



XAPP139 (v1.2) February 18, 2000

# Configuration and Readback of Virtex FPGAs Using (JTAG) Boundary-Scan

## Summary

This application note demonstrates using a boundary-scan (JTAG) interface to configure and readback Virtex™ FPGA devices. Virtex devices have boundary-scan features that are compatible with the IEEE Standard 1149.1. This application note is a complement to the configuration section in the Virtex Data Sheet and application note [XAPP138: “Virtex Configuration and Readback”](#). Review of both the datasheet and XAPP138 is recommended prior to reading this document.

## Introduction

The IEEE 1149.1 Test Access Port and Boundary-Scan Architecture, commonly referred to as JTAG, is a popular testing method. JTAG is an acronym for the Joint Test Action Group, the technical subcommittee initially responsible for developing the standard. This standard provides a means to assure the integrity of individual components and the interconnections between them at the board level. With increasingly dense multi-layer PC boards, and more sophisticated surface mounting techniques, boundary-scan testing is becoming widely used as an important debugging standard.

Devices containing boundary-scan logic can send data out on I/O pins in order to test connections between devices at the board level. The circuitry can also be used to send signals internally to test the device specific behavior. These tests are commonly used to detect opens and shorts at both the board and device level.

In addition to testing, boundary-scan offers the flexibility for a device to have its own set of user-defined instructions. The added common vendor specific instructions, such as configure and verify, have increased the popularity of boundary-scan testing and functionality.

## Boundary-Scan for Virtex Devices

The Virtex family is fully compliant with the IEEE Standard 1149.1 Test Access Port and Boundary-Scan Architecture. The architecture includes all mandatory elements defined in the IEEE 1149.1 Standard. These elements include the Test Access Port (TAP), the TAP controller, the instruction register, the instruction decoder, the boundary-scan register, and the bypass register. The Virtex family also supports some optional instructions; the 32-bit identification register and a configuration register in full compliance with the standard. Outlined in the following sections are the details of the JTAG architecture for Virtex devices.

### Test Access Port

The Virtex TAP contains four mandatory dedicated pins as specified by the protocol ([Table 1](#)).

*Table 1: Virtex TAP Controller Pins*

Pin	Description
TDI	Test Data In
TDO	Test Data Out
TMS	Test Mode Select
TCK	Test Clock

There are three input pins and one output pin to control the 1149.1 boundary-scan TAP controller. In addition to the required pins, there are optional control pins such as  $\overline{\text{TRST}}$  (Test Reset) and enable pins which may be found on devices from other manufacturers. It is important to be aware of these optional signals when interfacing Xilinx devices with parts from different vendors, because they may need to be driven.

The TAP controller is a 16-state, state machine shown in [Figure 1](#). The four mandatory TAP pins are outlined below:

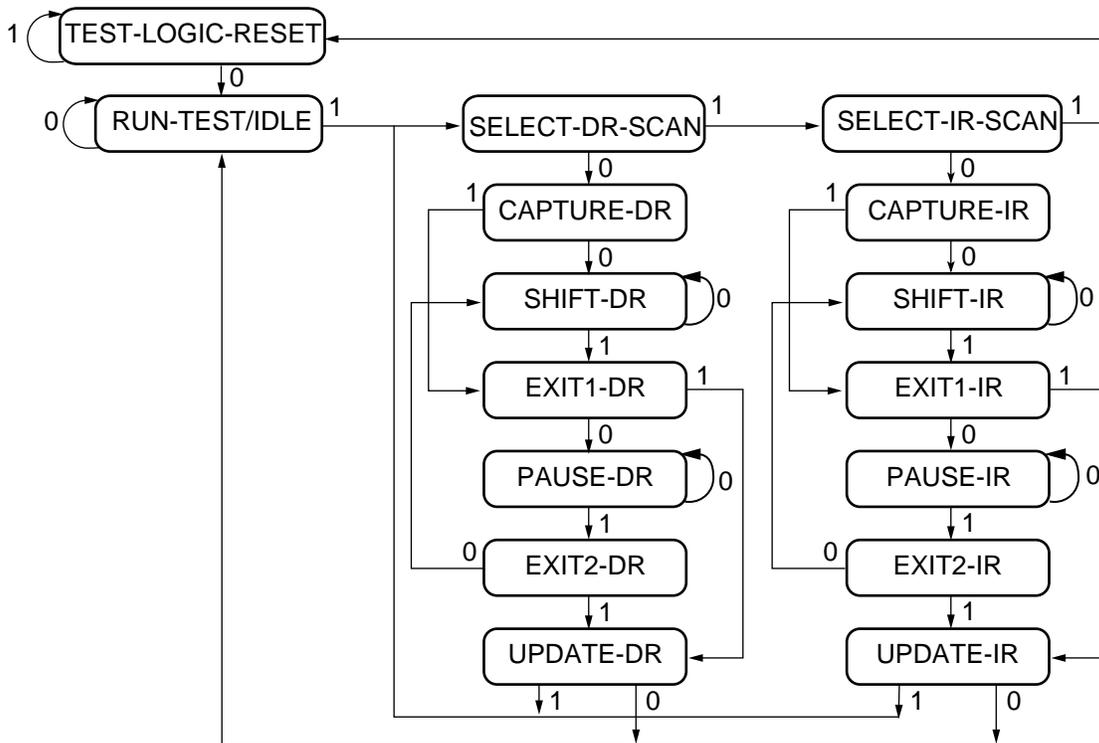
- TMS - The sequence of states through the TAP controller is determined by the state of the TMS pin on the rising edge of TCK. TMS has an internal resistive pull-up to provide a logic High if the pin is not driven.
- TCK - This pin is the JTAG test clock. It sequences the TAP controller and the JTAG registers in the Virtex devices.
- TDI - This pin is the serial input to all JTAG instruction and data registers. The state of the TAP controller and the current instruction held in the instruction register determine which register is fed by the TDI pin for a specific operation. TDI has an internal resistive pull-up to provide a logic High to the system if the pin is not driven. TDI is applied into the JTAG registers on the rising edge of TCK.
- TDO - This pin is the serial output for all JTAG instruction and data registers. The state of the TAP controller and the current instruction held in the instruction register determine which register (instruction or data) feeds TDO for a specific operation. TDO changes state on the falling edge of TCK and is only active during the shifting of instructions or data through the device. This pin is 3-stated at all other times.

