



XAPP333 (v1.7) December 24, 2002

# CoolRunner CPLD I<sup>2</sup>C Bus Controller Implementation

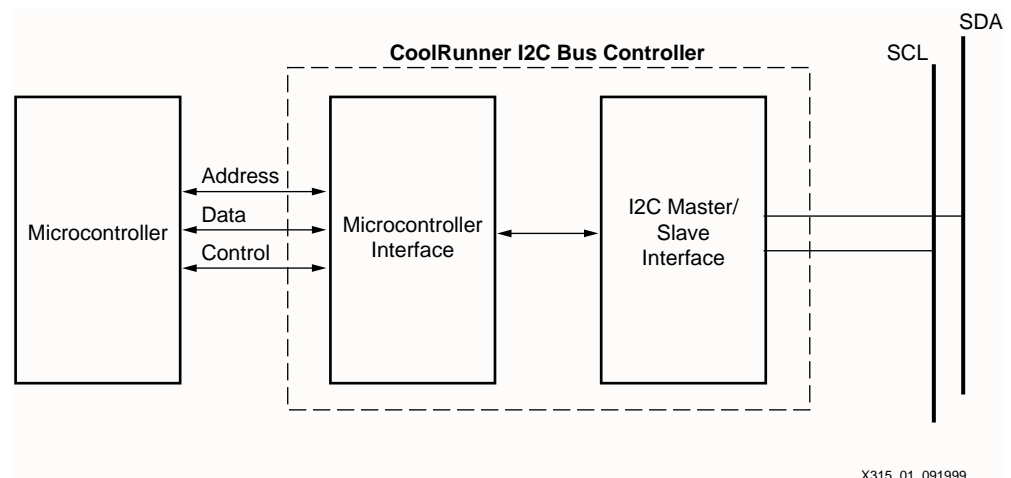
## Summary

This document details the VHDL implementation of an I<sup>2</sup>C controller in a Xilinx CoolRunner™ 256-macrocell CPLD. CoolRunner CPLDs are the lowest power CPLDs available, making this the perfect target device for an I<sup>2</sup>C controller. To obtain the VHDL code described in this document, go to section [VHDL Code Download](#), page 19 for instructions. This design fits both XPLA3 and CoolRunner-II CPLDs. For the CoolRunner-II CPLD version, please refer to [XAPP385, CoolRunner-II CPLD I<sup>2</sup>C Bus Controller Implementation](#).

## Introduction

The I<sup>2</sup>C bus is a popular serial, two-wire interface used in many systems because of its low overhead. The two-wire interface minimizes interconnections so ICs have fewer pins, and the number of traces required on printed circuit boards is reduced. Capable of 100 KHz operation, each device connected to the bus is software addressable by a unique address with a simple Master/Slave protocol.

The CoolRunner I<sup>2</sup>C Controller design contains an asynchronous microcontroller (μC) interface and provides I<sup>2</sup>C Master/Slave capability. It is intended to be used with a microcontroller (μC) or microprocessor (μP) as shown in [Figure 1](#).



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Figure 1: CoolRunner I<sup>2</sup>C Bus Controller

## I<sup>2</sup>C Background

This section will describe the main protocol of the I<sup>2</sup>C bus. For more details and timing diagrams, please refer to the I<sup>2</sup>C specification.

The I<sup>2</sup>C bus consists of two wires, serial data (SDA) and serial clock (SCL), which carry information between the devices connected to the bus. The number of devices connected to the same bus is limited only by a maximum bus capacitance of 400 pF. Both the SDA and SCL lines are bidirectional lines, connected to a positive supply voltage via a pull-up resistor. When

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the bus is free, both lines are High. The output stages of devices connected to the bus must have an open-drain or open-collector in order to perform the wired-AND function.

Each device on the bus has a unique address and can operate as either a transmitter or receiver. In addition, devices can also be configured as Masters or Slaves. A Master is the device which initiates a data transfer on the bus and generates the clock signals to permit that transfer. Any other device that is being addressed is considered a Slave. The I<sup>2</sup>C protocol defines an arbitration procedure that insures that if more than one Master simultaneously tries to control the bus, only one is allowed to do so and the message is not corrupted. The arbitration and clock synchronization procedures defined in the I<sup>2</sup>C specification are supported by the CoolRunner I<sup>2</sup>C Controller.

Data transfers on the I<sup>2</sup>C bus are initiated with a START condition and are terminated with a STOP condition. Normal data on the SDA line must be stable during the High period of the clock. The High or Low state of the data line can only change when SCL is Low. The START condition is a unique case and is defined by a High-to-Low transition on the SDA line while SCL is High. Likewise, the STOP condition is a unique case and is defined by a Low-to-High transition on the SDA line while SCL is High. The definitions of data, START, and STOP insure that the START and STOP conditions will never be confused as data. This is shown in Figure 2.

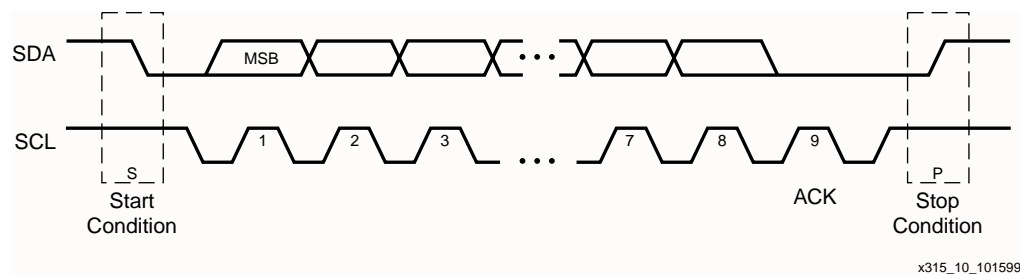


Figure 2: Data Transfer on the I<sup>2</sup>C Bus

Each data packet on the I<sup>2</sup>C bus consists of eight bits of data followed by an acknowledge bit so one complete data byte transfer requires nine clock pulses. Data is transferred with the most significant bit first (MSB). The transmitter releases the SDA line during the acknowledge bit and the receiver of the data transfer must drive the SDA line low during the acknowledge bit to acknowledge receipt of the data. If a Slave-receiver does not drive the SDA line Low during the acknowledge bit, this indicates that the Slave-receiver was unable to accept the data and the Master can then generate a STOP condition to abort the transfer. If the Master-receiver does not generate an acknowledge, this indicates to the Slave-transmitter that this byte was the last byte of the transfer.

Standard communication on the bus between a Master and a Slave is composed of four parts: START, Slave address, data transfer, and STOP. The I<sup>2</sup>C protocol defines a data transfer format for both 7-bit and 10-bit addressing. The implementation of the I<sup>2</sup>C controller in the Xilinx CoolRunner CPLD supports the seven-bit address format. After the START condition, a Slave address is sent. This address is seven bits long followed by an eighth-bit which is the read/write bit. A "1" indicates a request for data (read) and a "0" indicates a data transmission (write). Only the Slave with the calling address that matches the address transmitted by the Master responds by sending back an acknowledge bit by pulling the SDA line Low on the ninth clock.

