

# Implementation Report Analysis

Vivado

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# Chapter 1

## Introduction

This document is an analysis of the implementation report generated by Vivado for the `top` module. The report is generated after the implementation process is completed. The report contains information about the resources used by the design, the timing constraints, and the timing performance of the design. The report is used to analyze the design and to identify any potential issues that may need to be addressed.

## Chapter 2

# Resource Utilization

The resource utilization section of the report provides information about the resources used by the design. This includes information about the number of LUTs, FFs, BRAMs, and DSPs used by the design. The resource utilization section also provides information about the number of IOBs used by the design.

### 2.1 Common Resource Types

Here are some common resource types used in FPGA designs and Verilog codes that utilizes these resources:

#### 2.1.1 LUTs

LUTs (Look-Up Tables) are fundamental building blocks in FPGA designs. They are used to implement combinational logic functions. Each LUT has a fixed number of inputs and a single output. The Verilog code snippet below shows an example of a 2-input LUT implementation:

```
module lut2 (input wire a, b, output wire y);  
    assign y = a & b;  
endmodule
```

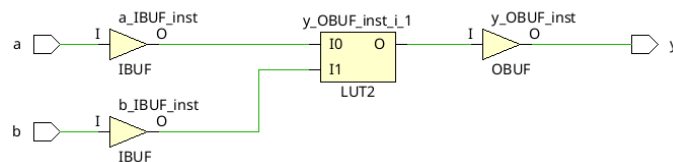


Figure 2.1.1.1: LUT Implemented

### 2.1.2 FFs

FFs (Flip-Flops) are sequential elements used to store and propagate data in FPGA designs. They are commonly used to implement registers and memory elements. The Verilog code snippet below shows an example of a D flip-flop implementation:

```
module dff (input wire clk, reset, input wire d, output reg q);
    always @(posedge clk or posedge reset)
        if (reset)
            q <= 1'b0;
        else
            q <= d;
endmodule
```

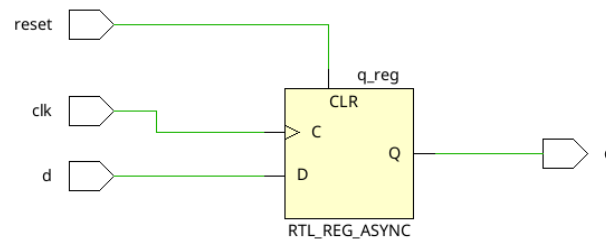


Figure 2.1.2.1: FF Synthesised

### 2.1.3 BRAMs

BRAMs (Block RAMs) are memory elements in FPGA designs. They provide large storage capacity and high-speed access. They can be coded into fpga, or The Verilog code snippet below shows an example of a simple dual-port RAM implementation:

```
module dual_port_ram (
    input wire clk,
    input wire [7:0] addr_a, addr_b,
    input wire [7:0] data_a, data_b,
    input wire we_a, we_b,
    output reg [7:0] q_a, q_b
);
    reg [7:0] mem [0:255];
    always @(posedge clk) begin
        if (we_a)
            mem[addr_a] <= data_a;
        q_a <= mem[addr_a]; // Synchronous read for port A
    end
    always @(posedge clk) begin
```

```

        if (we_b)
            mem[addr_b] <= data_b;
        q_b <= mem[addr_b]; // Synchronous read for port B
    end
endmodule

```

\* Vivado can pick BRAM, LUTRAM, or FFs to implement your design. If you want to force Vivado to use BRAM, you can use (\* ram\_style = "block" \*) in the module. If your design fits Bram conditions, Vivado will use BRAMs to implement your design. If you do not explicitly specify, Vivado will use LUTRAMs or FFs to implement your design depending on size required access speed etc.

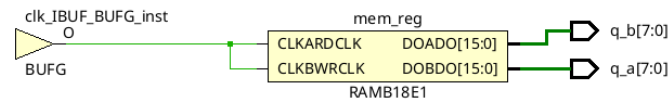


Figure 2.1.3.1: BRam Implemented

## 2.1.4 DSPs

DSPs (Digital Signal Processors) are specialized hardware blocks in FPGA designs used for high-performance signal processing operations. They are commonly used in applications such as image and audio processing. The Verilog code snippet below shows an example of a simple multiplier using DSP blocks:

```

module multiplier (input wire [9:0] a, b, output wire [19:0] result);
    assign result = a * b;
endmodule

```

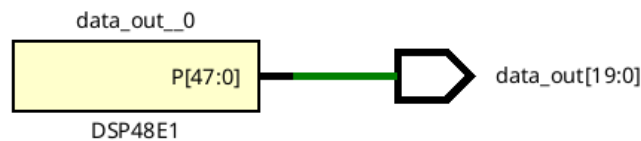


Figure 2.1.4.1: DSP Block Implemented

\*For Basys3 Vivado prefers to use dsp blocks 10 and more bits multiplication. For 9 bits and less, it uses LUTs and FFs, but adding (\* use\_dsp = "yes" \*) to the module can force Vivado to DSP for arithmetic operations.

### 2.1.5 IOBs

IOBs (Input/Output Blocks) are used to interface the FPGA design with external devices. They provide the necessary logic to drive and receive signals from the external world. The Verilog code snippet below shows an example of an IOB implementation for a simple GPIO (General Purpose Input/Output) interface:

```
module gpio (input wire clk, input wire reset, input wire [7:0] data_in,
             output wire [7:0] data_out, inout wire [7:0] io_pins);
    reg [7:0] internal_reg;

    always @(posedge clk or posedge reset)
        if (reset)
            internal_reg <= 8'b0;
        else
            internal_reg <= data_in;

    assign data_out = internal_reg;
    assign io_pins = internal_reg;
endmodule
```

## 2.2 Resource Utilization Report

The resource utilization report provides information about how many of these components are available in the FPGA and how many are used by your design. It helps you understand how efficiently your design is utilizing the available resources and whether any adjustments or optimizations are needed.

**There are 8 parts in the resource utilization report.**

1. Slice Logic: How many LUTs and FFs are used in the design. How many of LUTs are used as Logic or Memory and how many of FFs are used as Registers or Latches.
2. Slice Logic Distribution: How the LUTs and FFs are distributed across the slices.
3. Memory: Usage report of build in memory blocks. There can be different types for different fpga families.
4. DSPs: Usage report of DSP blocks.
5. IOs
6. BUFG/BUFGCTRL (Clocking): Usage report of clocking resources.

7. Specific Feature: Usage report of specific featured blocks of the fpga card.
8. Primitive: How many of each primitive type are utilized in your design. A more detailed report of the sources mentioned in the other tables used in the design. It doesn't give the utilization ratio.