Note: As specified by the IEEE Standard, the TMS and TDI pins all have internal pull-ups. These internal pull-ups of 50-150 K $\Omega$  are active regardless of the mode selection.

When using the boundary-scan operations in Virtex devices, the  $V_{\text{CCO}}$  for Bank 2 must be at 3.3V for the TDO pin to operate at the required LVTTTL level.

## TAP Controller

[Figure 1](#) diagrams a 16-state finite state machine. The four TAP pins control how the data is scanned into the various registers. The state of the TMS pin at the rising edge of the TCK determines the sequence of state transitions. There are two main sequences, one for shifting data into the data register and the other for shifting an instruction into the instruction register.



NOTE: The value shown adjacent to each state transition in this figure represents the signal present at TMS at the time of a rising edge at TCK.

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Figure 1: State Diagram for the TAP Controller

### Boundary-Scan Instruction Set

To determine the operation to be invoked, a 5-bit instruction is loaded into the instruction register. Table 2 lists the available instructions for Virtex devices.

Table 2: Virtex Boundary Scan Instructions

Boundary Scan Command	Binary Code (4:0)	Description
EXTEST	00000	Enables boundary-scan EXTEST operation
SAMPLE	00001	Enables boundary-scan SAMPLE operation
USER1	00010	Access user-defined register 1
USER2	00011	Access user-defined register 2
CFG_OUT	00100	Access the configuration bus for readback
CFG_IN	00101	Access the configuration bus for configuration
INTEST	00111	Enables boundary-scan INTEST operation
USERCODE	01000	Enables shifting out user code
IDCODE	01001	Enables shifting out of ID code
HIGHZ	01010	3-states output pins while enabling the bypass register

Table 2: Virtex Boundary Scan Instructions

Boundary Scan Command	Binary Code (4:0)	Description
JSTART	01100	Clocks the start-up sequence when StartClk is TCK
BYPASS	11111	Enables BYPASS
RESERVED	All other codes	Xilinx reserved instructions

The mandatory IEEE 1149.1 commands are supported in Virtex devices along with several Xilinx vendor specific commands. Virtex devices have a powerful command set. The EXTEST, INTEST, SAMPLE/PRELOAD, BYPASS, IDCODE, USERCODE, and HIGHZ instructions are all included. The TAP also supports two internal user-defined registers (USER1 and USER2) and configuration/readback of the device. The Virtex boundary-scan operations are independent of the mode selection. The boundary-scan mode in Virtex devices overrides the other mode selections. For this reason, boundary-scan instructions using the boundary-scan register (SAMPLE/PRELOAD, INTEST, EXTEST) must not be performed during configuration. All instructions except USER1 and USER2 are available before the Virtex device is configured. After configuration, all instructions are available.

JSTART is an instruction specific to the Virtex architecture and configuration flow. As described in [Table 2](#), the JSTART instruction clocks the startup sequence when the appropriate bitgen option is selected. The instruction does not work correctly without the correct bitgen option selected.

```
bitgen -g startupclk:jtagclk designName.ncd
```

For details on the standard boundary-scan instructions, EXTEST, INTEST, and BYPASS, please refer to the IEEE Standard. The user-defined registers (USER1/USER2) are described in a later section of this application note.

## Boundary-Scan Architecture

Virtex devices have several registers including all registers required by the IEEE 1149.1. In addition to the standard registers, the family contains optional registers for simplified testing and verification ([Table 3](#)).