Once successful Slave addressing is achieved, the data transfer can proceed byte-by-byte as specified by the read/write bit. The Master can terminate the communication by generating a STOP signal to free the bus. However, the Master may generate a START signal without generating a STOP signal first. This is called a repeated START.

## CoolRunner I<sup>2</sup>C Controller

The CoolRunner CPLD implementation of the I<sup>2</sup>C Controller supports the following features:

- Microcontroller interface

- Master or Slave operation
- Multi-master operation
- Software selectable acknowledge bit
- Arbitration lost interrupt with automatic mode switching from Master to Slave
- Calling address identification interrupt with automatic mode switching from Master to Slave
- START and STOP signal generation/detection
- Repeated START signal generation
- Acknowledge bit generation/detection
- Bus busy detection
- 100 KHz operation

## Signal Descriptions

The I/O signals of the CoolRunner I<sup>2</sup>C controller are described in Table 1. Pin numbers have not been assigned to this design, this can be done to meet the system requirements of the designer.

Table 1: CoolRunner I<sup>2</sup>C Controller Signal Description

| Name           | Direction     | Description   |
|----------------|---------------|---|
| SDA            | Bidirectional | I <sup>2</sup> C Serial Data.   |
| SCL            | Bidirectional | I <sup>2</sup> C Serial Clock.  |
| ADDR_BUS[23:0] | Input         | μC Address Bus.   |
| DATA_BUS[7:0]  | Bidirectional | μC Data Bus.  |
| AS             | Input         | <b>Address Strobe.</b> Active Low μC handshake signal indicating that the address present on the address bus is valid.  |
| DS             | Input         | <b>Data Strobe.</b> Active Low μC handshake signal indicating that the data present on the data bus is valid or that the μC is no longer driving the data bus and the I <sup>2</sup> C Controller can place data on the data bus.                                   |
| R_W            | Input         | <b>Read/Write.</b> "1" indicates a read, "0" indicates a write.   |
| DTACK          | Output        | <b>Data Transfer Acknowledge.</b> Active Low μC handshake signal indicating that the I <sup>2</sup> C Controller has placed valid data on the data bus for a read cycle or that the I <sup>2</sup> C Controller has received the data on the bus for a write cycle. |

Table 1: CoolRunner I<sup>2</sup>C Controller Signal Description

|     |        |  |
|-----|--------|--|
| IRQ | Output | <b>Interrupt Request.</b> Active Low.  |
| MCF | Output | <b>Data Transferring Bit.</b> While one byte of data is being transferred, this bit is cleared. It is set by the falling edge of the ninth clock of a byte transfer. This bit is used to signal the completion of a byte transfer to the $\mu$ C.        |
| CLK | Input  | <b>Clock.</b> This clock is input from the system. The constants used in generating a 100 KHz SCL signal assumes the frequency to be 1.832 MHz. Different clock frequencies can be used, but the constants in the VHDL source code must be recalculated. |

### Block Diagram

The block diagram of the CoolRunner I<sup>2</sup>C Controller, shown in Figure 3 was broken into two major blocks, the  $\mu$ C interface and the I<sup>2</sup>C interface.

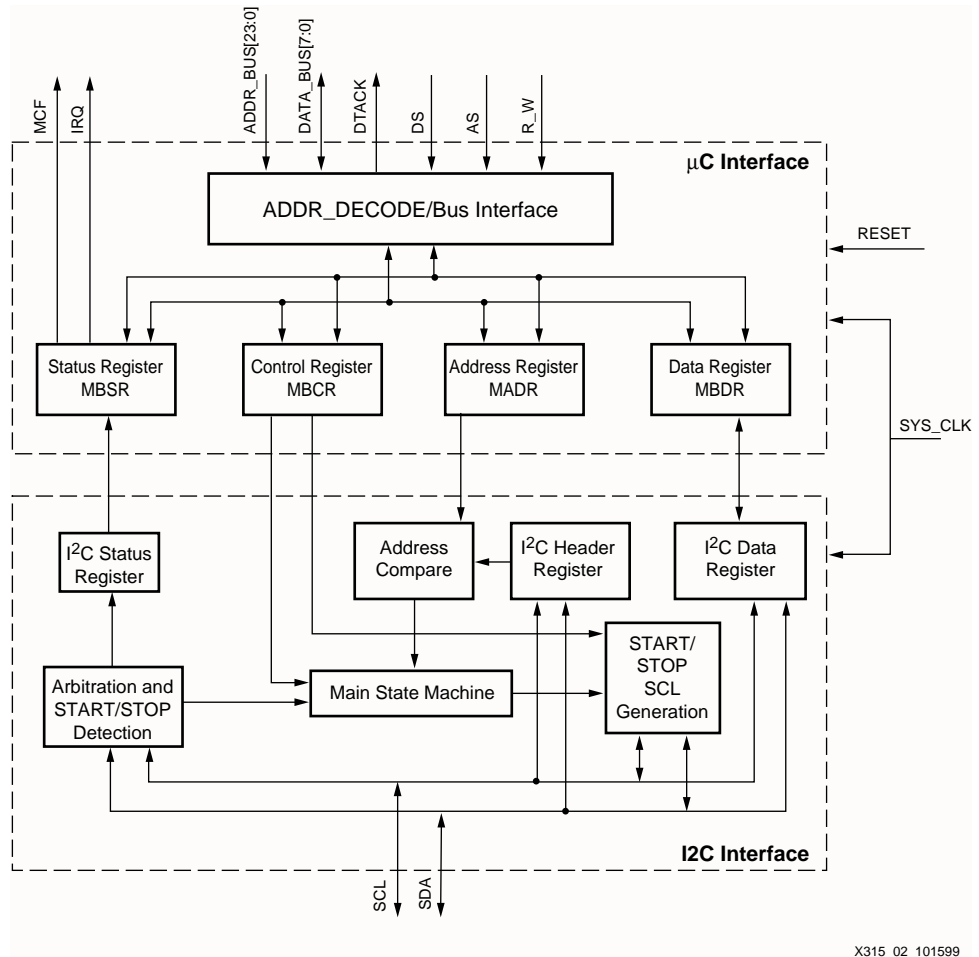
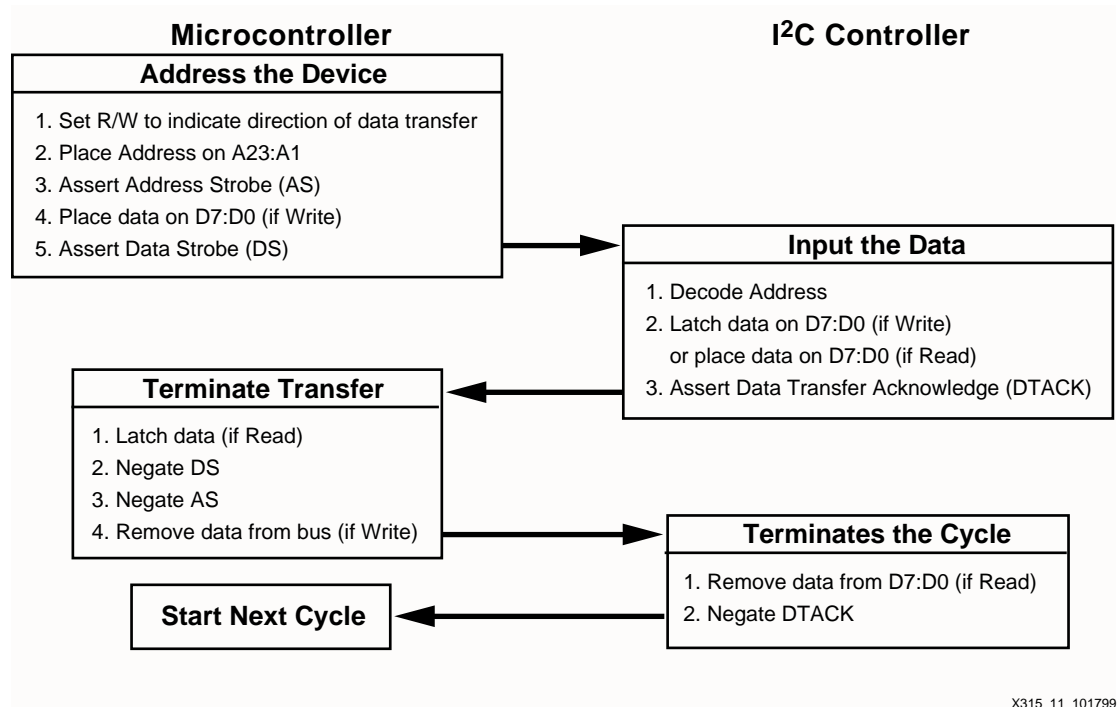


