 chip connected to the FPGA; rather, a command list must be generated from this class and then downloaded to the FPGA board using `Rhd2000EvalBoardUsb3::uploadCommandList`. Typically, one instance of `Rhd2000RegistersUsb3` will be created for each RHD2000 chip attached to the Rhythm USB3 interface. However, if all chips will receive the same MOSI commands, then only one instance of `Rhd2000RegistersUsb3` is required.

The public member functions of the `Rhd2000RegistersUsb3` class are listed below.

`Rhd2000RegistersUsb3(double sampleRate)`

Constructor. Sets RHD2000 register variables to default values.

`void defineSampleRate(double newSampleRate)`

Defines RHD2000 per-channel sampling rate so that certain sample-rate-dependent registers are set correctly. (This function does not change the sampling rate of the FPGA; for this, use `Rhd2000EvalBoardUsb3::setSampleRate`.)

`void setFastSettle(bool enabled)`

Enables or disables amplifier fast settle function.

`void setDigOutLow()`

`void setDigOutHigh()`

`void setDigiOutHiZ()`

Sets the auxiliary digital output variable to indicate a low, high, or high impedance (HiZ) output.

`void enableAux1(bool enabled)`

`void enableAux2(bool enabled)`

`void enableAux3(bool enabled)`

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)`

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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 RHD2000 chip.

int getRegisterValue(int reg)

Returns the value of a selected RHD2000 RAM register (0-21), based on the current register variables in the class instance.

double setUpperBandwidth(double upperBandwidth)

double setLowerBandwidth(double lowerBandwidth)

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.

int createRhd2000Command(Rhd2000CommandType commandType)

int createRhd2000Command(Rhd2000CommandType commandType, int arg1)

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int createRhd2000Command(Rhd2000CommandType commandType, int arg1, int arg2)

Returns a 16-bit MOSI command based on the **Rhd2000CommandType** enumeration; defined values are:

Rhd2000CommandConvert
Rhd2000CommandCalibrate
Rhd2000CommandCalClear
Rhd2000CommandRegWrite
Rhd2000CommandRegRead

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.

int createCommandListRegisterConfig(vector<int> &commandList, bool calibrate)

Creates a list of 128 commands to program most RAM registers on a RHD2000 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.

int createCommandListTempSensor(vector<int> &commandList)

Creates a list of 128 commands to sample auxiliary ADC inputs, temperature sensor, and supply voltage sensor. One temperature reading (one sample of ResultA and one sample of ResultB) is taken during this 128-command sequence. One supply voltage sample is taken. Auxiliary ADC inputs are continuously sampled at 1/4 the amplifier sampling rate.

Since this command list consists of writing to Register 3, it also sets the state of the auxiliary digital output. If the digital output value needs to be changed dynamically, then variations of this command list need to be generated for each state and programmed into different RAM banks, and the appropriate command list selected at the right time.

Returns the length of the command list.

int createCommandListZcheckDac(vector<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 createCommandListUpdateDigOut(vector<int> &commandList)

Creates a list of 128 commands to update Register 3 (controlling the auxiliary digital output pin) every sampling period. Since this command list consists of writing to Register 3, it also sets the state of the on-chip temperature sensor. The temperature sensor settings are therefore changed throughout this command list to coordinate with the 128-command list generated by **createCommandListTempSensor()**. This function returns the length of the command list.

Rhd2000DataBlockUsb3 Class Reference

This class creates a data structure storing SAMPLES_PER_DATA_BLOCK data samples from a Rhythm USB3 FPGA interface controlling up to 16 RHD2000 chips. (A #define statement in `rhd2000datablockusb3.h` currently sets SAMPLES_PER_DATA_BLOCK to 128.) Typically, instances of `Rhd2000DataBlockUsb3` 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 `Rhd2000DataBlockUsb3` class are listed below.

`Rhd2000DataBlockUsb3(int numDataStreams)`

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

`unsigned int getSamplesPerDataBlock()`

Returns the SAMPLES_PER_DATA_BLOCK, which is set to 128.

`unsigned int calculateDataBlockSizeInWords(int numDataStreams)`

Returns the size of a USB data block (in 16-bit words) when numDataStreams data streams (0-31) are enabled.

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

Fills the data block with raw data from the n^{th} data block in a USB input buffer in an `Rhd2000EvalBoardUsb3` 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 RHD2000 registers from a selected USB data stream (0-31) to the console. This function assumes that the command string generated by `Rhd2000RegistersUsb3::createCommandListRegisterConfig` has been uploaded to the AuxCmd3 slot.

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

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

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

Checks the first 64 bits of USB header against the fixed Rhythm USB3 “magic number” to verify proper data synchrony.