Table 3: Virtex JTAG Registers

Register Name	Register Length	Description
Instruction register	5 bits	Holds current instruction OPCODE and captures internal device status.
Boundary scan register	3 bits per I/O	Controls and observes input, output, and output enable.
Bypass register	1 bit	Device bypass.
Identification register	32 bits	Captures device ID.
JTAG configuration register	32 bits	Allows access to the configuration bus when using the CFG_IN or CFG_OUT instructions.
USERCODE register	32 bits	Captures user-programmable code

## Boundary-Scan Register

The test primary data register is the boundary-scan register. The boundary-scan operation is independent of individual IOB configurations. Each IOB, bonded or unbonded, starts out as bidirectional with 3-state control. Later, it can be configured to be an input, output, or 3-state only. Therefore, three data register bits are provided per IOB ([Figure 2](#)).

When conducting a data register (DR) operation, the DR captures data in a parallel fashion during the CAPTURE-DR state. The data is then shifted out and replaced by new data during the SHIFT-DR state. For each bit of the DR an update latch is used to hold the input data stable during the next SHIFT-DR state. The data is then latched during UPDATE-DR state when the TCK is low.

The update latch is opened each time the TAP Controller enters the UPDATE-DR state. Care is necessary when exercising an INTEST or EXTEST to ensure the proper data has been latched before exercising the command. This is typically accomplished by using the SAMPLE/PRELOAD instruction.

Consider internal pull-ups and pull-down resistors when developing test vectors for opens and shorts testing. The boundary-scan mode determines if the IOB has a pull-up resistor. (Table 6).

Figure 2 is a description of the Virtex Boundary-Scan Architecture.

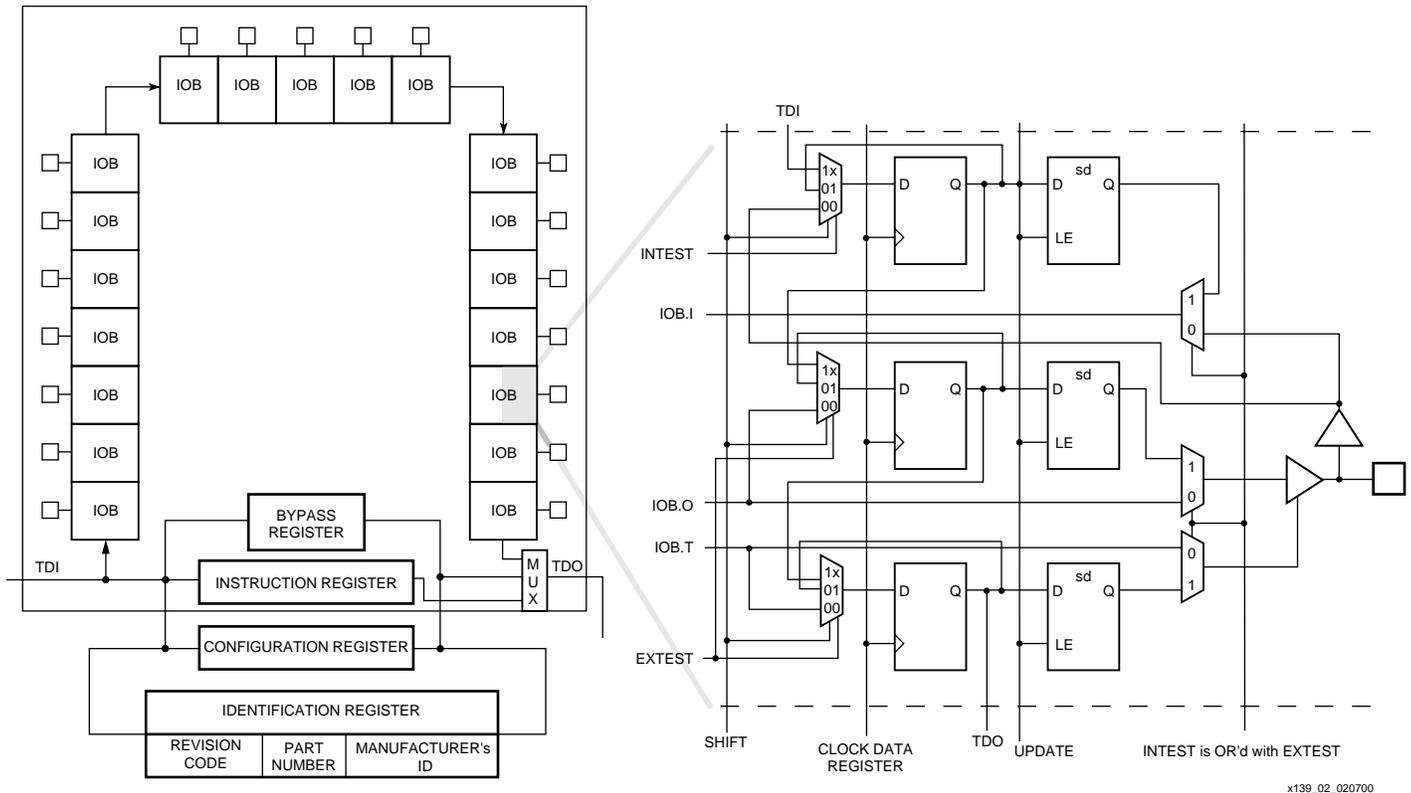


Figure 2: Virtex Series Boundary Scan Logic

### Bit Sequence

The order in each non-TAP IOB is described in this section. The input is first, followed by the output and finally the 3-state IOB control. The 3-state IOB control is closest to the TDO. The input-only pins contribute only the input bit to the boundary-scan I/O data register. The bit sequence of the device is obtainable from the “Boundary-Scan Description Language Files” (BSDL files) for the Virtex family. These files can be obtained from the Xilinx software download area. The bit sequence is invariant of the design. It always has the same bit order and the same number of bits.