Figure 3: CoolRunner I<sup>2</sup>C Controller

## Microcontroller Logic

The  $\mu$ C interface for the I<sup>2</sup>C controller design supports an asynchronous byte-wide bus protocol. This protocol is the method in which the  $\mu$ C reads and writes the registers in the design and is shown in Figure 4.

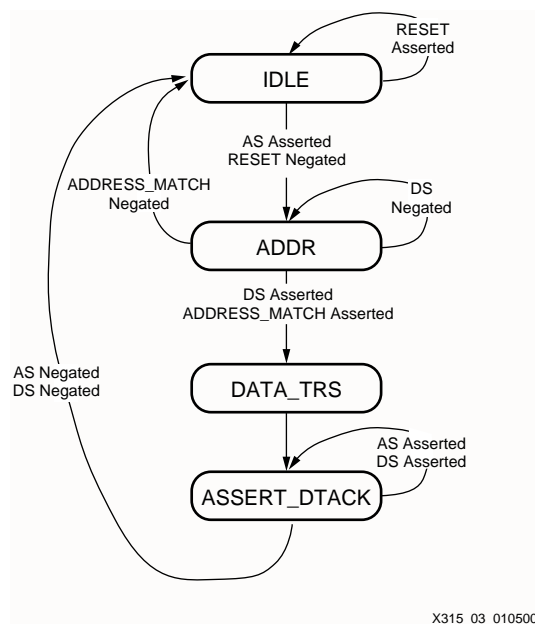


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Figure 4:  $\mu$ C Read/Write Protocol

## Address Decode/Bus Interface Logic

The  $\mu$ C bus protocol is implemented in the CoolRunner I<sup>2</sup>C Controller in the state machine shown in Figure 5.



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Figure 5:  $\mu$ C Bus Interface State Machine

In the first cycle, the  $\mu$ C places the address on the address bus, sets the read/write line to the correct state, and asserts address strobe (AS) and data strobe (DS). Address strobe indicates that the address present on the address bus is valid. If this is a write cycle, the  $\mu$ C also places the data on the data bus and DS indicates that valid data is present on the data bus. If this is a read cycle, the  $\mu$ C 3-states the data bus and DS indicates that the CoolRunner I<sup>2</sup>C Controller can place data on the data bus.

Upon the assertion of AS, the CoolRunner I<sup>2</sup>C Controller transitions to the ADDR state to decode the address and determine if it is the device being addressed. The enables for the internal registers are set in this state. If the CoolRunner I<sup>2</sup>C Controller is being addressed and DS is asserted, the CoolRunner I<sup>2</sup>C controller progresses to the DATA\_TRS state. If this is a read cycle, the requested data is placed on the bus and if this is a write cycle, the data from the data bus is latched in the addressed register. The CoolRunner I<sup>2</sup>C Controller automatically progresses to the ASSERT\_DTACK state and asserts DTACK indicating that the data requested is ready if a read cycle or that the data has been received if a write cycle.

Upon the assertion of DTACK, the  $\mu$ C either removes data from the bus if this is a write cycle, or latches the data present on the bus if this is a read cycle. The read/write line is set to read and AS and DS are negated to indicate that the data transfer is complete. The negation of AS and DS causes the CoolRunner I<sup>2</sup>C Controller to negate DTACK and transition to the IDLE state.

## CoolRunner I<sup>2</sup>C Controller Registers

The base address used for address decoding is set in the VHDL code via the constant `BASE_ADDRESS`. The base address is the upper 16 bits of the address bus. The lower address bits determine which register is being accessed.

The registers supported in the CoolRunner I<sup>2</sup>C Controller are described in the [Table 2](#). The  $\mu$ C interface logic of the CoolRunner I<sup>2</sup>C Controller handles the reading and writing of these registers by the  $\mu$ C and supplies and/or retrieves these bits to/from the I<sup>2</sup>C interface logic.

*Table 2: I<sup>2</sup>C Controller Registers*

| Address       | Register | Description                        |
|---------------|----------|------------------------------------|
| MBASE + \$8Dh | MADR     | I <sup>2</sup> C Address Register  |
| MBASE + \$8Fh | MBCR     | I <sup>2</sup> C Control Register  |
| MBASE + \$93h | MBSR     | I <sup>2</sup> C Status Register   |
| MBASE + \$95h | MBDR     | I <sup>2</sup> C Data I/O Register |

### Address Register (MADR)

This field contains the specific Slave address to be used by the I<sup>2</sup>C Controller. This register is read/write. ([Table 3](#)).

*Table 3: Address Register Bits*

| Bit Location | Name          | $\mu$ C Access | Description   |
|--------------|---------------|----------------|---|
| 7-1          | Slave Address | Read/Write     | Address used by the I <sup>2</sup> C controller when in Slave mode. |
| 0            | -             | -              | Unused  |

### Control Register (MBCR)

This register contains the bits to configure the I<sup>2</sup>C controller. (Table 4).