Example scenarios to chose which part to look at:

- If you wanted to know exactly how many flip-flops or LUTs of a particular configuration (like FDRE for a flip-flop with enable) were used, you would consult the Primitive Types Report.
- If the design is using a lot of memory resources as LUT, you may want to look at the Memory section to see if there are any optimizations that can be made.
- If the design is using a lot math operations, you may want to look at the DSP and LUT section to see if the design is close to the limits.
- **\*\*\*The synthesis tool might not be able to utilize the desing as desired. A different block of fpga can be used to implement your design. For example a buffer can be utilized in BRAMs, LUTRAMs, or FFs. Simple changes in your design can make implementation tool to chose a different resource. \*\*\***

An example table from resource utilization report for the top module is shown below:

#### 8. Primitives

-----

+-----+-----+-----+-----+			
Ref Name	Used	Functional Category	
+-----+-----+-----+-----+			
FDRE	178	Flop & Latch	
LUT6	79	LUT	
LUT4	48	LUT	
LUT5	22	LUT	
LUT2	21	LUT	
LUT3	18	LUT	
CARRY4	11	CarryLogic	
FDSE	10	Flop & Latch	
OBUF	7	IO	
RAMB18E1	4	Block Memory	
IBUF	3	IO	
LUT1	2	LUT	
BUFG	2	Clock	
+-----+-----+-----+-----+			

General file names for this report are Module\_Name\_utilization\_routed.rpt or Module\_Name\_utilization\_placed.rpt

### 2.2.1 TCL Commands

The most useful setting for utilization analysis when calling tcl option is hierarchical. This option gives a single table report, but with primitive types used by all submodules and theirs. This is useful to see which module is using the most of a specific resource. You can set this setting in the tcl command as follows:

```
report_utilization -hierarchical
```

\*This command can help you to see which module is using the most of a specific resource. If you see a module is using a lot of a specific resource, you can optimize that module to reduce the resource usage.



## Chapter 3

# Power Analysis

Power analysis is an important aspect of FPGA design as it helps in understanding the power consumption of the implemented design. By analyzing the power utilization, we can optimize the design to reduce power consumption and improve overall efficiency. Power analysis provides insights into the power consumption of different components in the design, such as LUTs, FFs, BRAMs, DSPs, and IOBs. It also helps in identifying any potential power-related issues that may need to be addressed. In this section, we will explore the power utilization of the `top` module and analyze the power consumption of various components in the design.

### 3.1 Power Utilization Report

The power utilization report provides information about the power consumption of different components in the design. It includes details about the dynamic power, static power, and total power consumption of the design. There are 3 parts in the power utilization report. The content of the report may vary depending on the FPGA family and the tool used.

**However, The first two table 1.1 and 1.2 and the last table 3.1 are the most useful table for power analysis.**

- **1.1 Power Summary:** This table provides an overview of the power consumption of the design. It includes information about the dynamic power, static power, dynamic power, and total power consumption of the design. It also provides details about constraints (if you set).
- **1.2 Power by Component:** This table provides detailed information about the power consumption of different components in the design. It includes information about the power consumption of LUTs, FFs, BRAMs, DSPs, and IOBs. It helps in understanding the power consumption of different components and optimizing the design to reduce power consumption.
- **3.1 Power by Hierarchy:** This table provides a hierarchical view of the power consumption of the design. It includes information about the power consumption of different modules in the design and helps in identifying the power consumption of individual modules.

### 3.1.1 Power Summary (1.1)

An example table from power utilization report for the `top` module is shown below:

+-----+		
Total On-Chip Power (W)	0.082	
Design Power Budget (W)	Unspecified*	
Power Budget Margin (W)	NA	
Dynamic (W)	0.010	
Device Static (W)	0.072	
Effective TJA (C/W)	5.0	
Max Ambient (C)	84.6	
Junction Temperature (C)	25.4	
Confidence Level	Medium	
Setting File	---	
Simulation Activity File	---	
Design Nets Matched	NA	
+-----+		

An explanation of the fields and tips about some fields in the table is as follows:

- Total On-Chip Power (W): The total power consumption of the design on the FPGA chip.
- Design Power Budget (W): The specified power budget for the design. **If you set a power budget, you can compare the actual power consumption with the specified power budget to ensure that the design meets the power requirements. If you need to run on battery power, this might be important.**
- Power Budget Margin (W): The margin between the actual power consumption and the specified power budget.
- Dynamic (W): The dynamic power consumption of the design. **High dynamic power drawn when performance required. It is best to keep power drawn low when not required. For example, if your design uses multiple modules used as needed, you can disable their clocks when they are not used. This should reduce dynamic power.**
- Device Static (W): The static power consumption of the FPGA device. **This should be reduced to keep power consumption and temperature low. Power gating can be used to reduce static power. This is not available for all FPGAs please research.**
- Effective TJA (C/W): The thermal junction-to-ambient resistance of the FPGA device.
- Max Ambient (C): The maximum ambient temperature for the design.
- Junction Temperature (C): The junction temperature of the FPGA device.
- Confidence Level: The confidence level of the power analysis results. This depends on the user specifications. **If you want a more accurate result, you can increase the confidence level by setting io and clock activity using GUI or constraints file.**

- Setting File: The settings file used for the power analysis.
- Simulation Activity File: The simulation activity file used for the power analysis.
- Design Nets Matched: The number of design nets matched during the power analysis.

### 3.1.2 Power by Component (1.2)

An example table from power utilization report for the `top` module is shown below:

On-Chip	Power (W)	Used	Available	Utilization (%)
Clocks	0.001	5	---	---
Slice Logic	<0.001	406	---	---
LUT as Logic	<0.001	164	20800	0.79
Register	<0.001	188	41600	0.45
CARRY4	<0.001	11	8150	0.13
Others	0.000	17	---	---
Signals	<0.001	363	---	---
Block RAM	<0.001	2	50	4.00
I/O	0.007	10	106	9.43
Static Power	0.072			
Total	0.082			

Using this table and information from the previous section, you can analyze the power consumption of different components in the design and identify areas where power optimization is needed. For example, if the design is using a large number of LUTs, you can optimize the design to reduce the number of LUTs used and reduce power consumption. Similarly, if the design is using a large number of a component, and if it is more efficient to use other blocks you can force to use other blocks for your design.

### 3.1.3 Power by Hierarchy (3.1)

An example table from power utilization report for the `top` module is shown below:

Name	Power (W)
MemController	0.010

This table is not a great example, but if yours include your sub modules you can analyze the power consumption of different modules in the design and identify areas where power optimization is needed. For example, if a particular module is consuming a large amount of power, you can optimize that module to reduce power consumption. This because of the hierarchical depth setting. At next session you will see how to set this setting.

### 3.1.4 TCL Commands

The most useful setting for power analysis when calling tcl option is hierarchical\_depth. When implem run it usually set to 1 by default. However, if you set it to 0, you can see the power consumption of the submodules and their submodules until the least piece. This is useful to see which module is consuming the most power, or you can set the depth you desire You can set this setting in the tcl command as follows:

```
report_power -hierarchical_depth 0
```

## Chapter 4

# Methodology Warnings

The methodology warnings section of the report provides information about any potential issues or warnings that may need to be addressed. This section includes information about the timing constraints, clock constraints, and other design constraints that may impact the performance of the design. The methodology warnings section helps in identifying any potential issues that may need to be addressed to improve the performance of the design.

### 4.1 Methodology Warnings Report

Example issues from methodology warnings report for the `top` module is shown below:

```
[Timing 38-282] The design failed to meet the timing requirements.  
Please see the timing summary report for details on the timing violations.
```

```
[Place 30-58] IO placement is not user specified.
```

```
TIMING-18#1 Warning
```

```
Missing input or output delay
```

```
An input delay is missing on reset relative to the rising and/or falling clock edge(s)  
of sys_clk_pin.
```

```
Related violations: <none>
```

Some of these issues are about the constraints that you did not set. Some can be ignored if you are confident about timing latency of those pins. However, if you are not sure about the latency of the pins, you can set the constraints for those pins. Then if you get timing failed warning, your system will be high probably not working as desired stably. IO placement is more important, there might be bitstream write issues even if it is implemented. Also, if the tool can place as it wants, the design may not function as desired on the device. You can check the io placement in `Module_Name_io_placed.rpt` file.

