Summary

This application note demonstrates the performance measurement of the Xilinx® universal serial bus 2.0 (USB 2.0) high-speed device with an advanced microcontroller bus architecture (AMBA®) advanced eXtensible interface (AXI) for bulk and isochronous transactions. The test system generated is based on a Kintex®-7 FPGA. The performance is measured with two separate host drivers for bulk and isochronous transactions. This application note describes how to develop a USB system and corresponding ELF files for bulk and isochronous transactions. It is assumed that the user has general knowledge of the Xilinx Platform Studio (XPS) [Ref 1].

Introduction

The AXI USB 2.0 device enables USB connectivity for a design using a minimal amount of resources. This interface is suitable for USB-centric, high-performance designs, bridges, and legacy port replacement operations. The USB 2.0 protocol multiplexes many devices over a single, half-duplex, serial bus. The AXI USB 2.0 device runs at 480 Mb/s (high speed) or at 12 Mb/s (full speed), and is designed to be plug-and-play. The host controls the bus and sends tokens to the device specifying the required action. The AXI USB 2.0 device supports up to eight endpoints, including default control endpoints that are sources or sinks of data. Endpoint 0 of the USB 2.0 device is used to enumerate the device with control transactions.

The seven user endpoints of the AXI USB 2.0 device can be configured as bulk, interrupt, or isochronous. Also, endpoints can be configured as input (to the host) or output (from the host). Each of these endpoints has two ping-pong buffers of the same size for endpoint data. The user endpoints data buffers are unidirectional and are configured by the endpoint configuration and status register of the respective endpoint. The size of the buffers can be configured from 0 to 512 bytes for bulk, 64 bytes for interrupt, and up to 1024 bytes for isochronous endpoints.

This application note is targeted to demonstrate USB bulk and isochronous transactions performance. The following elements are used in the application:

- A MicroBlaze™ reference system with AXI USB 2.0 device and DDR controller.
- Executable and linkable format (ELF) files that configure the device as bulk or isochronous endpoints.
- Host application used to measure the USB device performance.

The AXI USB 2.0 device consists of a built-in direct memory access (DMA) controller to transfer the data from endpoint buffers to the memory and vice versa. The USB 2.0 device core consists of a dedicated AXI4 slave interface and an optional AXI4 master interface. The optional master interface is configured through the device parameter C_INCLUDE_DMA. When the parameter is set to 1, the DMA logic is included in the design. When the DMA logic is included, the user endpoint buffer location is not accessible from the AXI slave interface. When the DMA is disabled, the endpoint buffer location can be accessed by the AXI slave interface.
Mass Storage Application

The mass storage application uses bulk transactions, which require two endpoint buffers configured as bulk-in and bulk-out endpoints and a maximum packet size set to 512 bytes. The bulk-in endpoint is used to measure the performance for a read operation and the bulk-out endpoint is used to measure the performance for a write operation.

The bulk application initializes the system to enable the USB and UART devices. Responds for device enumeration commands (SET/GET descriptor) are from the host. Once the enumeration is completed, if the device receives a read request from the host the following occurs.

1. Data is written into the ping/pong buffers present in the USB device through the DMA.
2. Upon receiving the IN token from the host device, the device responds with the data present in the ping/pong buffer.
3. An interrupt is sent to the Microblaze reference system to indicate a buffer free condition for the corresponding end point.
4. The Microblaze reference system detects the buffer free interrupt and fills the ping/pong buffer with the next data to send.
5. This process is repeated.

If the device receives a write command, following steps will take place.

1. The host device sends an OUT token followed by a data packet.
2. Upon reception of the data, the received data is written into the ping/pong buffer.
3. An interrupt is send to the Microblaze reference system to indicate a buffer full condition for the corresponding end-point.
4. The Microblaze reference system reads the data and stores it into the DDR through the DMA.
5. This procedure is repeated as long as the host sends data.