Table 4: Control Register Bits

| Bit Location | Name     | $\mu$ C Access | Description  |
|--------------|----------|----------------|--|
| 7            | MEN      | Read/Write     | <b>I<sup>2</sup>C Controller Enable.</b> This bit must be set before any other MBCR bits have any effect<br>"1" enables the I <sup>2</sup> C controller<br>"0" resets and disables the I <sup>2</sup> C controller   |
| 6            | MIEN     | Read/Write     | <b>Interrupt Enable.</b><br>"1" enables interrupts. An interrupt occurs if MIF bit in the status register is also set<br>"0" disable interrupts but does not clear any currently pending interrupts  |
| 5            | MSTA     | Read/Write     | <b>Master/Slave Mode Select.</b> When the $\mu$ C changes this bit from "0" to "1", the I <sup>2</sup> C controller generates a START condition in Master mode. When this bit is cleared, a STOP condition is generated and the I <sup>2</sup> C controller switches to Slave mode. If this bit is cleared, however, because arbitration for the bus has been lost, a STOP condition is not generated.                             |
| 4            | MTX      | Read/Write     | <b>Transmit/Receive Mode Select.</b> This bit selects the direction of Master/Slave transfers.<br>"1" selects an I <sup>2</sup> C Master transmit<br>"0" selects an I <sup>2</sup> C Master receive  |
| 3            | TXAK     | Read/Write     | <b>Transmit Acknowledge Enable.</b> This bit specifies the value driven onto the SDA line during acknowledge cycles for both Master and Slave receivers<br>"1" - ACK bit = "1" - no acknowledge<br>"0" - ACK bit = "0" - acknowledge<br><br>Since Master receivers indicate the end of data reception by not acknowledging the last byte of the transfer, this bit is the means for the $\mu$ C to end a Master receiver transfer. |
| 2            | RSTA     | Read/Write     | <b>Repeated Start.</b> Writing a "1" to this bit generates a repeated START condition on the bus if the I <sup>2</sup> C controller is the current bus Master. This bit is always read as "0". Attempting a repeated START at the wrong time if the bus is owned by another Master results in a loss of arbitration.   |
| 1-0          | Reserved |                |  |

### Status Register (MBSR)

This register contains the status of the I<sup>2</sup>C controller. This status register is read-only with the exception of the MIF and MAL bits, which are software clearable. All bits are cleared upon reset except the MCF and RXAK bits. (Table 5).

Table 5: Status Register Bits

| Bit Location | Name     | μC Access                  | Description  |
|--------------|----------|----------------------------|--|
| 7            | MCF      | Read                       | <p><b>Data Transferring Bit.</b> While one byte of data is being transferred, this bit is cleared. It is set by the rising edge of SCL during the acknowledge cycle of the transfer and is only High for this SCL clock period.</p> <p>"1" transfer is complete<br/>                     "0" transfer in progress</p> <p>Note that in the CoolRunner I<sup>2</sup>C controller, this bit is also an output pin so that a register read cycle is not required to determine that a transfer is complete.</p> |
| 6            | MAAS     | Read                       | <p><b>Addressed as Slave Bit.</b> When the address on the I<sup>2</sup>C bus matches the Slave address in the MADR register, the I<sup>2</sup>C controller is being addressed as a Slave and switches to Slave mode.</p>   |
| 5            | MBB      | Read                       | <p><b>Bus Busy Bit.</b> This bit indicates the status of the I<sup>2</sup>C bus. This bit is set when a START condition is detected and cleared when a STOP condition is detected.</p> <p>"1" indicates the bus is busy<br/>                     "0" indicates the bus is idle</p>   |
| 4            | MAL      | Read<br>Software Clearable | <p><b>Arbitration Lost Bit.</b> This bit is set by hardware when arbitration for the I<sup>2</sup>C bus is lost. This bit must be cleared by the μC software writing a "0" to this bit.</p>  |
| 3            | Reserved |                            |  |



Table 5: Status Register Bits (Continued)

| Bit Location | Name | μC Access                     | Description  |
|--------------|------|-------------------------------|--|
| 2            | SRW  | Read                          | <p><b>Slave Read/Write Bit.</b> When the I<sup>2</sup>C controller has been addressed as a Slave (MAAS is set), this bit indicates the value of the read/write bit sent by the Master. This bit is only valid when a complete transfer has occurred and no other transfers have been initiated.</p> <p>"1" indicates Master reading from Slave<br/>"0" indicates Master writing to Slave</p> |
| 1            | MIF  | Read<br>Software<br>Clearable | <p><b>Interrupt Bit.</b> This bit is set when an interrupt is pending, which causes a processor interrupt request if MIEN is set. This bit must be cleared by the μC software writing a "0" to this bit in the interrupt service routine.</p>  |
| 0            | RXAK | Read                          | <p><b>Received Acknowledge Bit.</b> This bit reflects the value of the SDA signal during the acknowledge cycle of the transfer.</p> <p>"1" indicates that no acknowledge was received<br/>"0" indicates that an acknowledge was received</p>   |

### Data Register (MBDR)

This register contains data to/from the I<sup>2</sup>C bus. Physically, this register is implemented by two byte-wide registers at the same address, one for the I<sup>2</sup>C transmit data and one for the I<sup>2</sup>C received data. This eliminates any possible contention between the μC and the CoolRunner I<sup>2</sup>C Controller. Since these registers are at the same address they appear as the same register to the μC and will continue to be described as such. In transmit mode, data written into this register is output on the I<sup>2</sup>C bus, in receive mode, this register contains the data received from the I<sup>2</sup>C bus. Note that in receive mode, it is assumed that the μC will be able to read this register during the next I<sup>2</sup>C transfer. The received I<sup>2</sup>C data is placed in this register after each complete transfer, the I<sup>2</sup>C interface logic does not wait for an indication from the μC that this register has been read before proceeding with the next transfer. (Table 6)

Table 6: I<sup>2</sup>C Data Register Bit

| Bit Location | Name  | μC Access  | Description           |
|--------------|-------|------------|-----------------------|
| 7-0          | D7:D0 | Read/Write | I <sup>2</sup> C Data |

## I<sup>2</sup>C Interface Logic

The I<sup>2</sup>C bus interface logic consists of several different processes as seen in Figure 3. Control bits from the μC interface registers determine the behavior of these processes.

### Arbitration

Arbitration of the I<sup>2</sup>C bus is lost in the following circumstances:

- The SDA signal is sampled as a "0" when the Master outputs a "1" during an address or data transmit cycle
- The SDA signal is sampled as a "0" when the Master outputs a "1" during the acknowledge bit of a data receive cycle
- A start cycle is attempted when the bus is busy

- A repeated start cycle is requested in Slave mode
- A STOP condition is detected when the Master did not request it

If the CoolRunner I<sup>2</sup>C Controller is in Master mode, the outgoing SDA signal is compared with the incoming SDA signal to determine if control of the bus has been lost. The SDA signal is checked only when SCL is High during all cycles of the data transfer except for acknowledge cycles to insure that START and STOP conditions are not generated at the wrong time. If the outgoing SDA signal and the incoming SDA signals differ, then arbitration is lost and the MAL bit is set. At this point, the CoolRunner I<sup>2</sup>C Controller switches to Slave mode and resets the MSTA bit.