### Bypass Register

The other standard data register is the single flip-flop BYPASS register. It directly passes data serially from the TDI pin to the TDO pin during a bypass instruction. This register is initialized to zero when the TAP controller is in the UPDATE-DR state.

### Instruction Register

The instruction register is a 5-bit register that loads the OPCODE necessary for the Virtex boundary-scan instruction set. This register loads the current OPCODE and captures internal device status.

## Configuration Register (Boundary-Scan)

The configuration register is a 32-bit register. This register allows access to the configuration bus and readback operations.

## Identification Register

The Virtex devices have an identification register, commonly referred to as the IDCODE register. This register is based upon the IEEE Standard 1149.1 and allows easy identification of the part being tested or programmed via boundary-scan. The general format of the IDCODE in the Virtex family is identified in [Figure 3](#). Specific Virtex IDCODES are listed in [Table 4](#).

Revision Code	Part Number		Manufacturers ID	LSB
	Family Code	Part Size Code		
31 ... 28	27 ... 21	20 ... 12	11 ... 1	0
XXXX	0000011	YYYYYYYYY	000 1001 001	1

Figure 3: Virtex Identification Register

Table 4: IDCODEs Assigned to Virtex FPGAs

FPGA	IDCODE
XCV50	v0610093h
XCV100	v0614093h
XCV150	v0618093h
XCV200	v061C093h
XCV300	v0620093h
XCV400	v0628093h
XCV600	v0630093h
XCV800	v0638093h
XCV1000	v0640093h

### Notes:

1. The “v” in the IDCODE is the revision code field.

## USERCODE Register

USERCODE is supported in the Virtex family as well. This register allows a user to specify a design-specific identification code. The USERCODE can be programmed into the device and read back for verification at a later time. The USERCODE is embedded into the bitstream during bitstream generation (bitgen -g UserID option) and is only valid after configuration.

## USER1, USER2 Registers

The USER1 and USER2 registers are only valid after configuration. These two registers must be defined by the user within the design. The registers can be accessed once created in the design by the TAP pins.

The BSCAN\_VIRTEX library macro is required when creating these registers. This symbol is only required for driving internal scan chains (USER1 and USER2). The BSCAN\_VIRTEX macro provides two user pins (SEL1 and SEL2) which determine the usage of USER1 or USER2 instructions respectively. For these instructions, two corresponding pins (TDO1 and TDO2) allow user scan data to be shifted out of TDO. In addition, there are individual clock pins (DRCK1 and DRCK2) for each user register. There is a common input pin (TDI) and shared output pins that represent the state of the TAP controller (RESET, SHIFT, and UPDATE). Unlike the earlier FPGA families where the BSCAN macro was required to dedicate the TAP pins for

boundary-scan, the Virtex TAP pins are dedicated, and do not require the BSCAN\_VIRTEX macro for normal boundary-scan instructions or operations.

Note that these are user-defined registers. The example (Figure 4) is one of many implementations. For HDL, the BSCAN\_VIRTEX macro needs to be instantiated in the design.