Isochronous Application

The isochronous application is tested for Read and Write with separate applications. The isoc_in application tests the read operation using isochronous transactions, and the isoc_out application measures the performance of the write operation. The isoc_in application programs the device as a microphone and uses one endpoint as an isochronous In endpoint. The isoc_out application programs the device as a speaker and uses one endpoint as an isochronous out endpoint.

The isochronous application initializes the system to enable the USB and UART devices. Responds for device enumeration commands (SET/GET descriptor) are from the host. Once the enumeration is completed, if the device is configured as a microphone, the following steps occur.

1. Data is written into the ping/pong buffers present in the USB device through the DMA.
2. Upon receiving the IN token from the host device, the device responds with data present in the ping/pong buffer.
3. An interrupt is sent to the Microblaze reference system to indicate a buffer free condition for the corresponding end point.
4. The Microblaze reference system detects the buffer free interrupt and fills the ping/pong buffer with the next data to send.
5. This process is repeated.

If the device is configured as a speaker, the following steps occur.

1. The host device sends an OUT token followed by a data packet.
2. Upon reception of the data, the received data is written into the ping/pong buffer.
3. An interrupt is send to the Microblaze reference system to indicate a buffer full condition for the corresponding end-point.
4. The Microblaze reference system reads the data and stores it into the DDR through the DMA.
5. This procedure is repeated.

**Core Parameters**

Table 1 includes the description, name, and usage guidelines for the core parameters.

<table>
<thead>
<tr>
<th>Feature/Description</th>
<th>Parameter Name</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>AXI4 memory mapped: Base address</td>
<td>C_BASEADDR</td>
<td>Required</td>
</tr>
<tr>
<td>AXI4 memory mapped: High address</td>
<td>C_HIGHADDR</td>
<td>Required</td>
</tr>
<tr>
<td>Use DMA logic</td>
<td>C_INCLUDE_DMA</td>
<td>1</td>
</tr>
<tr>
<td>Choice of PHY reset type</td>
<td>C_PHY_RESET_TYPE</td>
<td>active_low</td>
</tr>
<tr>
<td>Choice of including error logic</td>
<td>C_INCLUDE_USBERR_LOGIC</td>
<td>1</td>
</tr>
<tr>
<td>Choice of buffer type used</td>
<td>C_ULPI_CLK_BUFFER_TYPE</td>
<td>BUFR</td>
</tr>
<tr>
<td>Choice of unaligned transaction support</td>
<td>C_DMA_UA_TRANS_SUPPORT</td>
<td>1</td>
</tr>
</tbody>
</table>

**Hardware Requirements**

The hardware boards and additional equipment required for this reference system include:
- Xilinx KC705 production board
- USB PHY FMC card with LPC connector
- JTAG platform cable USB
- Two USB mini-B cables

The installed software tool requirements for building and downloading this reference system are:
- Xilinx Platform Studio 14.3
- ISE Design Suite 14.3
- SDK 14.3
Using AXI USB 2.0 Device

The AXI USB 2.0 device IP can be connected on an AXI-based system with a 32-bit data width. The IP supports a ULPI interface on the USB PHY side. The IP can be configured in DMA mode or non-DMA mode with the parameter C_INCLUDE_DMA. When the DMA is enabled, the AXI master interface is enabled and the AXI4 master interface must be connected to an AXI4 full interconnect to which a DDR controller is connected as slave. The interrupt pin of the IP should be connected to the interrupt controller block (axi_intc) of the MicroBlaze system. The parameters used to configure the IP are:

- **C_INCLUDE_DMA**: When set to 1, a built-in DMA block is included in the design along with the AXI4 master interface. The addition of the DMA block disconnects the user endpoint buffers from the AXI slave interface.
- **C_DMA_UA_TRNS_SUPPORT**: When set to 1, data realignment support is added to the design.
- **C_PHY_RESET_TYPE**: This parameter must be set according to the PHY requirements. When set as ACTIVE_LOW, the ULPI reset generated by the AXI USB 2.0 device IP is an active Low signal. When set to ACTIVE_HIGH, the ULPI reset generated by the AXI USB 2.0 device IP is an active High signal.
- **C_INCLUDE_USBERR_LOGIC**: When set to 1, the USB link error logging counters are added in the design.
- **C_ULPI_CLOCK_BUFFER_TYPE**: This parameter indicates the type of buffer that needs to be used to route the ULPI clock in the design. The supported values are IBUF, IBUFG, BUFG, and BUFR. This parameter is used to route the ULPI clock for better timing results on the ULPI clock domain.