The CoolRunner I<sup>2</sup>C design will not generate a START condition while the bus is busy, however, the MAL bit will be set if the  $\mu$ C requests a START or repeated START while the bus is busy. The MAL bit is also set if a STOP condition is detected when this Master did not generate it.

If arbitration is lost during a byte transfer, SCL continues to be generated until the byte transfer is complete.

### START/STOP Detection

This process monitors the SDA and SCL signals on the I<sup>2</sup>C bus for START and STOP conditions. When a START condition is detected, the Bus Busy bit is set. This bit stays set until a STOP condition is detected. The signals, DETECT\_START and DETECT\_STOP are generated by this process for use by other processes in the logic. Note that this logic detects the START and STOP conditions even when the CoolRunner I<sup>2</sup>C Controller is the generator of these conditions.

### Generation of SCL, SDA, START and STOP Conditions

This process generates the SCL and SDA signals output on the I<sup>2</sup>C bus when in Master mode. The clock frequency of the SCL signal is ~100 KHz and is determined by dividing down the input clock. The number of input clock cycles required for generation of a 100 KHz SCL signal is set by the constant CNT\_100 KHZ and is currently calculated for a system clock of 1.832 MHz. This constant can easily be modified by a designer based on the clock available in the target system. Likewise, the constants START\_HOLD and DATA\_HOLD contain the number of system clock cycles required to meet the I<sup>2</sup>C requirements on hold time for the SDA lines after generating a START condition and after outputting data.

The state machine that generates SCL and SDA when in Master mode is shown in Figure 6. Note that SCL and SDA are held at the default levels if the bus is busy. This state machine generates the controls for the system clock counter.

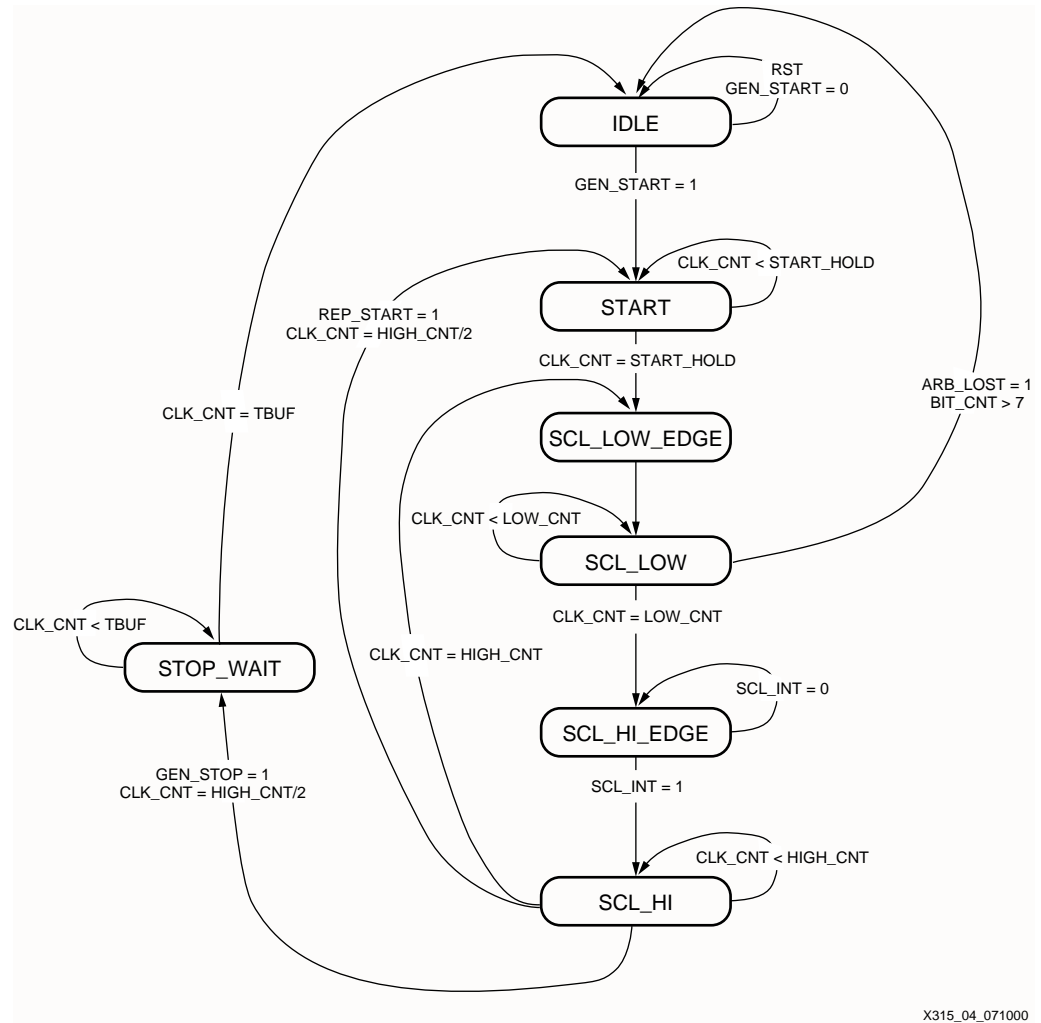


Figure 6: SCL, SDA, START, and STOP Generation State Machine

The internal SDA signal output from this design is either the SDA signal generated by this state machine for START and STOP conditions or the data from the MBDR register when the CoolRunner I<sup>2</sup>C Controller is in transmit mode. Note that both SCL and SDA are open-collector outputs, therefore, they are only driven to a "0". When a "1" is to be output on these signals, the CoolRunner I<sup>2</sup>C Controller 3-states their output buffers. The logic in the design will set internal SDA and SCL signals to "1" or "0". These internal signals actually control the output enable of the 3-state buffer for these outputs.

In the IDLE state, SCL and SDA are 3-stated, allowing any Master to control the bus. Once a request has entered to generate a start condition, the CoolRunner I<sup>2</sup>C Controller is in Master mode, and the bus is not busy, the state machine transitions to the START state.

The START state holds SCL High, but drives SDA Low to generate a START condition. The system clock counter is started and the state machine stays in this state until the required hold time is met. At this point, the next state is SCL\_LOW\_EDGE.

The SCL\_LOW\_EDGE state simply creates a falling edge on SCL and resets the system clock counter. On the next clock edge, the state machine moves to state SCL\_LOW. In this state, the SCL line is held Low and the system clock counter begins counting. If the REP\_START signal

is asserted then the SDA signal will be set High, if the GEN\_STOP signal is asserted, SDA will be set Low.