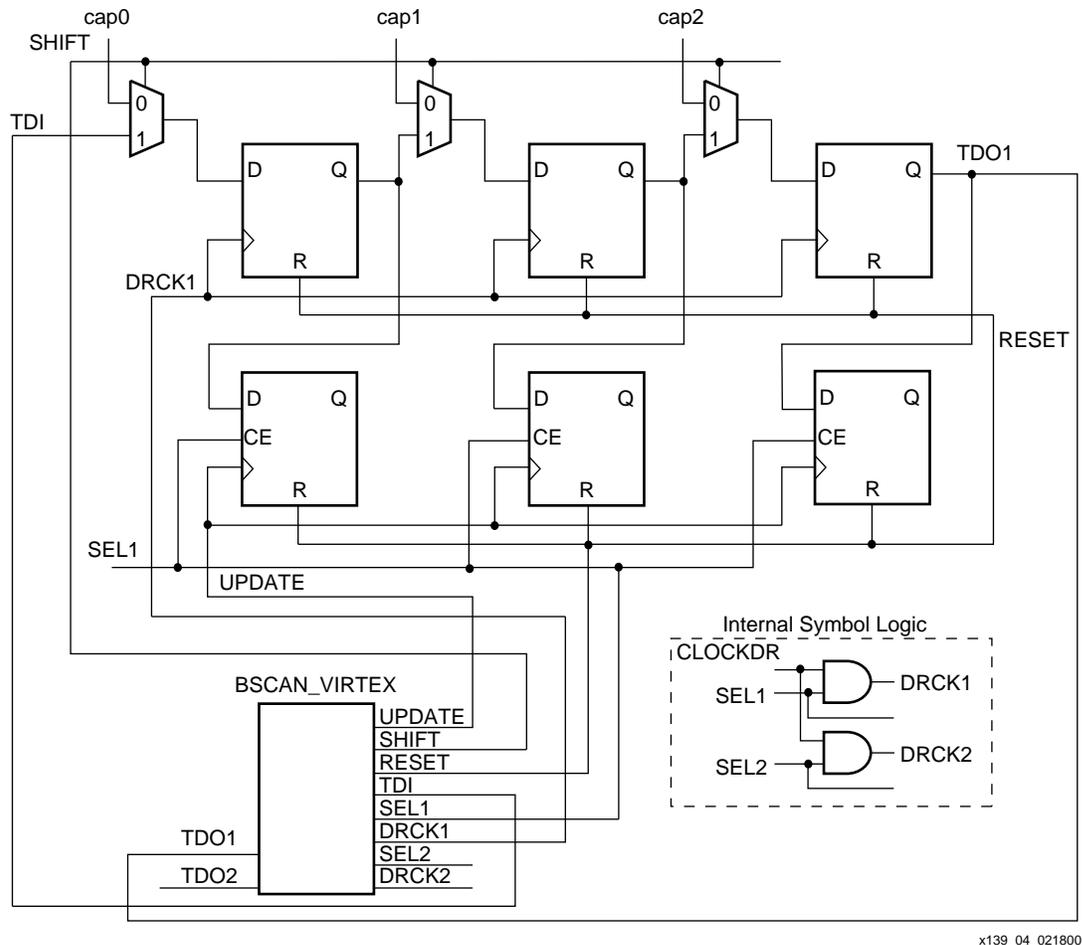
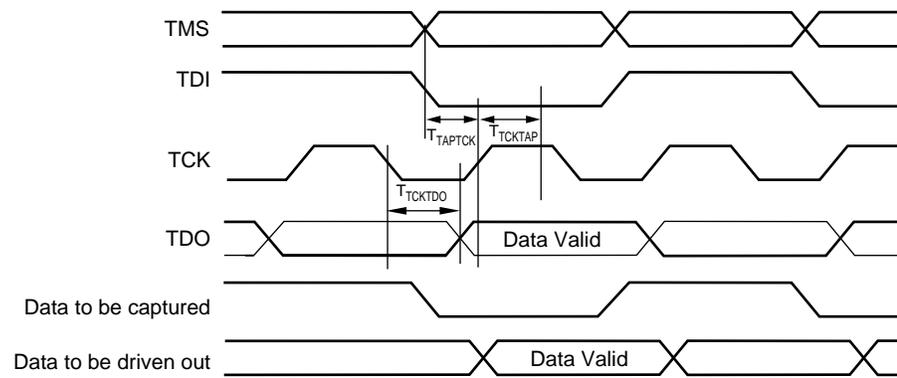


Figure 4: BSCAN\_VIRTEX (Example Usage)

## Using Boundary-Scan in Virtex Devices

Characterization data for some of the most commonly requested timing parameters are listed in [Table 5](#).

Please review the Application Note [XAPP138 “Virtex Configuration and Readback”](#) for further information on the Startup sequence, bitstream, and internal configuration registers referred to in this application note.



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Figure 5: Virtex Boundary Scan Port Timing Waveforms

Table 5: Boundary-Scan Port Timing Specifications

Symbol	Parameter	-6	-5	-4	Units
$T_{TAPTCK}$	TMS and TDI setup time before TCK	4.0	4.0	4.0	ns minimum
$T_{TCKTAP}$	TMS and TDI hold times after TCK	2.0	2.0	2.0	ns minimum
$T_{TCKTDO}$	TCK falling edge to TDO output valid	11.0	11.0	11.0	ns maximum
$F_{TCK}$	Maximum TCK clock frequency	33.0	33.0	33.0	MHz maximum

### Configuring through Boundary-Scan

One of the most common boundary-scan vendor specific instructions is the configure instruction. An individual Virtex device is configured via JTAG on power-up using the TAP. If the Virtex device is configured on power-up, it is recommended to tie the mode pins to one of the boundary-scan configuration mode settings; 101 (M2=1, M1=0, M0=1: contains no pull-ups on I/Os) or 001 (M2=0, M1=0, M0=1: contains pull-ups on I/Os). Table 6 shows the mode pin settings for all the configuration modes, including the boundary-scan modes.