System Design

A typical system for the AXI USB 2.0 device application is shown in Figure 1.

![Typical System for AXI USB 2.0 Device Application](image)

**Figure 1**: Typical System for AXI USB 2.0 Device Application

The system is based on AXI, which is a standardized IP interface protocol based on the AMBA specification. The AXI interfaces used in the reference design consist of AXI4 memory mapped and AXI4-Lite. A clock generator and processor system reset block supplies clocks and resets throughout the system. High-level control of the system is provided by an embedded MicroBlaze processor subsystem containing I/O peripherals and processor support IP. To
To optimize the system to balance performance and area, multiple AXI interconnect blocks are used to implement segmented or hierarchical AXI interconnect networks with each AXI interconnect block individually tuned and optimized.

Table 2 lists the IP reference design components, version, base address, and high address.

<table>
<thead>
<tr>
<th>IP</th>
<th>Version</th>
<th>Base Address</th>
<th>High Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>MicroBlaze</td>
<td>8.40.a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>axi_7series_ddrx</td>
<td>1.06.a</td>
<td>0xb0000000</td>
<td>0xbfffffff</td>
</tr>
<tr>
<td>axi_usb2_device</td>
<td>3.02.a</td>
<td>0x44800000</td>
<td>0x4480ffff</td>
</tr>
<tr>
<td>axi_uartlite</td>
<td>1.02.a</td>
<td>0x40600000</td>
<td>0x4060ffff</td>
</tr>
<tr>
<td>lmb_bram_if_cntlr</td>
<td>3.10.a</td>
<td>0x00000000</td>
<td>0x00001fff</td>
</tr>
<tr>
<td>axi_intc</td>
<td>1.02.a</td>
<td>0x41200000</td>
<td>0x4120ffff</td>
</tr>
<tr>
<td>Mdm</td>
<td>2.10.a</td>
<td>0x41400000</td>
<td>0x4140ffff</td>
</tr>
<tr>
<td>axi_gpio</td>
<td>1.01.b</td>
<td>0x40000000</td>
<td>0x4000ffff</td>
</tr>
<tr>
<td>proc_sys_reset</td>
<td>3.00.a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>clock_generator</td>
<td>4.03.a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>axi_interconnect – lite</td>
<td>1.06.a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>axi_interconnect – full interface</td>
<td>1.06.a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

A ready-to-use system BIT file and ELF file are provided with this application note for the USB device and the MicroBlaze application. The hardware system consists of a USB 2.0 device system with a MicroBlaze processor and a 7 series FPGA DDR3 controller.

To create a reference system:

1. Start the XPS and create a new system with the base system builder (BSB) wizard.
2. Select AXI system and click OK.
3. Select the Kintex-7 board and click Next.
4. Include the following blocks along with the MicroBlaze processor peripherals:
   a. DDR3_SDRAM (cached)
   b. Push.Buttons_5bits (enable interrupt)
   c. RS232_Uart_1 (enable interrupt)
5. Click Finish.
   A default MicroBlaze system with the selected peripherals is created, including the interrupt controller.
6. Select and right click axi_usb2_device IP from:
   IP Catalog > Communication High Speed > axi_usb2_device and select the Add IP option.
7. A window is displayed, as shown in Figure 2, to confirm the addition of the `axi_usb2_device` IP to the system. Click Yes.

![Add IP Instance to Design](image)

Figure 2: Add IP Instance to Design

8. Select the parameters as shown in Figure 3. Click OK and the tool automatically makes the connections to AXI interfaces and external ports.