When the SCL low time has been reached, the state machine will transition to the IDLE state if arbitration has been lost and the byte transfer is complete to insure that SCL continues until the end of the transfer. Otherwise the next state is the SCL\_HI\_EDGE state.

The SCL\_HI\_EDGE state generates a rising edge on SCL by setting SCL to "1". Note, however, that the state machine will not transition to the SCL\_HI state until the sampled SCL signal is also High to obey the clock synchronization protocol of the I<sup>2</sup>C specification. Clock synchronization is performed using the wired-AND connection of the SCL line. The SCL line will be held Low by the device with the longest low period. Devices with shorter low periods enter a high wait state until all devices have released the SCL line and it goes High. Therefore the SCL\_HI\_EDGE state operates as the high wait state as the SCL clock is synchronized.

The SCL\_HI state then starts the system clock counter to count the high time for the SCL signal. If a repeated START or a STOP condition has been requested, the state machine will transition to the appropriate state after half of the SCL high time so that the SDA line can transition as required. If neither of these conditions has been requested, then the state machine transitions to the SCL\_LOW\_EDGE state when the SCL high time has been achieved.

The STOP\_WAIT state is used to insure that the hold time requirement after a STOP condition is met.

### I<sup>2</sup>C Interface Main State Machine

The main state machine for the I<sup>2</sup>C Interface logic is shown in [Figure 7](#). This state machine is the same for both Slave and Master modes. In each state, the mode is checked to determine the proper output values and next state conditions. This allows for immediate switching from

Master to Slave mode if arbitration is lost or if the CoolRunner I<sup>2</sup>C Controller is addressed as a Slave.

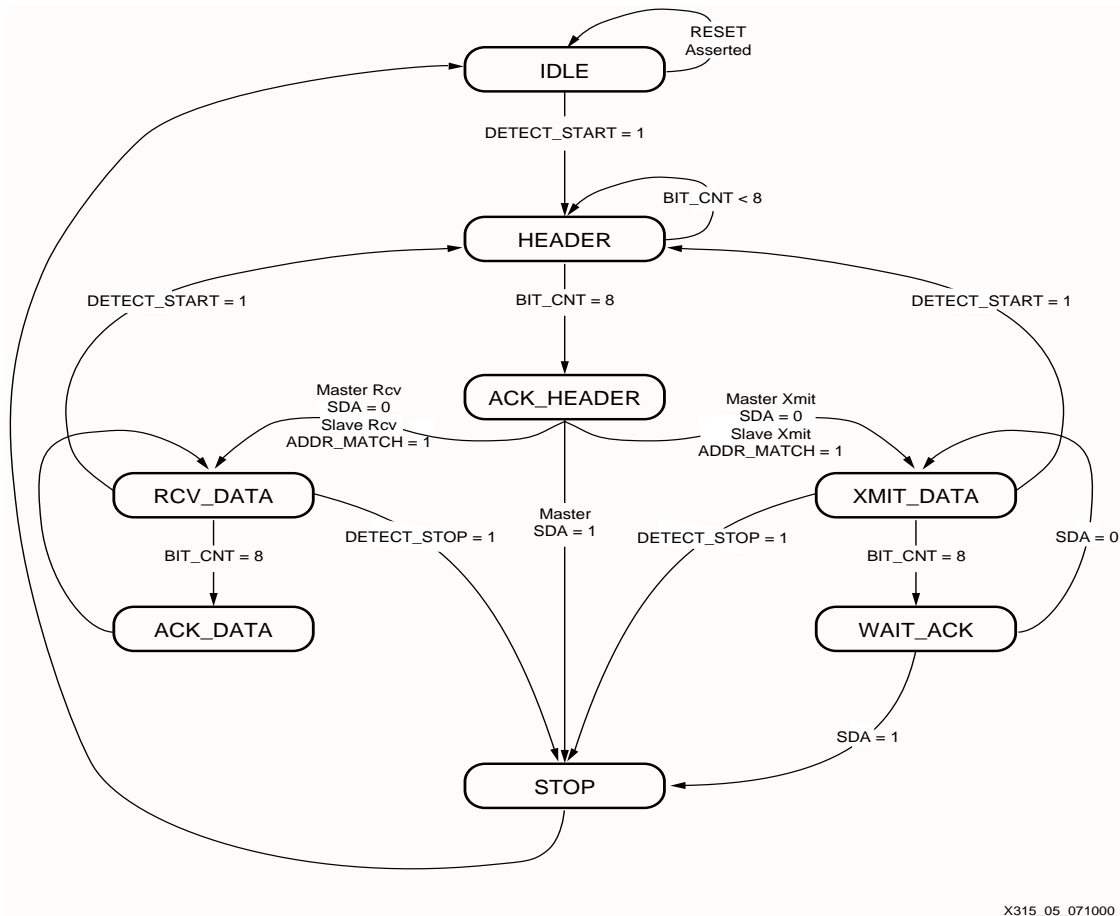


Figure 7: I<sup>2</sup>C Interface Main State Machine

This state machine utilizes and controls a counter that counts the I<sup>2</sup>C bits that have been received. This count is stored in the signal BIT\_CNT. This state machine also controls two shift registers, one that stores the I<sup>2</sup>C header that has been received and another that stores the I<sup>2</sup>C data that has been received or is to be transmitted.

**Note:**

This state machine and the associated counters and shift registers are clocked on the falling edge of the incoming SCL clock. If the load is heavy on the SCL line, the rise time of the SCL signal may be very slow which can cause susceptibility to noise for some systems. This can be particularly dangerous on a clock signal. The designer is strongly encouraged to investigate the signal integrity of the SCL line and if necessary, use external buffers for the SCL signal.

When a START signal has been detected, the state machine transitions from the IDLE state to the HEADER state. The START signal detection circuit monitors the incoming SDA and SCL lines to detect the START condition. The START condition can be generated by the CoolRunner I<sup>2</sup>C controller or another Master—either source will transition the state machine to the HEADER state.

The HEADER state is the state where the I<sup>2</sup>C header is transmitted on the I<sup>2</sup>C bus from the MBDR register if in Master mode. In this state, the incoming I<sup>2</sup>C data is captured in the I<sup>2</sup>C Header shift register. In Master mode, the I<sup>2</sup>C Header shift register will contain the data that was just transmitted by this design. When all eight bits of the I<sup>2</sup>C header have been shifted in, the state machine transitions to the ACK\_HEADER state.

In the ACK\_HEADER state, the CoolRunner I<sup>2</sup>C design samples the SDA line if in Master mode to determine whether the addressed I<sup>2</sup>C Slave acknowledged the header. If the addressed Slave does not acknowledge the header, the state machine will transition to the STOP state which signals the SCL/START/STOP generator to generate a STOP. If the addressed Slave has acknowledged the address, then the LSB of the I<sup>2</sup>C header is used to determine if this is a transmit or receive operation and the state machine transitions to the appropriate state to either receive data, RCV\_DATA, or to transmit data, XMIT\_DATA.