## Chapter 5

# Timing Analysis

The timing analysis section of the report provides information about the timing performance of the design. This includes information about the clock constraints, setup and hold times, clock-to-q delays, and other timing parameters that impact the performance of the design. The timing analysis section helps in identifying any potential timing issues that may need to be addressed to improve the performance of the design. This is the most complex and important part of the report.

### 5.1 Definitions and Explanations

These are some common terms used in the timing analysis report in order to understand the report better:

- **Setup Time:** The amount of time the input signal must be stable before the active edge of the clock signal. If the input signal changes too close to the active edge of the clock signal, the flip-flop may not capture the correct value.
- **Hold Time:** The amount of time the input signal must be stable after the active edge of the clock signal. If the input signal changes too soon after the active edge of the clock signal, the flip-flop may not capture the correct value.
- **Slack:** The slack is the amount of time by which the actual timing of the design exceeds the required timing. A positive slack indicates that the design meets the timing requirements, while a negative slack indicates that the design fails to meet the timing requirements.
- **Clock-to-Q Delay:** The amount of time it takes for the output signal to change after the active edge of the clock signal. This is the delay through the flip-flop.
- **Clock Skew:** The difference in arrival times of the clock signal at different flip-flops. Clock skew can cause timing violations if the clock signal arrives at different flip-flops at different times.
- **Clock Uncertainty:** The amount of uncertainty in the clock signal arrival time. Clock uncertainty can cause timing violations if the clock signal arrives at different flip-flops at different times.

- **Critical Path:** The path in the design with the longest delay. The critical path determines the maximum clock frequency of the design.
- **Timing Violation:** A timing violation occurs when the design fails to meet the timing requirements specified in the constraints file. Timing violations can cause the design to malfunction or fail to meet the desired performance.
- **Clock Domain Crossing:** Clock domain crossing occurs when signals from one clock domain are transferred to another clock domain. Clock domain crossing can cause timing violations if the signals are not synchronized properly.
- **False Path:** A false path is a path in the design that is not required to meet the timing requirements. False paths are ignored by the timing analysis tool to reduce the analysis time.
- **TNS:** Total Negative Slack. The sum of all negative slack values in the design.
- **WNS:** Worst Negative Slack. The worst negative slack value in the design.
- **THS:** Total Hold Slack. The sum of all hold slack values in the design.
- **WHS:** Worst Hold Slack. The worst hold slack value in the design.
- **WPWS:** Worst Pulse Width Slack. The worst pulse width slack value in the design.
- **Data Path Delay:** The amount of time it takes for the data signal to propagate through the combinational logic in the design. Data path delay is a critical parameter that impacts the overall performance of the design.
- **System Jitter:** The amount of variation in the clock signal arrival time. System jitter can cause timing violations if the clock signal arrives at different flip-flops at different times.
- **Input Jitter:** The amount of variation in the input signal arrival time. Input jitter can cause timing violations if the input signal changes too close to the active edge of the clock signal.

## 5.2 Calculation of Slack

The slack is calculated as follows:

```
Time Available for Data Setup = Clock Period - Data Path Delay
Setup Slack = (Clock Period) - (Time Available for Data Setup)
```

```
Time Available for Data Hold = Data Change Time after Clock Edge
Hold Slack = Time Available for Data Hold - Hold Time
```

```
Time Required = Time Required for Pulse to be High
Actual Pulse Width = Time that the Pulse is High
Pulse Width Slack = Actual Pulse Width - Time Required
```

## 5.3 Timing Analysis Report

The timing analysis doesn't have explicit sections like the other reports. It is a long report that includes all the timing information of the design. However, we can break it down into 4 parts:

### 5.3.1 Timing Checks

At the start of the timing analysis report, there is a summary of the timing checks. These checks make sure that an accurate timing report is produced. The summary provides timing warnings for your design. These suggestions might be useful to fix the timing issues. An example from the timing analysis report for the `top` module is shown below:

#### Table of Contents

- ```
-----
1. checking no_clock (0)
2. checking constant_clock (0)
3. checking pulse_width_clock (0)
4. checking unconstrained_internal_endpoints (0)
5. checking no_input_delay (2)
6. checking no_output_delay (6)
7. checking multiple_clock (0)
8. checking generated_clocks (0)
9. checking loops (0)
10. checking partial_input_delay (0)
11. checking partial_output_delay (0)
12. checking latch_loops (0)
```

#### 1. checking no\_clock (0)

```
-----
```

There are 0 register/latch pins with no clock.

#### 2. checking constant\_clock (0)

```
-----
```

There are 0 register/latch pins with constant\_clock.

#### 3. checking pulse\_width\_clock (0)

```
-----
```

There are 0 register/latch pins which need pulse\_width check

#### 4. checking unconstrained\_internal\_endpoints (0)

```
-----
```

There are 0 pins that are not constrained for maximum delay.

There are 0 pins that are not constrained for maximum delay due to constant clock.



5. checking no\_input\_delay (2)

-----  
There are 2 input ports with no input delay specified. (HIGH)

There are 0 input ports with no input delay but user has a false path constraint.

6. checking no\_output\_delay (6)

-----  
There are 6 ports with no output delay specified. (HIGH)

There are 0 ports with no output delay but user has a false path constraint

There are 0 ports with no output delay but with a timing clock defined on it  
or propagating through it

7. checking multiple\_clock (0)

-----  
There are 0 register/latch pins with multiple clocks.

8. checking generated\_clocks (0)

-----  
There are 0 generated clocks that are not connected to a clock source.

9. checking loops (0)

-----  
There are 0 combinational loops in the design.

10. checking partial\_input\_delay (0)

-----  
There are 0 input ports with partial input delay specified.

11. checking partial\_output\_delay (0)

-----  
There are 0 ports with partial output delay specified.

12. checking latch\_loops (0)

There are 0 combinational latch loops in the design through latch input

Using this information, you can identify any potential timing issues in the design and take appropriate actions to address them. For example, if there are input ports with no input delay specified, you can set the input delay constraints to ensure that the design meets the timing requirements. If the design has a negative slack, the input delay that is not specified might be causing this result. This warnings effect the detailed design timing summary which comes after.

### 5.3.2 Design Timing Summary

After the checks, there is a timing report of the whole module. An example from the timing analysis report for this part is shown below:

|                        |                       |                       |                     |                     |          |
|------------------------|-----------------------|-----------------------|---------------------|---------------------|----------|
| -----                  |                       |                       |                     |                     |          |
| Design Timing Summary  |                       |                       |                     |                     |          |
| -----                  |                       |                       |                     |                     |          |
| -----                  |                       |                       |                     |                     |          |
| WNS(ns)                | TNS(ns)               | TNS Failing Endpoints |                     | TNS Total Endpoints | WHS(ns)  |
| -----                  | -----                 | -----                 |                     | -----               | -----    |
| 3.864                  | 0.000                 | 0                     |                     | 561                 | 0.058    |
|                        |                       |                       |                     |                     |          |
| THS(ns)                | THS Failing Endpoints |                       | THS Total Endpoints | WPWS(ns)            | TPWS(ns) |
| -----                  | -----                 |                       | -----               | -----               | -----    |
| 0.000                  | 0                     |                       | 561                 | 4.500               | 0.000    |
|                        |                       |                       |                     |                     |          |
| TPWS Failing Endpoints |                       | TPWS Total Endpoints  |                     |                     |          |
| -----                  |                       | -----                 |                     |                     |          |
| 0                      |                       | 198                   |                     |                     |          |

The titles are already explained in the previous part. If there is no negative value or close to zero, the design is working as desired. If there is a negative value, you should check the detailed timing report to see which part of the design is causing the issue. Hold times are close to zero, but they are how they are suppose to be as hold time is already a small value.