![Select Parameters](image)

Figure 3: Select Parameters
9. Go to the ports tab (Figure 4) in the XPS window and expand the microblaze_0_intc block. Click the INTR pin connected ports column and move the axi_usb2_device_0_irpt pin from the unconnected interrupts window to the connected interrupts window. Click OK.

10. Remove the debug ports displayed in Figure 5 from the external ports list and the AXI USB 2.0 device IP instance in the system.mhs file. These ports are debug ports and are not needed in the actual system.

Figure 4: Ports Tab
11. Copy the following system location constraints for the ULPI signals into the `system.ucf` file in the `data` folder of the workspace.

```
###                SMSC2_USB   KC705 constraints             ###
NET axi_usb2_device_0_ULPI_Clock_pin   LOC = AD27 | IOSTANDARD=LVCMOS25;
NET axi_usb2_device_0_ULPI_Reset_pin   LOC = AB30 | IOSTANDARD=LVCMOS25 | TIG;
NET axi_usb2_device_0_ULPI_Stop_pin    LOC = AE28 | IOSTANDARD=LVCMOS25;
NET axi_usb2_device_0_ULPI_Next_pin    LOC = AE30 | IOSTANDARD=LVCMOS25;
NET axi_usb2_device_0_ULPI_Data_pin<7> LOC = AK29 | IOSTANDARD=LVCMOS25;
NET axi_usb2_device_0_ULPI_Data_pin<6> LOC = AK30 | IOSTANDARD=LVCMOS25;
NET axi_usb2_device_0_ULPI_Data_pin<5> LOC = AJ28 | IOSTANDARD=LVCMOS25;
NET axi_usb2_device_0_ULPI_Data_pin<4> LOC = AJ29 | IOSTANDARD=LVCMOS25;
```

12. Generate the bitstream file by selecting Hardware > Generate BitStream.

13. After the bitstream file is generated, export it to SDK by selecting Project > Export Hardware to SDK.

---

**Figure 5:** Remove Debug Ports
Creating an ELF File

The following steps describe how to create an ELF file for bulk transactions. These same steps can be used to create ELF files for isochronous In and Out transactions. The source files are located in bulk, isoc_in, and isoc_out folders in the SW/Device_Files directory.

1. Select the Export and Launch option from the pop-up window.
2. Once the SDK is open, create an application project for a bulk endpoint application by selecting File > New > Application Project. See Figure 6.

![Figure 6: Creating New Project](image)

3. Enter bulk_perfmon for the project name.
4. Select the Use default location check box.

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www.xilinx.com
6. Select **Empty application** from Available Templates, and click **Finish**.
7. From the Project Explorer window, select the **src** folder under the mass_storage_perf project.
8. Right click on the SRC directory and click **Import**.
9. Select **General > File System** and click **Next**.
10. Browse to the directory SW/Device_Files/bulk and click **OK**.
11. Select the following files and click **Finish**:
   - xusb_cp9.c
   - xusb_cp9.h
   - xusb_storage.c
   - xusb_storage.h
   - xusb_types.h

---

**Installing Host Side Driver**

This section describes how to install the host side driver.

**Software Requirements**

The USB bulk performance monitor has the following software requirements.

- Windows XP (SP3) or higher (32-bit or 64-bit)
- NET Framework 4

**Installing the Driver**

Separate applications are provided for bulk and isochronous transaction performance measurement. For the isochronous transactions performance measurements, go to the SW/Host_Files/USBISOC_Setup directory. For bulk transaction performance measurements, go to the SW/Host_Files/USBBulk_Setup/ directory.

Double-click **Xilinx USB Perfmon Setup x86.msi** for a 32-bit machine or **Xilinx USB Perfmon Setup x64.msi** for a 64-bit machine. Follow the instructions to complete the installation.

**Note:** For Windows 7 64-bit, after starting the PC and when Windows starts loading, keep pressing the F8 key to open the setup window. In the setup window, disable the Disable Driver Signature Enforcement by setting it to No.

**Note:** Ensure that the board is configured with a *.bit file and that the *.elf file is loaded before installing the drivers.

If the application does not work, load the MicroBlaze application again. It might need to be loaded several times until it works (maximum 2-3 times.)