Table 6: Virtex Configuration Modes

Configuration Mode	M2	M1	M0	Pull-ups
Master Serial	0	0	0	NO
Slave Serial	1	1	1	NO
SelectMAP	1	1	0	NO
Boundary-Scan	1	0	1	NO
Master Serial (w/Pull-ups)	1	0	0	YES
Slave Serial (w/Pull-ups)	0	1	1	YES
SelectMAP (w/Pull-ups)	0	1	0	YES
Boundary-Scan (w/Pull-ups)	0	0	1	YES

The configuration flow for Virtex device configuration with JTAG is shown in Figure 6. The sections that follow describe how the Virtex device can be configured as a single device via boundary-scan or as part of a multiple-device scan chain.

A configured device can be reconfigured by toggling the TAP and entering the CFG\_IN instruction after pulsing the  $\overline{\text{PROG}}$  pin or issuing the shut-down sequence. (Refer to the

“Reconfiguring a Virtex Device” section.) For additional details on power-up or the start-up sequence in Virtex devices, please refer to application note [XAPP138](#). In addition, application note [XAPP058](#) has detailed information on using Virtex devices in an embedded solution.

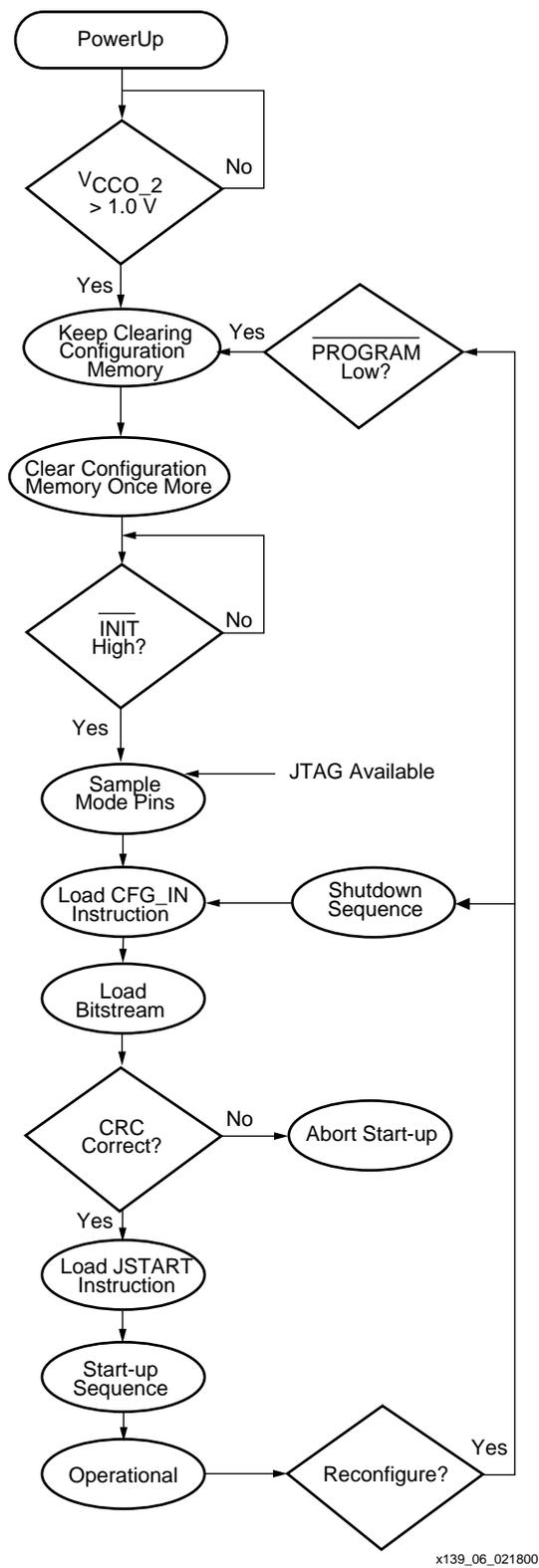


Figure 6: Device Configuration Flow Diagram

### Single Device Configuration

To configure a Virtex part as a single device via boundary-scan operations, the following steps should be followed. Ensure the bitstream is generated with the JTAG clock option:

```
bitgen -g startupclk:jtagclk designName.ncd
```

Also, when programming with JTAGProgrammer, verify that the most current version of software is used.

**Table 7** describes the TAP controller commands required to configure a Virtex device. Refer to **Figure 1** for the TAP controller states. These TAP controller commands are issued automatically if configuring the part with the JTAGProgrammer software.