### 5.3.3 Clock Timing Summary

After the design timing summary, there is a clock timing summary. This part provides information about the clock constraints, slacks for each clock's own domain, slacks between clock domains, and clock uncertainty of the design. It helps in understanding the clock performance of the design and identifying any potential clock-related issues that may need to be addressed. An example from the timing analysis report for this part is shown below:

|       |               |
|-------|---------------|
| ----- |               |
|       | Clock Summary |
|       | -----         |
| ----- |               |

| Clock       | Waveform(ns)     | Period(ns) | Frequency(MHz) |
|-------------|------------------|------------|----------------|
| -----       | -----            | -----      | -----          |
| sys_clk_pin | {0.000 5.000}    | 10.000     | 100.000        |
| rx_clk      | {0.000 270.000}  | 540.000    | 1.852          |
| tx_clk      | {0.000 4340.000} | 8680.000   | 0.115          |

-----  
| Intra Clock Table  
| -----  
-----

| Clock       | WNS(ns)  | TNS(ns) | TNS Failing Endpoints | TNS Total Endpoints |
|-------------|----------|---------|-----------------------|---------------------|
| -----       | -----    | -----   | -----                 | -----               |
| sys_clk_pin | 4.227    | 0.000   | 0                     | 445                 |
| rx_clk      | 535.110  | 0.000   | 0                     | 74                  |
| tx_clk      | 8675.541 | 0.000   | 0                     | 34                  |

| WHS(ns) | THS(ns) | THS Failing Endpoints | THS Total Endpoints | WPWS(ns) |
|---------|---------|-----------------------|---------------------|----------|
| -----   | -----   | -----                 | -----               | -----    |
| 0.058   | 0.000   | 0                     | 445                 | 4.500    |
| 0.177   | 0.000   | 0                     | 74                  | 269.500  |
| 0.191   | 0.000   | 0                     | 34                  | 4339.500 |

| TPWS(ns) | TPWS Failing Endpoints | TPWS Total Endpoints |
|----------|------------------------|----------------------|
| -----    | -----                  | -----                |
| 0.000    | 0                      | 140                  |
| 0.000    | 0                      | 40                   |
| 0.000    | 0                      | 18                   |

-----  
| Inter Clock Table  
| -----  
-----

| From Clock  | To Clock    | WNS(ns) | TNS(ns) | TNS Failing Endpoints |
|-------------|-------------|---------|---------|-----------------------|
| -----       | -----       | -----   | -----   | -----                 |
| rx_clk      | sys_clk_pin | 3.864   | 0.000   | 0                     |
| tx_clk      | sys_clk_pin | 5.181   | 0.000   | 0                     |
| sys_clk_pin | tx_clk      | 6.771   | 0.000   | 0                     |

| TNS Total Endpoints | WHS(ns) | THS(ns) | THS Failing Endpoints |
|---------------------|---------|---------|-----------------------|
| -----               | -----   | -----   | -----                 |
| 69                  | 0.945   | 0.000   | 0                     |
| 5                   | 0.747   | 0.000   | 0                     |
| 25                  | 0.131   | 0.000   | 0                     |

### THS Total Endpoints

69  
5  
25

The first table in this part gives wave specifications of the clocks. The second table gives the slack values of the clocks. The third table gives the slack values between the clocks. If there is a negative value in the slack, you should check the detailed timing report to see which part of the design is causing the issue.

As you can realize slower clocks has no problem with timing as they have a lot of slack. However, the faster clock has a tight timing. This is a common issue in the designs.

Inter Clock table is formed by the clocks that are crossing each other. If two systems with different clocks are not connected at all, they are not in this table. If they are connected in a way (output/input), it is in this table. From this report, we can understand that the module with main clock both reads and writes to the module with tx\_clk in always @(clk) block.

When a design slack problem is detected, the first thing to do is to check the detailed timing report to see which part or module interaction of the design is causing the issue.

### 5.3.4 Detailed Timing Report

For each clock domain and cross domain, for each path the timing report is placed here ordered slack worst to best. All component's delay on the path can be seen with input and clock jitter calculation available. An example part from the timing analysis report for this part is shown below (For single path):

```
Slack (MET) :          4.227ns (required time - arrival time)
Source:          time_out_counter_reg[12]/C
                  (rising edge-triggered cell FDRE clocked by sys_clk_pin {rise@0.000ns fall@5.000ns pe
Destination:      time_out_counter_reg[24]/R
                  (rising edge-triggered cell FDRE clocked by sys_clk_pin {rise@0.000ns fall@5.000ns pe
Path Group:       sys_clk_pin
Path Type:        Setup (Max at Slow Process Corner)
Requirement:      10.000ns (sys_clk_pin rise@10.000ns - sys_clk_pin rise@0.000ns)
Data Path Delay:  5.188ns (logic 1.014ns (19.546%) route 4.174ns (80.453%))
Logic Levels:     4 (LUT2=1 LUT3=1 LUT4=1 LUT6=1)
Clock Path Skew:  -0.026ns (DCD - SCD + CPR)
Destination Clock Delay (DCD):  4.857ns = ( 14.857 - 10.000 )
Source Clock Delay (SCD):  5.156ns
Clock Pessimism Removal (CPR):  0.273ns
Clock Uncertainty: 0.035ns ((TSJ^2 + TIJ^2)^1/2 + DJ) / 2 + PE
Total System Jitter (TSJ):  0.071ns
Total Input Jitter (TIJ):  0.000ns
Discrete Jitter (DJ):  0.000ns
Phase Error (PE):  0.000ns
```