**Hardware Requirements**

To demonstrate the USB bulk application on an FPGA, the following hardware components are required:

- KC705 board with power cable
- One FMC card (HW-FMC-Number-USB-G)
- Three mini-USB cables

**Hardware Setup**

The following steps describe how to set up the Kintex-7 FPGA board.

1. On a Kintex-7 FPGA board, insert the USB PHY FMC card in the LPC slot.
2. Connect the JTAG port and UART ports to the system from which the Xilinx microprocessor debugger (XMD) is run.

3. Connect the J5 USB port of the FMC card to the system on which the host application is run. Figure 7 shows the board setup.

![Kintex-7 Board Setup](image)

**Figure 7: Kintex-7 Board Setup**

**Configuring the Board as Bulk USB**

1. Go to the Ready_2Use folder provided with the release.

2. Open the command prompt and run `xmd`.

   **Note:** XMD must be installed on the user machine.

3. Run the `fpga -f system.bit` command on the XMD terminal.

4. Run the `connect mb mdm` command on the XMD terminal.

5. Run the `rst;stop;dow bulk_perfmon.elf;run` command on the XMD terminal.
6. Make sure that the output shown in Figure 8 is displayed on the hyperterminal. If USB enumerated is not displayed, run the previous commands again.

![PuTTY terminal output](image)

**Figure 8:** Configuring Board as Bulk USB

**Configuring the Board as IsoC USB**

*Note:* To configure the board, XMD must be installed on the designer's system.

1. Go to the **Ready_2Use** folder provided with the release. The *system.bit*, *isoc_in.elf*, and *isoc_out.elf* files are used to configure the board.

   *Note:* The following steps are for the isoc_in case. The same steps can be repeated for isoc_out.

2. Open the command prompt and run **xmd**.

3. Run the **fpga -f system.bit** command on the XMD terminal.

4. Run the **connect mb mdm** command on the XMD terminal.

5. Run the **rst;stop; dow isoc_in.elf; run** command on the XMD terminal.

   The hardware is ready to be used as an In-mode isochronous device.

6. Once the device is ready, the application can be run with **UsbPerfmon.exe**. After the full configuration is completed, carefully remove all the USB ports except the one that is connected to the FMC card. Run **UsbPerform.exe**.

   *Note:* The start rate should not be less than 1024K and the rate/graph can vary based on the transaction on the USB hub. Normally, it should not vary more than 10%. However, it can change significantly if a new USB device is plugged into the system.
Results and Conclusion

Once the driver is installed and the system is detected, after opening the `UsbPerfmon.exe`, the screen shown in Figure 9 appears on the display.

![USB Performance Monitor](image)

Figure 9: USB Performance Monitor

The performance measurement software includes options to change the transfer rates and type of test through the GUI. The options that can be changed by the user are provided at the bottom of the display. The outputs are on the right side of the display. The following parameters can be set by the user:

- **Test Type**: The test can be carried out in Read or Write mode. The throughput measurement for Read and Write transactions can be measured separately.
- **Data Limit Settings**: The maximum data to be transmitted per transaction can be constrained through this tab.
- **Data Transfer Settings**: Transfer rate settings can be changed through this tab. The Start Rate option indicates the starting transfer rate from the host. Change pattern of the transfer rate can be set through the transfer pattern setting option.
Performance Measurements for Bulk Transactions

Performance can be measured for Read and Write operations separately. For a Write operation, the performance measurement is determined for the following GUI parameters:

- Start Rate = 40024 KB/s
- Transfer Pattern = Steady

With these settings, a maximum performance of 36.114 was obtained with the AXI USB 2.0 device. Figure 10 shows the result.