**Table 7: Single Device Configuration Sequence**

TAP Controller Step Description		Set and Hold		# of Clocks
		TDI	TMS	TCK
1	On power-up, place a '1' on the TMS and clock the TCK five times. (This ensures starting in the TLR (Test-Logic-Reset) state)	X	1	5
2	Move into the RTI state	X	0	1
3	Move into the SELECT-IR state	X	1	2
4	Enter the SHIFT-IR state	X	0	2
5	Start loading the CFG_IN instruction <sup>(1)</sup>	0101	0	4
6	Load the last bit of CFG_IN instruction when exiting SHIFT-IR (defined in the IEEE standard)	0	1	1
7	Enter the SELECT-DR state	X	1	2
8	Enter the SHIFT-DR state	X	0	2
9	Shift in the Virtex bitstream. (bit <sub>N</sub> (MSB) is the first bit in the bitstream <sup>(1)</sup> )	bit <sub>1</sub> ... bit <sub>N</sub>	0	(# of bits in bitstream) - 1
10	Shift in the last bit of the bitstream. (bit <sub>0</sub> (LSB) is shifted on the transition to EXIT1-DR)	bit <sub>0</sub>	1	1
11	Enter UPDATE-DR state	X	1	1
12	Enter the SELECT-IR state	X	1	2
13	Move to the SHIFT-IR state	X	0	2
14	Start loading the JSTART instruction. <sup>(1)</sup> (The JSTART instruction initializes the startup sequence.)	1100	0	4
15	Load the last bit of the JSTART instruction.	0	1	1
16	Move to the SELECT-DR state	X	1	2
17	Move to SHIFT-DR and clock the STARTUP sequence. (by applying a minimum of 12 clock cycles to the TCK).	X	0	≥14
18	Move to the UPDATE-DR state	X	1	2
19	Return to the RTI state. (The device is now functional).	X	0	1

#### Notes:

1. In the TDI column, the right-most bit is shifted in first.

### Multiple Device Configuration

It is possible to configure multiple Virtex devices in a chain. The devices in the JTAG chain are configured one at a time. The multiple device configuration steps are described generally to be applied to any size chain. Ensure the bitstream is generated with the JTAG clock option:

```
bitgen -g startupclk:jtagclk designName.ncd
```

Refer to **Figure 1** for the following TAP controller steps:

1. On power-up, place a '1' on the TMS and clock the TCK five times. This ensures starting in the TLR (Test-Logic-Reset) state.
2. Load the CFG\_IN instruction into the target device (and BYPASS in all other devices.)
3. For a chain of Virtex devices, it may be necessary to shift in leading zeros before the bitstream if the value of N is not equal to zero. Use the following equation to determine the number of leading zeros for each bitstream. M is the targeted device position in the chain. As shown in **Figure 7**, the first device position in the chain is zero. N is the number of zeros required. Mod is the modulus operation.

$$N = 32 - \text{mod}\left(\frac{M}{32}\right)$$

$$N = 32 - M \text{ for } (M \leq 32)$$

**Example**

The third device, position 2, in **Figure 7** requires 30 leading zeros.

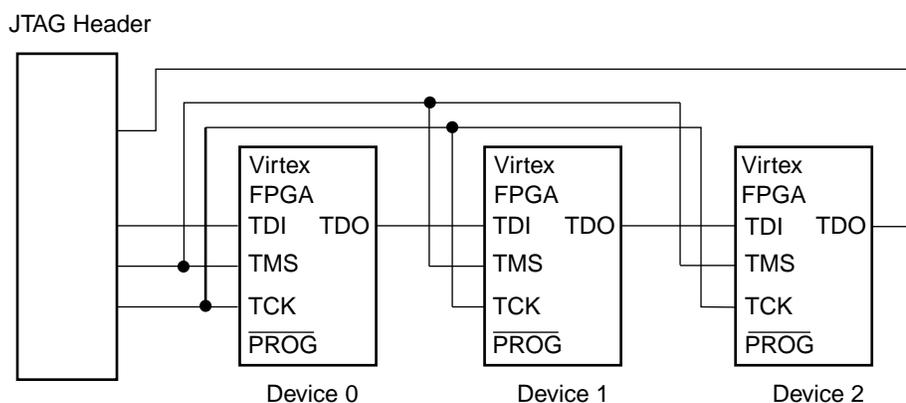
$$N = 32 - 2 \quad N = 30 \quad \text{number of leading 0s}$$

The following example is for position 47:

$$N = 32 - \text{mod}\left(\frac{47}{32}\right) \quad N = 17 \text{ number of leading 0s}$$

4. Go through RTI (RUN-TEST/IDLE)
- Repeat steps 2 through 4 for each successive device.
5. Load the JSTART command into all devices.
  6. Go to SHIFT-DR and clock TCK 12 times.

All devices are active at this point.



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**Notes:**

1. The  $\overline{\text{PROG}}$  pin should be deasserted during JTAG operations.

*Figure 7: Boundary Scan Chain of Devices*

**Reconfiguring Through Boundary Scan**

The ability of Virtex devices to perform partial reconfiguration is the reason that the configuration memory is not cleared when reconfiguring the device. When reconfiguring a

chain of devices, refer to step 3 on page 10. There are two methods to reconfigure Virtex devices without possible internal contention. The first method is to pulse the  $\overline{\text{PROG}}$  pin which will reset the internal configuration memory. The alternate method is to perform a shutdown sequence, placing the device in a safe state. The following shutdown sequence includes using internal registers. (For details on internal registers, please refer to application note: [XAPP138](#).)