| Location      | Delay type                    | Incr(ns) | Path(ns) | Netlist Resource(s)                        |
|---------------|-------------------------------|----------|----------|--------------------------------------------|
| -----         |                               |          |          |                                            |
|               | (clock sys_clk_pin rise edge) |          |          |                                            |
|               |                               | 0.000    | 0.000 r  |                                            |
| W5            |                               | 0.000    | 0.000 r  | clk (IN)                                   |
|               | net (fo=0)                    | 0.000    | 0.000    | clk                                        |
| W5            | IBUF (Prop_ibuf_I_0)          | 1.458    | 1.458 r  | clk_IBUF_inst/0                            |
|               | net (fo=1, routed)            | 1.967    | 3.425    | clk_IBUF                                   |
| BUFGCTRL_X0Y0 | BUFG (Prop_bufg_I_0)          | 0.096    | 3.521 r  | clk_IBUF_BUFG_inst/0                       |
|               | net (fo=139, routed)          | 1.635    | 5.156    | clk_IBUF_BUFG                              |
| SLICE_X6Y4    | FDRE                          |          | r        | time_out_counter_reg[12]/C                 |
| -----         |                               |          |          |                                            |
| SLICE_X6Y4    | FDRE (Prop_fdre_C_Q)          | 0.518    | 5.674 f  | time_out_counter_reg[12]/Q                 |
|               | net (fo=2, routed)            | 0.653    | 6.328    | nolabel_line102/time_out_counter[0]_i_     |
| SLICE_X7Y5    | LUT4 (Prop_lut4_I0_0)         | 0.124    | 6.452 f  | nolabel_line102/time_out_counter[0]_i_6/0  |
|               | net (fo=1, routed)            | 1.154    | 7.605    | nolabel_line102/time_out_counter[0]_i_     |
| SLICE_X7Y5    | LUT6 (Prop_lut6_I3_0)         | 0.124    | 7.729 f  | nolabel_line102/time_out_counter[0]_i_2/0  |
|               | net (fo=3, routed)            | 0.597    | 8.327    | nolabel_line102/time_out_counter[0]_i_     |
| SLICE_X9Y5    | LUT2 (Prop_lut2_I0_0)         | 0.124    | 8.451 f  | nolabel_line102/FSM_sequential_state[2]_i_ |
|               | net (fo=4, routed)            | 0.898    | 9.349    | nolabel_line102/time_out_counter_reg[0]    |
| SLICE_X7Y4    | LUT3 (Prop_lut3_I2_0)         | 0.124    | 9.473 r  | nolabel_line102/time_out_counter[26]_i_1/  |
|               | net (fo=26, routed)           | 0.871    | 10.344   | nolabel_line102_n_21                       |
| SLICE_X6Y7    | FDRE                          |          | r        | time_out_counter_reg[24]/R                 |
| -----         |                               |          |          |                                            |
|               | (clock sys_clk_pin rise edge) |          |          |                                            |
|               |                               | 10.000   | 10.000 r |                                            |
| W5            |                               | 0.000    | 10.000 r | clk (IN)                                   |
|               | net (fo=0)                    | 0.000    | 10.000   | clk                                        |
| W5            | IBUF (Prop_ibuf_I_0)          | 1.388    | 11.388 r | clk_IBUF_inst/0                            |
|               | net (fo=1, routed)            | 1.862    | 13.250   | clk_IBUF                                   |
| BUFGCTRL_X0Y0 | BUFG (Prop_bufg_I_0)          | 0.091    | 13.341 r | clk_IBUF_BUFG_inst/0                       |
|               | net (fo=139, routed)          | 1.516    | 14.857   | clk_IBUF_BUFG                              |
| SLICE_X6Y7    | FDRE                          |          | r        | time_out_counter_reg[24]/C                 |
|               | clock pessimism               | 0.273    | 15.130   |                                            |
|               | clock uncertainty             | -0.035   | 15.095   |                                            |
| SLICE_X6Y7    | FDRE (Setup_fdre_C_R)         | -0.524   | 14.571   | time_out_counter_reg[24]                   |
| -----         |                               |          |          |                                            |
|               | required time                 |          | 14.571   |                                            |
|               | arrival time                  |          | -10.344  |                                            |
| -----         |                               |          |          |                                            |
|               | slack                         |          | 4.227    |                                            |

Lets break down the information in the report:

This is a setup timing path. The slack calculated is 4.227ns. This means that the path is 4.227ns faster than the required time. This is a good slack value. The source and destination of the path are given. The source is the register named `time_out_counter_reg[12]` that is sending the signal,

and the destination is the register named `time_out_counter_reg[24]` that is receiving the signal. There are calculation logic between these two registers. Now let's look at times:

- Event: Clock Rised at 0.000ns
- Clock signal reached the source register at 5.156ns (Source Clock Delay), starting logic flow.
- Then the signal of source register is processed by the logic between and reached the destination register at 10.344ns. (Data Path Delay:  $10.344\text{ns} - 5.156\text{ns} = 5.188\text{ns}$ )
- The data already ready for destination to setup.
- Event: Clock Rised at 10.000ns again
- Clock signal reached the destination register at 14.857 (Destination Clock Delay:  $14.857\text{ns} - 10\text{ns} = 4.857\text{ns}$ ), starting setup time.
- The setup is ready at 14.571ns, with calculation of clock pessimism and uncertainty. (Slack:  $14.571\text{ns} - 10.344\text{ns} = 4.227\text{ns}$ )

\*Tip: When you see a border line (separator) after a row in the path timings, a key event happens which are in the graph below.

**To sum up, time required is when the second rise of the clock signal reaches the destination register. Time arrival is the exact time data gets to D pin. Data path delay is Q to D.** The clock reached at different times to the two registers. This is a clock skew example.

A graphical representation of the path as follows:

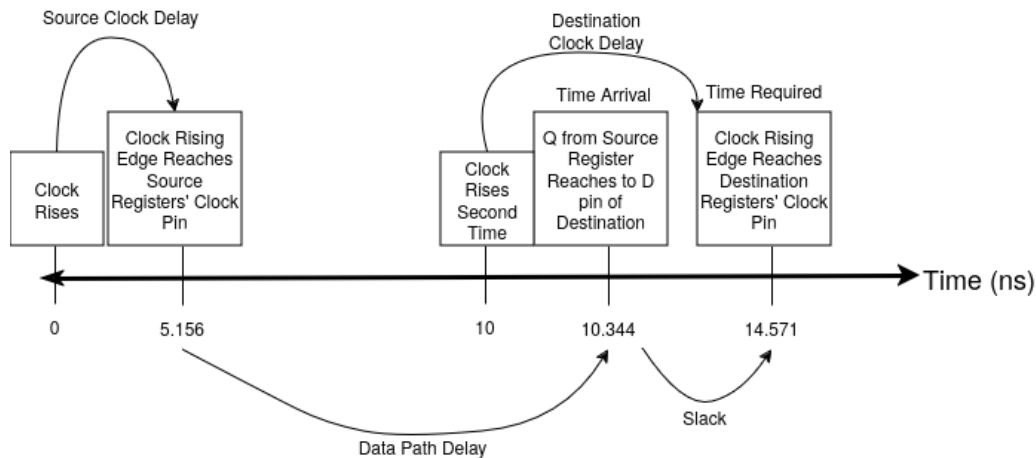


Figure 5.3.4.1: Setup Timing Path

When it is a hold slack timing path, the time that data reaches the destination register is calculated. Then the hold time is calculated by the time that data is stable after the clock edge. Unlike it is given as two flows starting at  $t = 0\text{ns}$ , one is data path, the other flow includes parts inside the register, which is to find hold time. An example hold slack timing path is shown below:

# Min Delay Paths

```

Slack (MET) :          0.177ns (arrival time - required time)
Source:          nolabel_line85/data_reg_reg[1]/C
                  (rising edge-triggered cell FDSE clocked by rx_clk {rise@0.000ns fall@270.000ns period})
Destination:     nolabel_line85/data_out_reg[1]/D
                  (rising edge-triggered cell FDRE clocked by rx_clk {rise@0.000ns fall@270.000ns period})
Path Group:      rx_clk
Path Type:       Hold (Min at Fast Process Corner)
Requirement:     0.000ns (rx_clk rise@0.000ns - rx_clk rise@0.000ns)
Data Path Delay: 0.266ns (logic 0.141ns (52.911%) route 0.125ns (47.089%))
Logic Levels:    0
Clock Path Skew: 0.013ns (DCD - SCD - CPR)
Destination Clock Delay (DCD): 3.331ns
Source Clock Delay (SCD): 2.476ns
Clock Pessimism Removal (CPR): 0.842ns