The I<sup>2</sup>C Header shift register is constantly compared with the I<sup>2</sup>C address set in the MADR register. If these values match in the ACK\_HEADER state, the CoolRunner I<sup>2</sup>C Controller has been addressed as a Slave and the mode immediately switches to Slave mode. The MAAS bit is then set in the MBSR status register. The SDA line will be driven as set in the TXAK register to acknowledge the header to the current I<sup>2</sup>C bus Master. Again, the LSB of the I<sup>2</sup>C header is used to determine the direction of the data transfer and the appropriate state is chosen.

The RCV\_DATA state shifts the incoming I<sup>2</sup>C data into the I<sup>2</sup>C shift register for transfer to the  $\mu$ C. When the whole data byte has been received, the state machine transitions to the ACK\_DATA state and the value of the TXAK register is output on the SDA line to acknowledge the data transfer. Note that in Master mode, the indication that the Slave has transmitted the required number of data bytes is to not acknowledge the last byte of data. The  $\mu$ C must negate the TXAK bit to prohibit the ACK of the last data byte. The state machine exits this pair of states when a STOP condition has been detected, otherwise, the transition between these two states continues. In Master mode, the  $\mu$ C requests a STOP condition by negating the MSTA bit.

The XMIT\_DATA state shifts the data from the I<sup>2</sup>C data register to the SDA line. When the entire byte has been output, the state machine transitions to the WAIT\_ACK state. If an acknowledge is received, the state machine goes back to the XMIT\_DATA to transmit the next byte of data. This pattern continues until either a STOP condition is detected, or an acknowledge is not received for a data byte.

Note that the data transfer states of this state machine assume that the  $\mu$ C can keep up with the rate at which data is received or transmitted. If interrupts are enabled, an interrupt is generated at the completion of each byte transfer. The MCF bit is set as well providing the same indication. Data is transferred to/from the I<sup>2</sup>C data register to/from the  $\mu$ C data register during the acknowledge cycle of the data transfer. The state machine does not wait for an indication that the  $\mu$ C has read the received data or that new data has been written for transmission. The designer should be aware of the effective data rate of the  $\mu$ C to insure that this is not an issue.

The STOP state signals the SCL/START/STOP generator to generate a STOP condition if the CoolRunner I<sup>2</sup>C design is in Master mode. The next state is always the IDLE state and the I<sup>2</sup>C activity is completed.

## Operational Flow Diagrams

The flow of the interface between the  $\mu$ C and the CoolRunner I<sup>2</sup>C Controller is detailed in the following flow charts. These flow charts are meant to be a guide for utilizing the CoolRunner I<sup>2</sup>C Controller in a  $\mu$ C system.

### Initialization

Before the CoolRunner I<sup>2</sup>C Controller can be utilized, certain bits and registers must be initialized as shown in [Figure 8](#).

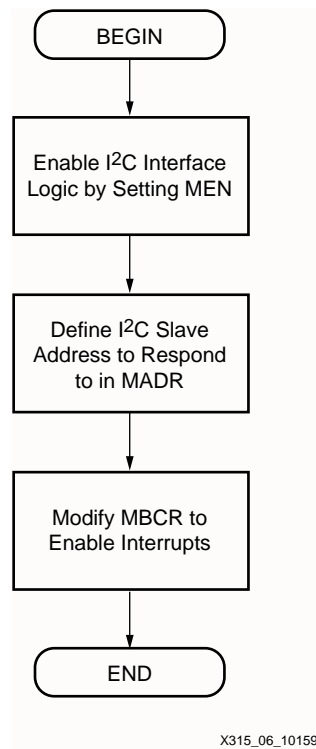


Figure 8: CoolRunner I<sup>2</sup>C Controller Initialization Flow Chart

### Master Transmit/Receive

The flow charts for transmitting data and receiving data while I<sup>2</sup>C bus Master are shown in [Figure 9](#) and [Figure 10](#). The major difference between transmitting and receiving is the additional step in the Master Receive flow chart of turning off the acknowledge bit on the second to last data word.