1. Load the CFG\_IN instruction into the JTAG instruction register. Next, go to the SHIFT-DR state.
2. In the SHIFT-DR state, shift in the following sequences in steps 2 through 4. (This writes the COR (Configuration Option Register) with the SHUTDOWN bit = 1. It also indicates that the startup sequencer should perform a shutdown sequence.) The most significant bit (MSB) is the left bit and it is shifted in first.

```
0011 0000 0000 0001 0010 0000 0000 0001
```

```
-> Header: Write to COR
```

```
0000 0000 1010 0000 1011 1111 0010 1101
```

```
-> COR data sets SHUTDOWN = 1
```

3. Write the START command to the CMD (Command) register by shifting in the following data:

```
0011 0000 0000 0000 1000 0000 0000 0001
```

```
-> Header: Write to CMD
```

```
0000 0000 0000 0000 0000 0000 0000 0101
```

```
-> START command
```

4. Write the precalculated CRC value to the CRC (Cyclic Redundancy Check) register, or write the RCRC (Reset CRC Register) command to the CMD register as shown:

```
0011 0000 0000 0000 1000 0000 0000 0001
```

```
-> Header: Write to CMD
```

```
0000 0000 0000 0000 0000 0000 0000 0111
```

```
-> RCRC command
```

```
0000 0000 0000 0000 0000 0000 0000 0000
```

```
-> flush pipe
```

5. Now proceed to the SHIFT-IR and load the JTAG JSTART command into the instruction register.
6. Go to the SHIFT-DR and clock TCK 12 times to clock the shutdown sequence.
7. Proceed to the SHIFT-IR state and load the CFG\_IN instruction again.
8. In the SHIFT-DR state, shift in the sequences in steps 8 and 9. This writes the AGHIGH command to the CMD register to assert the GHIGH\_B signal. This prevents contention while writing configuration data.

```
0011 0000 0000 0000 1000 0000 0000 0001
```

```
-> Header: Write to CMD
```

```
0000 0000 0000 0000 0000 0000 0000 1000
```

```
-> AGHIGH command asserts GHIGH_B
```

9. Write the COR with SHUTDOWN = 0 and go to RTI (RUN-TEST/IDLE) by shifting in the following sequence:

```
0011 0000 0000 0001 0010 0000 0000 0001
```

```
-> Header: Write to COR
```

```
0000 0000 1010 0000 0011 1111 0010 1101
```

```
-> COR data sets SHUTDOWN = 0
```

```
0000 0000 0000 0000 0000 0000 0000 0000
-> flush pipe
```

## Debugging Configuration

To verify successful configuration, there are several options. Some of the most helpful verification steps include using the TAP pins and the readback command. Using the Virtex TAP controller and status pins is discussed first.

When using the TAP controller pins, TDO is only driven in the SHIFT-DR and SHIFT-IR state. If the output of the TDO can be changed via an external pull-up, the TAP is not in SHIFT-IR or SHIFT-DR. If the TAP can be controlled precisely, use this to test the application.

In JTAG configuration, the status pin (DONE) functions the same as in the other configuration modes. The DONE pin can be monitored to determine if a bitstream has been completely loaded into the device. If DONE is Low, the entire bitstream has not been sent or the start-up sequence is not finished. If DONE is High, the entire bitstream has been received correctly. The INIT pin functions similar to a normal INIT but will not indicate a configuration error in boundary-scan configuration.

If the DONE pin is not asserted High, there are several possible reasons.

1. The bitstream option, `bitgen -g startupclk:jtagclk` described in the section "Software Support and Data Files", may not have been used.
2. The JSTART instruction was not issued.
3. There was an error in the bitstream.

In addition to the external pin monitoring, an internal test can be conducted. The second method includes the following steps to capture the contents of the internal device status register:

1. Move the TAP to the TLR (Test-Logic-Reset) state.
2. Go to the SHIFT-IR state and load in the CFG\_IN instruction.
3. Go to the SHIFT-DR state and shift in the following 64-bit pattern with the MSB (left most bit), shifted in first.

```
0010 1000 0000 0000 1110 0000 0000 0001
```

```
-> Header: Read Status Register
```

```
0000 0000 0000 0000 0000 0000 0000 0000
```

```
-> flush pipe
```

4. After shifting in this pattern, load the CFG\_OUT instruction in the SHIFT-IR state.
5. Move to the SHIFT-DR and clock TCK 32 times while reading TDO. The data seen on TDO is the contents of the status register. The last bit out is a one if a CRC error occurred. If successful, it should be:

```
0000 0000 0000 0000 0111 1111 0101 1110
          CRC Bit
```

The device status register also gives the status of the DONE and INIT signals. For information on the status register, refer to [Figure 8](#) and the application note: [XAPP151](#).



```
bitgen -g startupclk:jtagclk designName.ncd
```

For Readback operations this option can be used:

```
bitgen -w -l -m -g readback
```

Readback is not supported in the current version of JTAGProgrammer Software.

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## Revision History

The following table shows the revision history for this document.

Date	Revision #	Activity
10/28/99	1.0	Initial release
12/8/99	1.1	Fixed error on AGHIGH command on page 11.
2/18/00	1.2	Reformatted to one column.