```

| Location      | Delay type               | Incr(ns) | Path(ns) | Netlist Resource(s)                 |
|---------------|--------------------------|----------|----------|-------------------------------------|
| -----         |                          |          |          |                                     |
|               | (clock rx_clk rise edge) | 0.000    | 0.000 r  |                                     |
| W5            |                          | 0.000    | 0.000 r  | clk (IN)                            |
|               | net (fo=0)               | 0.000    | 0.000    | clk                                 |
| W5            | IBUF (Prop_ibuf_I_0)     | 0.226    | 0.226 r  | clk_IBUF_inst/0                     |
|               | net (fo=1, routed)       | 0.631    | 0.858    | clk_IBUF                            |
| BUFGCTRL_X0Y0 | BUFG (Prop_bufg_I_0)     | 0.026    | 0.884 r  | clk_IBUF_BUFG_inst/0                |
|               | net (fo=139, routed)     | 0.562    | 1.445    | clk_div/clk_IBUF_BUFG               |
| SLICE_X35Y45  | FDRE (Prop_fdre_C_Q)     | 0.141    | 1.586 r  | clk_div/clk_rx_uart_out_reg/Q       |
|               | net (fo=2, routed)       | 0.268    | 1.854    | rx_clk                              |
| BUFGCTRL_X0Y1 | BUFG (Prop_bufg_I_0)     | 0.026    | 1.880 r  | rx_clk_BUFG_inst/0                  |
|               | net (fo=39, routed)      | 0.596    | 2.476    | nolabel_line85/rx_clk_BUFG          |
| SLICE_X3Y1    | FDSE                     |          | r        | nolabel_line85/data_reg_reg[1]/C    |
| -----         |                          |          |          |                                     |
| SLICE_X3Y1    | FDSE (Prop_fdse_C_Q)     | 0.141    | 2.617 r  | nolabel_line85/data_reg_reg[1]/Q    |
|               | net (fo=2, routed)       | 0.125    | 2.742    | nolabel_line85/data_reg_reg_n_0_[1] |
| SLICE_X2Y1    | FDRE                     |          | r        | nolabel_line85/data_out_reg[1]/D    |
| -----         |                          |          |          |                                     |
|               | (clock rx_clk rise edge) | 0.000    | 0.000 r  |                                     |
| W5            |                          | 0.000    | 0.000 r  | clk (IN)                            |
|               | net (fo=0)               | 0.000    | 0.000    | clk                                 |
| W5            | IBUF (Prop_ibuf_I_0)     | 0.414    | 0.414 r  | clk_IBUF_inst/0                     |
|               | net (fo=1, routed)       | 0.685    | 1.099    | clk_IBUF                            |
| BUFGCTRL_X0Y0 | BUFG (Prop_bufg_I_0)     | 0.029    | 1.128 r  | clk_IBUF_BUFG_inst/0                |
|               | net (fo=139, routed)     | 0.831    | 1.958    | clk_div/clk_IBUF_BUFG               |
| SLICE_X35Y45  | FDRE (Prop_fdre_C_Q)     | 0.175    | 2.133 r  | clk_div/clk_rx_uart_out_reg/Q       |
|               | net (fo=2, routed)       | 0.302    | 2.436    | rx_clk                              |

|               |                      |        |        |   |                                  |
|---------------|----------------------|--------|--------|---|----------------------------------|
| BUFGCTRL_X0Y1 | BUFG (Prop_bufg_I_0) | 0.029  | 2.465  | r | rx_clk_BUFG_inst/0               |
|               | net (fo=39, routed)  | 0.867  | 3.331  |   | nolabel_line85/rx_clk_BUFG       |
| SLICE_X2Y1    | FDRE                 |        |        | r | nolabel_line85/data_out_reg[1]/C |
|               | clock pessimism      | -0.842 | 2.489  |   |                                  |
| SLICE_X2Y1    | FDRE (Hold_fdre_C_D) | 0.076  | 2.565  |   | nolabel_line85/data_out_reg[1]   |
| -----         |                      |        |        |   |                                  |
|               | required time        |        | -2.565 |   |                                  |
|               | arrival time         |        | 2.742  |   |                                  |
| -----         |                      |        |        |   |                                  |
|               | slack                |        | 0.177  |   |                                  |

This report tries to calculate when destination register's data pin is changed after the clock edge for a path. To break down the information in the report:

- Time axis analyzed twice, one for data path, the other for hold time.
- The clock signal reached the source register at 2.476ns (Source Clock Delay), starting data path flow.
- Then the signal of source register is processed by the logic between and reached the destination register at 2.742ns. (Data Path Delay: 2.742ns - (2.476ns) = 0.266ns)
- The data pin is changed 2.742ns after the clock edge.
- Time axis analyzed again for hold time. Starting from 0ns, the clock signal reached the destination register at 2.489ns (Destination Clock Delay), starting hold time flow (for previous data that analyzed in setup time, this report looks for future change not back).
- After adding the hold time of the destination register, it is found that the data pin must not change before  $t=2.489\text{ns}+0.076\text{ns}$ (Hold Time).
- But we already found that the data pin is changed at  $t=2.742\text{ns}$ . Therefore, the hold slack is calculated as 0.177ns. (Time Arrival - Time Required).

**To sum up, time required is when the destination register completed hold (the data before the current clock rise). Time arrival is the exact time data changes D pin. Data path delay is Q to D.**

A graphical representation of the path as follows:



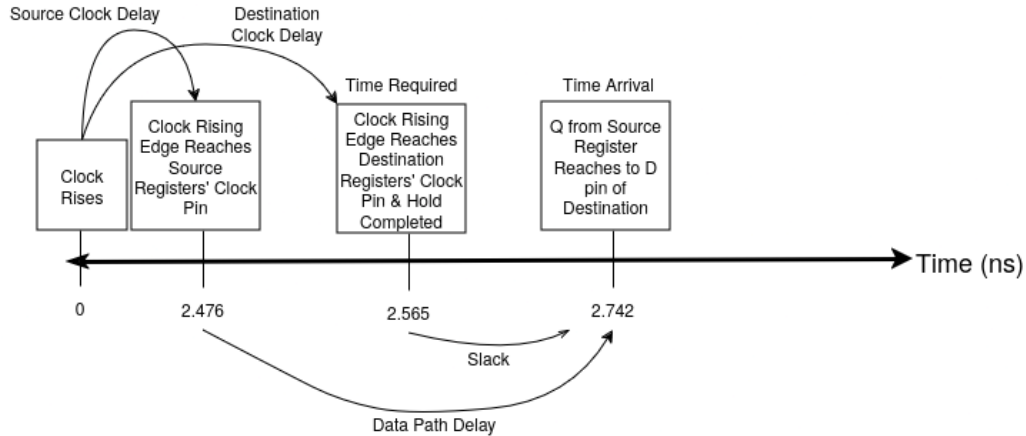


Figure 5.3.4.2: Hold Timing Path

As this path reports are categorized by clock, hold and setup, you can find the problematic sequence by inspecting the data path report like above. There are several solutions available for negative setup slack:

- Add clock buffer to destination clock / Fix clock skew
- Optimizing the data path delay
- Pipeline the design (insert extra stages/states)
- Decrease the clock frequency

*\*In timing analysis, clock pessimism is initially introduced to ensure safety. However, when calculating timing slack (e.g., setup slack), the tools may apply Clock Pessimism Removal (CPR) to reduce or eliminate some of this conservative estimation. CPR adjusts the clock arrival times so that the analysis is more realistic. Therefore, the slack value is calculated by subtracting the arrival time from the required time. Don't get confused.*

### 5.3.5 Input Delays and Importance to Timing Report

When input delay is not specified in the constraints file, the tool assumes that the input signal arrives at the flip-flop at the same time as the clock edge, therefore slacks are given infinite. This can cause timing violations if the input signal arrives too close to the clock edge. Therefore, it is important to specify the input delay in the constraints file to ensure that the design meets the timing requirements. This can change:

- Your design might have a negative hold slack because of this issue, **which is not a real issue.**
- Your design meet the timing requirements, but **with a input delay setup time might be violated in practice.**

Therefore, to ensure that design meets the timing requirements in the real world, you should set the input delay in the constraints file. To set the input delay in the constraints file, you can use the following syntax:

```
set_input_delay -clock [clock_name] -max [delay_value] [port_name]
set_input_delay -clock [clock_name] -min [delay_value] [port_name]
```

This is range of delay that input signal can arrive any time inside. For hold time analysis -min is used. For setup time analysis -max is used by Vivado. **Testing the effect of input delay to the report** For this purpose a simple module is created as follows:

- Makes calculation using input and writes to a register.

```
module InputDelayTest(
    input wire clk,
    input wire reset,
    input wire [7:0] data_in,
    output reg [11:0] data_out
);
    reg [7:0] prev; // Data Store

    always @(posedge clk or posedge reset) begin
        if (reset) begin
            data_out <= 9'b00000000; // Initialize the register
            prev <= 8'b00000000; // Initialize the register
        end else begin
            prev <= data_in;
            data_out <= prev * 14;
        end
    end
end
endmodule
```

The design is implemented and the timing report is analyzed without constraints at first. Lets take the paths going into the prev register.

```
report_timing -from [get_ports *data_in*] -to [get_cells *prev_reg*] -path_type summary -max_paths 1
```

Timing Report

| Startpoint | Endpoint      | Slack(ns) |
|------------|---------------|-----------|
| -----      |               |           |
| data_in[0] | prev_reg[6]/D | inf       |
| data_in[0] | prev_reg[7]/D | inf       |
| data_in[0] | prev_reg[5]/D | inf       |
| data_in[0] | prev_reg[4]/D | inf       |
| data_in[0] | prev_reg[3]/D | inf       |
| data_in[0] | prev_reg[2]/D | inf       |
| data_in[0] | prev_reg[1]/D | inf       |

```
report_timing -from [get_ports *data_in*] -to [get_cells *prev_reg*] -path_type summary -max_paths 1
```

#### Timing Report

| Startpoint | Endpoint      | Slack(ns) |
|------------|---------------|-----------|
| -----      |               |           |
| data_in[6] | prev_reg[7]/D | inf       |
| data_in[4] | prev_reg[5]/D | inf       |
| data_in[3] | prev_reg[4]/D | inf       |
| data_in[4] | prev_reg[6]/D | inf       |
| data_in[1] | prev_reg[2]/D | inf       |
| data_in[2] | prev_reg[3]/D | inf       |
| data_in[0] | prev_reg[1]/D | inf       |

As you can see, the design meets the timing requirements without any constraints. Now, lets set the input delay to 5ns at maximum and 2ns at minimum and analyze the timing report again.

```
set_input_delay -clock [get_clocks sys_clk_pin] -max 5 [get_ports *data_in*]
set_input_delay -clock [get_clocks sys_clk_pin] -min 2 [get_ports *data_in*]
```

After setting the input delay, the timing report is analyzed again:

```
report_timing -from [get_ports *data_in*] -to [get_cells *prev_reg*] -path_type summary -max_paths 1
```

#### Timing Report

| Startpoint | Endpoint      | Slack(ns) |
|------------|---------------|-----------|
| -----      |               |           |
| data_in[0] | prev_reg[6]/D | 3.541     |
| data_in[0] | prev_reg[5]/D | 3.573     |
| data_in[0] | prev_reg[7]/D | 3.573     |
| data_in[0] | prev_reg[4]/D | 3.634     |
| data_in[0] | prev_reg[3]/D | 3.660     |
| data_in[0] | prev_reg[2]/D | 3.713     |
| data_in[0] | prev_reg[1]/D | 3.761     |

```
report_timing -from [get_ports *data_in*] -to [get_cells *prev_reg*] -path_type summary -max_paths 1
```

#### Timing Report

| Startpoint | Endpoint      | Slack(ns) |
|------------|---------------|-----------|
| -----      |               |           |
| data_in[2] | prev_reg[6]/D | 0.275     |
| data_in[0] | prev_reg[4]/D | 0.335     |
| data_in[2] | prev_reg[7]/D | 0.543     |
| data_in[0] | prev_reg[5]/D | 0.601     |
| data_in[1] | prev_reg[2]/D | 0.636     |

|            |               |       |
|------------|---------------|-------|
| data_in[1] | prev_reg[3]/D | 0.904 |
| data_in[0] | prev_reg[1]/D | 1.319 |

As you can see, the slack values are now finite and the design meets the timing requirements with the input delay constraints. Lets examine the timings one more time by changing input time values that we can assume that it will create violation:

- As the worst setup slack is 3.541ns, if we set input delay to max 9ns, it is assumed to be violating the setup time.
- As the hold slack is 0.275ns, if we set input delay to min 0ns, it is assumed to be violating the hold time.

```
set_input_delay -clock [get_clocks sys_clk_pin] -max 9 [get_ports *data_in*]
set_input_delay -clock [get_clocks sys_clk_pin] -min 0 [get_ports *data_in*]
```

After setting the input delay, the timing report is analyzed again:

```
report_timing -from [get_ports *data_in*] -to [get_cells *prev_reg*] -path_type summary -max_paths 1
Timing Report
```

| Startpoint | Endpoint      | Slack(ns) |
|------------|---------------|-----------|
| data_in[1] | prev_reg[6]/D | -2.161    |
| data_in[1] | prev_reg[7]/D | -2.066    |
| data_in[1] | prev_reg[5]/D | -2.050    |
| data_in[1] | prev_reg[4]/D | -1.917    |
| data_in[1] | prev_reg[3]/D | -1.857    |
| data_in[1] | prev_reg[2]/D | -1.504    |
| data_in[0] | prev_reg[1]/D | -0.752    |

```
report_timing -from [get_ports *data_in*] -to [get_cells *prev_reg*] -path_type summary -max_paths 1
Timing Report
```

| Startpoint | Endpoint      | Slack(ns) |
|------------|---------------|-----------|
| data_in[5] | prev_reg[6]/D | 0.067     |
| data_in[2] | prev_reg[3]/D | 0.139     |
| data_in[3] | prev_reg[4]/D | 0.163     |
| data_in[0] | prev_reg[1]/D | 0.276     |
| data_in[5] | prev_reg[7]/D | 0.335     |
| data_in[2] | prev_reg[5]/D | 0.403     |
| data_in[0] | prev_reg[2]/D | 0.410     |

As the reports indicate, the worst setup slack is dropped down by almost 5.7 which is more than the input delay we increased by 4. The hold slack is also decreased by 0.2ns. This is a good example to show the importance of input delay constraints in the timing analysis. **Even though the slack changes exact the amount of the delay due to required and arrival time factors, our hypothesis is correct. The design is not meeting the timing requirements anymore.**

### 5.3.6 TCL Commands

The most useful settings for timing analysis when calling tcl option are:

- -from [pin]: The starting point of the path to be analyzed.
- -to [pin]: The ending point of the path to be analyzed.
- -setup: The setup time analysis for the paths.
- -hold: The hold time analysis for the paths.
- -nworst or max\_paths [#]: The number of worst paths per clock domain if grouped or first # paths to be analyzed.
- -through [names]: The paths that are crossing a specific nets/pins/cells.
- -path\_type summary: This is useful only to see slack and path.