Example Usage

A simple **main.cpp** C++ program presented below opens an Opal Kelly XEM6310 board, configures it with the Rhythm USB3 FPGA configuration bitfile (**main.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 RHD2000 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 RHD2000 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 "okFrontPanelDLL.h"
#include "rhd2000evalboardusb3.h"
#include "rhd2000registersusb3.h"
#include "rhd2000datablockusb3.h"

int main(int argc, char *argv[])
{
    // Open Opal Kelly XEM6310 board, load Rhythm USB3 bitfile, and initialize.
    Rhd2000EvalBoardUsb3 *evalBoard = new Rhd2000EvalBoardUsb3;
    evalBoard->open();
    evalBoard->uploadFpgaBitfile("main.bit");
    evalBoard->initialize();
    evalBoard->enableDataStream(0, true);

    // Select a per-amplifier sampling rate.
    evalBoard->setSampleRate(Rhd2000EvalBoardUsb3::SampleRate20000Hz);

    // Now that we have set our sampling rate, we can set the MISO sampling delay
    // which is dependent on the sample rate. We assume a 3-foot cable.
    evalBoard->setCableLengthFeet(Rhd2000EvalBoardUsb3::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};
    evalBoard->setLedDisplay(ledArray);

    // Set up an RHD2000 register object using this sample rate.
    Rhd2000RegistersUsb3 *chipRegisters;
    chipRegisters = new Rhd2000RegistersUsb3(evalBoard->getSampleRate());

    // Create command lists to be uploaded to auxiliary command slots.
    int commandSequenceLength;
    vector<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);
    evalBoard->uploadCommandList(commandList, Rhd2000EvalBoardUsb3::AuxCmd1, 0);
    evalBoard->selectAuxCommandLength(Rhd2000EvalBoardUsb3::AuxCmd1, 0,
        commandSequenceLength - 1);
```

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```
evalBoard->selectAuxCommandBank(Rhd2000EvalBoardUsb3::PortA,
    Rhd2000EvalBoardUsb3::AuxCmd1, 0);
// evalBoard->printCommandList(commandList); // optionally, print command list

// Next, we'll create a command list for the AuxCmd2 slot. This command sequence
// will sample the temperature sensor and other auxiliary ADC inputs.
commandSequenceLength = chipRegisters->createCommandListTempSensor(commandList);
evalBoard->uploadCommandList(commandList, Rhd2000EvalBoardUsb3::AuxCmd2, 0);
evalBoard->selectAuxCommandLength(Rhd2000EvalBoardUsb3::AuxCmd2, 0,
    commandSequenceLength - 1);
evalBoard->selectAuxCommandBank(Rhd2000EvalBoardUsb3::PortA,
    Rhd2000EvalBoardUsb3::AuxCmd2, 0);
// evalBoard->printCommandList(commandList); // optionally, print command list

// For the AuxCmd3 slot, we will create two command sequences. Both sequences
// will configure and read back the RHD2000 chip registers, but one sequence will
// also run ADC calibration.

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

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->createCommandListRegisterConfig(commandList, false);
// Upload version with no ADC calibration to AuxCmd3 RAM Bank 0.
evalBoard->uploadCommandList(commandList, Rhd2000EvalBoardUsb3::AuxCmd3, 0);

chipRegisters->createCommandListRegisterConfig(commandList, true);
// Upload version with ADC calibration to AuxCmd3 RAM Bank 1.
evalBoard->uploadCommandList(commandList, Rhd2000EvalBoardUsb3::AuxCmd3, 1);
evalBoard->selectAuxCommandLength(Rhd2000EvalBoardUsb3::AuxCmd3, 0,
    commandSequenceLength - 1);
// Select RAM Bank 1 for AuxCmd3 initially, so the ADC is calibrated.
evalBoard->selectAuxCommandBank(Rhd2000EvalBoardUsb3::PortA,
    Rhd2000EvalBoardUsb3::AuxCmd3, 1);
// evalBoard->printCommandList(commandList); // optionally, print command list

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

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

// Read the resulting single data block from the USB interface.
Rhd2000DataBlockUsb3 *dataBlock =
    new Rhd2000DataBlockUsb3(evalBoard->getNumEnabledDataStreams());
evalBoard->readDataBlock(dataBlock);

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

// Now that ADC calibration has been performed, we switch to the command sequence
// that does not execute ADC calibration.
```

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```
evalBoard->selectAuxCommandBank(Rhd2000EvalBoardUsb3::PortA,
    Rhd2000EvalBoardUsb3::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);

queue<Rhd2000DataBlockUsb3> dataQueue;

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

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

evalBoard->queueToFile(dataQueue, saveOut);

saveOut.close();

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

An elaborated version of this **main.cpp** program file is included with the Rhythm USB3 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);

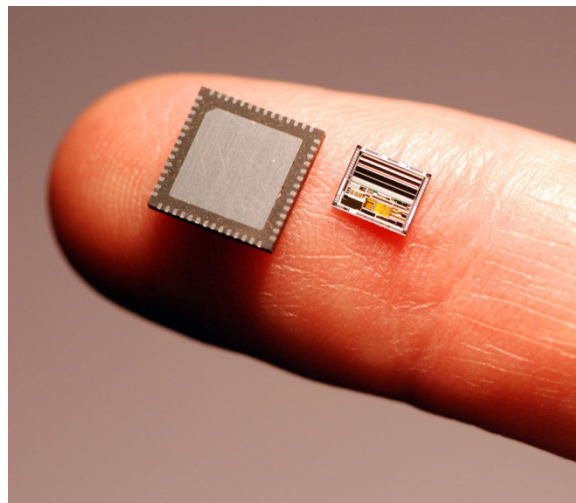
data = reshape(data, 46, L/46);

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

Contact Information

This datasheet is meant to acquaint engineers and scientists with the Rhythm USB3 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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