As shown in Figure 10, in the transfer rate section, the current reading shows the performance measured at that instance (for one second). The average reading shows the average of the performance numbers calculated until that point of time. The minimum reading shows the minimum value of the performance number measured over the time. The maximum reading shows the maximum value of the performance number measured until that second of the time.
Figure 11 shows the results for these GUI parameter settings:

- Start Rate = 1240 KB/s
- Transfer Pattern = Fixed Increment
- Data increments = 1000 KB
- Update frequency = 1 sec (frequency at which data rate is increased)

Note: The performance numbers vary depending on the number of other USB devices connected to the system, and the number of packets the host can initiate in a micro frame.
Performance Measurements for Isochronous Transaction

Figure 12 shows the performance measurement for an isochronous Out transaction with a starting data rate of 1024 KB/s and fixed increment pattern. The maximum throughput achieved is 22.7 MB/s and the theoretical maximum throughput is 24 MB/s.

Figure 12: Performance Measurement for Isochronous Out Transaction
Figure 13 shows the performance measurement for an isochronous In transaction with a starting data rate of 1024 KB/s and fixed increment pattern. The maximum throughput achieved is 22.6 MB/s and the theoretical maximum throughput is 24 MB/s.

Figure 13: Performance Measurement for Isochronous In Transaction
Reference Design Parameters

The reference design files for this application note can be downloaded from:
https://secure.xilinx.com/webreg/clickthrough.do?cid=199301

Table 3 lists the reference design parameters.

Table 3: Reference Design Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General</strong></td>
<td></td>
</tr>
<tr>
<td>Developer name</td>
<td>Ravi Kiran Boddu, Dinesh Kumar</td>
</tr>
<tr>
<td>Target devices</td>
<td>Kintex-7</td>
</tr>
<tr>
<td>Source code provided</td>
<td>Yes</td>
</tr>
<tr>
<td>Source code format</td>
<td>VHDL/Verilog (some cores are encrypted)</td>
</tr>
<tr>
<td>Design uses code/IP from existing Xilinx</td>
<td>VHDL/Verilog (some cores are encrypted)</td>
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<td>application note/reference designs, CORE</td>
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<tr>
<td>Generator software, or third party</td>
<td></td>
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<tr>
<td><strong>Simulation</strong></td>
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<tr>
<td>Generator software, or third party</td>
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<td>Functional simulation performed</td>
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<td>Timing simulation performed</td>
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<td>Simulator software/version used</td>
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<td>SPICE/IBIS simulations</td>
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<td>Synthesis software tools/version used</td>
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<td>Static timing analysis performed</td>
<td>Yes (passing timing in PAR/TRCE)</td>
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<tr>
<td><strong>Hardware Verification</strong></td>
<td></td>
</tr>
<tr>
<td>Hardware verified</td>
<td>Yes</td>
</tr>
<tr>
<td>Hardware platform used for verification</td>
<td>KC705 board</td>
</tr>
</tbody>
</table>

Device and Utilization

Table 4 shows the utilization for the XC7K325T device.

Table 4: Device and Utilization

<table>
<thead>
<tr>
<th>Device</th>
<th>Speed Grade</th>
<th>Package</th>
<th>Slice Registers</th>
<th>Occupied Slices</th>
<th>Slice LUTs</th>
<th>I/Os</th>
<th>RAMB36E1s</th>
</tr>
</thead>
<tbody>
<tr>
<td>XC7K325T</td>
<td>-2</td>
<td>FFG900</td>
<td>8002 (1%)</td>
<td>4364 (8%)</td>
<td>10995 (5%)</td>
<td>61 (12%)</td>
<td>11 (2%)</td>
</tr>
</tbody>
</table>
References
This section lists the references used in this document.

1. **UG683**, *EDK Concepts, Tools, and Techniques*
2. **DS785**, *LogiCORE IP AXI Universal Serial Bus (USB) 2.0 Device (v3.02.a) Data Sheet (EDK 14.3 Release)*

Revision History
The following table shows the revision history for this document.

<table>
<thead>
<tr>
<th>Date</th>
<th>Version</th>
<th>Description of Revisions</th>
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<td>12/19/12</td>
<td>1.0</td>
<td>Initial Xilinx release.</td>
</tr>
<tr>
<td>02/14/13</td>
<td>1.0.1</td>
<td>Minor typographical edits. Updated PDF properties.</td>
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</table>

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