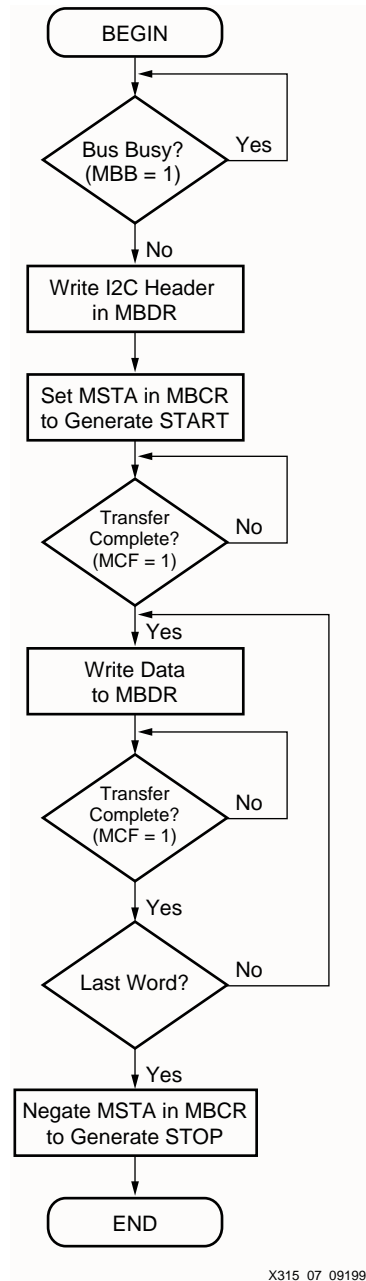


Figure 9: Master Transmit Flow Chart



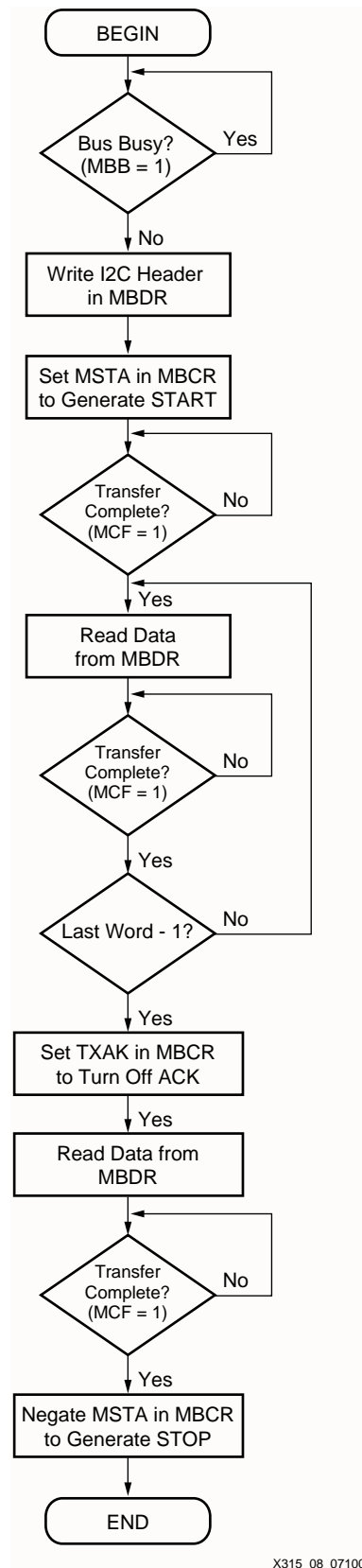


Figure 10: Master Receive Flow Chart

### Slave Flow Chart

The flow chart for receiving or transmitting data in Slave mode is shown in Figure 11. If in receive mode, the first read from the MBDR register is a dummy read because data has not yet been received. Since the CoolRunner I<sup>2</sup>C Controller is in Slave mode, the only way to know that the transaction is complete is to check that the bus is busy and that the Addressed as Slave bit is still set.

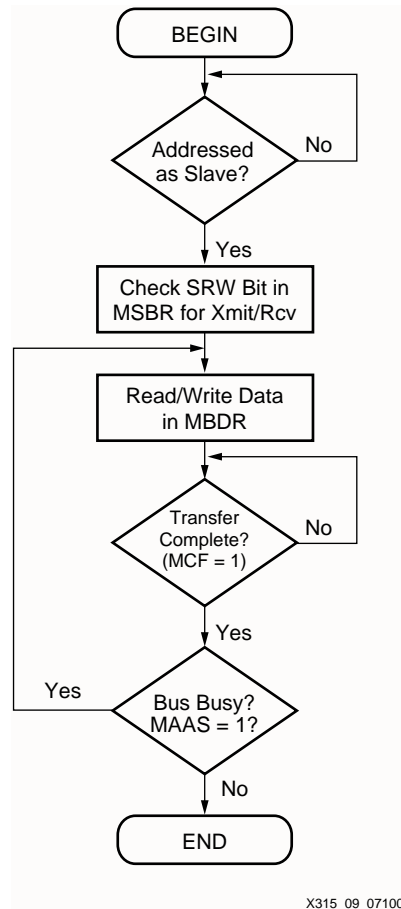


Figure 11: Slave/Transmitter Flow Chart

## CoolRunner XPLA3 CPLD Implementation

The design of the CoolRunner I<sup>2</sup>C Controller was implemented in VHDL and targeted to a 256 macrocell CoolRunner CPLD in a 144-pin TQFP package (XCR3256XL-10TQ144C) using Xilinx Project Navigator. (Xilinx Project Navigator software is available free-of-charge from the Xilinx website: [www.xilinx.com/products/software/webpowered.htm](http://www.xilinx.com/products/software/webpowered.htm)).

**Note:**

Since the system clock frequency was 1.832 MHz, the speed of the design was not critical and any speed grade part could have been used.

**Note:**

The I<sup>2</sup>C SCL line is used as a clock input into the CoolRunner I<sup>2</sup>C Controller. If there are many loads on the I<sup>2</sup>C bus, the rise time of the SCL line can be quite slow. The CoolRunner CPLD for this design requires a rise time no greater than 100 ns, therefore, the designer is strongly encouraged to examine the characteristics of the SCL signal in the I<sup>2</sup>C system. If the rise time of the I<sup>2</sup>C signals are greater than 100 ns, external buffers can be used between the actual I<sup>2</sup>C bus connections and the CoolRunner CPLD.

The I<sup>2</sup>C design utilization in an XPLA3 256-macrocell device is shown in Table 7. This utilization was achieved using certain fitter parameters, actual results may vary. As shown,

there is plenty of room remaining in the device for the implementation of other logic in the system.

**Table 7: CoolRunner XPLA3 256-Macrocell Utilization**

| Resource                   | Available | Used | Utilization |
|----------------------------|-----------|------|-------------|
| Macrocells                 | 256       | 124  | 48%         |
| P-terms                    | 896       | 326  | 36%         |
| Registers Used             | 256       | 110  | 43%         |
| I/O Pins                   | 116       | 42   | 36%         |
| Function Block Inputs Used | 640       | 289  | 45%         |

## Design Verification

The Xilinx Project Navigator software package outputs a timing VHDL model of the fitted design. This post-fit VHDL was simulated with the original VHDL test benches to insure design functionality. Also, the CoolRunner I<sup>2</sup>C Controller design was simulated with an independently generated VHDL model of an I<sup>2</sup>C Slave design to verify that the interface specifications were implemented correctly. Please note that all verification of this design has been done through simulations.

## VHDL Code Download

VHDL source code and test benches are available for this design. THE DESIGN IS PROVIDED TO YOU "AS IS". XILINX MAKES AND YOU RECEIVE NO WARRANTIES OR CONDITIONS, EXPRESS, IMPLIED, STATUTORY OR OTHERWISE, AND XILINX SPECIFICALLY DISCLAIMS ANY IMPLIED WARRANTIES OF MERCHANTABILITY, NON-INFRINGEMENT, OR FITNESS FOR A PARTICULAR PURPOSE. This design has not been verified on hardware (as opposed to simulations), and it should be used only as an example design, not as a fully functional core. XILINX does not warrant the performance, functionality, or operation of this Design will meet your requirements, or that the operation of the Design will be uninterrupted or error free, or that defects in the Design will be corrected. Furthermore, XILINX does not warrant or make any representations regarding use or the results of the use of the Design in terms of correctness, accuracy, reliability or otherwise.

**XAPP333** - <http://www.xilinx.com/products/xaw/coolvhdlq.htm>

## Disclaimer

I<sup>2</sup>C is a registered trademark of Philips Electronics N.V.. Xilinx provides this reference design as one possible implementation of this standard and claims no rights to this interface. To use this reference design, you must contact Philips to obtain any necessary rights associated with this interface.

## Conclusion

This document has detailed the design of an I<sup>2</sup>C Controller design for a CoolRunner XPLA3 CPLD. Though the design has been extensively verified in simulations, Xilinx assumes no responsibility for the accuracy or the functionality of this design.

## Revision History

The following table shows the revision history for this document.

| Date     | Version | Revision   |
|----------|---------|--|
| 01/05/00 | 1.0     | Initial Xilinx release.                                |
| 03/24/00 | 1.2     | Added VHDL disclaimer and code link.                   |
| 05/02/00 | 1.3     | Added I <sup>2</sup> C disclaimer.                     |
| 07/21/00 | 1.4     | Corrected document errors and repeated start condition |
| 11/07/00 | 1.5     | Updated disclaimer for HDL code.                       |
| 10/01/02 | 1.6     | Minor revisions  |
| 12/24/02 | 1.7     | Updated resource usage.                                |