You can combine these options, adding them to options place `report_timing [options]` to get the report you desire. To find pin/path/cell names, you can use `get_pins`, `get_paths`, `get_cells` commands, with search option `*keyword*`. Example: `get_pins *clk*`. you can combine these commands like this:

```
report_timing -to [get_cells *prev_reg*] -path_type summary -max_paths 20 -setup
```

\*It is useful when the original report only gives worse 10 slacks and you need to know the exact path slack for improvement. For example you can find and get timings of all paths to a single register with these commands.

## Chapter 6

# Examining Reports of Common Designs & Questions

In this section, we will examine the reports of some common designs to understand the information provided in the reports and we will see how LUT/DSP arithmetic, shifting registers effect power, timing, and resource utilization.

### 6.1 Multiplication

In this design, we will try to find best way to multiply two 8,16,32-bit numbers. We will compare LUTs, DSPs, and using Multiply IP and '\*' operator.

#### 6.1.1 First Case

In this case, we will use the '\*' operator and Multilier IP (No Stages) to multiply two numbers, using only LUTs.

The modules used are below:

```
(* USE_DSP="no", keep_hierarchy = "yes" *) module Multiplier #(parameter A_WIDTH = 8,
    B_WIDTH = 8)(input wire clk,
    input wire [A_WIDTH-1:0] a,
    input wire [B_WIDTH-1:0] b,
    output reg [A_WIDTH+B_WIDTH-1:0] product
);

    always @(clk) begin
        product <= a * b;
    end

endmodule
```

```

module Main(
    input wire clk, input wire [31:0] raw_a_32, input wire [31:0] raw_b_32,
    input wire rst, output reg [5:0] fake_out
);

    wire AHundredMHz_clk;
    wire TwoHundredMHz_clk;
    wire locked;

    reg [31:0] a_32;
    reg [31:0] b_32;
    reg [15:0] product_16;
    reg [31:0] product_32;
    reg [63:0] product_64;
    reg [15:0] product_ip_16;
    reg [31:0] product_ip_32;
    reg [63:0] product_ip_64;

    clk_wiz_0 clk_prov(.clk_out1(AHundredMHz_clk), .clk_out2(TwoHundredMHz_clk), .reset(rst), .locked(locked));

    wire [15:0] product_w_16;
    wire [31:0] product_w_32;
    wire [63:0] product_w_64;
    wire [15:0] product_ip_w_16;
    wire [31:0] product_ip_w_32;
    wire [63:0] product_ip_w_64;

    Multiplier #(.A_WIDTH(8), .B_WIDTH(8)) mult_8(.clk(AHundredMHz_clk), .a(a_32[7:0]), .b(b_32[7:0]));
    Multiplier #(.A_WIDTH(16), .B_WIDTH(16)) mult_16(.clk(AHundredMHz_clk), .a(a_32[15:0]), .b(b_32[15:0]));
    Multiplier #(.A_WIDTH(32), .B_WIDTH(32)) mult_32(.clk(AHundredMHz_clk), .a(a_32[31:0]), .b(b_32[31:0]));

    mult_gen_0 mult_gen_8(a_32[7:0], b_32[7:0], product_ip_w_16);
    mult_gen_1 mult_gen_16(a_32[15:0], b_32[15:0], product_ip_w_32);
    mult_gen_2 mult_gen_32(a_32[31:0], b_32[31:0], product_ip_w_64);

    always @(posedge AHundredMHz_clk or posedge rst) begin
        if (rst) begin
            product_16 <= 16'b0;
            product_32 <= 32'b0;
            product_64 <= 64'b0;
            product_ip_16 <= 16'b0;
            product_ip_32 <= 32'b0;
            product_ip_64 <= 64'b0;
        end
        else begin
            product_16 <= product_w_16;

```

```

        product_32 <= product_w_32;
        product_64 <= product_w_64;
        product_ip_16 <= product_ip_w_16;
        product_ip_32 <= product_ip_w_32;
        product_ip_64 <= product_ip_w_64;
        fake_out[0] <= product_16[15];
        fake_out[1] <= product_32[31];
        fake_out[2] <= product_64[63];
        fake_out[3] <= product_ip_16[15];
        fake_out[4] <= product_ip_32[31];
        fake_out[5] <= product_ip_64[63];
        a_32 <= raw_a_32;
        b_32 <= raw_b_32;
    end
end
endmodule

```

The results of the first case are shown below: **Utilization:**








| Name                                                                                                                    | ^1 | Slice LUTs<br>(20800) | Slice Registers<br>(41600) | Slice<br>(8150) | LUT as Logic<br>(20800) | Bonded IOB<br>(106) | BUFGCTRL<br>(32) | PLLE2_ADV<br>(5) |
|-------------------------------------------------------------------------------------------------------------------------|----|-----------------------|----------------------------|-----------------|-------------------------|---------------------|------------------|------------------|
| ▼ <b>N Main</b>                                                                                                         |    | 2788                  | 132                        | 816             | 2788                    | 72                  | 2                | 1                |
| >  clk_prov (clk_wiz_0)                |    | 0                     | 0                          | 0               | 0                       | 0                   | 2                | 1                |
|  mult_8 (Multiplier)                   |    | 69                    | 0                          | 21              | 69                      | 0                   | 0                | 0                |
|  mult_16 (Multiplier_parameterized0)  |    | 294                   | 0                          | 85              | 294                     | 0                   | 0                | 0                |
|  mult_32 (Multiplier_parameterized1) |    | 1105                  | 0                          | 309             | 1105                    | 0                   | 0                | 0                |
| >  mult_gen_8 (mult_gen_0)           |    | 60                    | 0                          | 21              | 60                      | 0                   | 0                | 0                |
| >  mult_gen_16 (mult_gen_1)          |    | 249                   | 0                          | 77              | 249                     | 0                   | 0                | 0                |
| >  mult_gen_32 (mult_gen_2)          |    | 1012                  | 0                          | 288             | 1012                    | 0                   | 0                | 0                |

Figure 6.1.1.1: Only LUT Multilier Utilization Hierarchical

The submodules that has 'gen' in their names are IP multipliers build with only LUTs. The results indicate that the IP has better resource utilization than the '\*' operator.

**Power:**


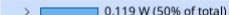



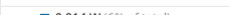











| Utilization                                                                                                  | Name                                                                                                                    | Clocks (W) | Signals (W) | Data (W) | Clock Enable (W) | Logic (W) | Clock Manager (W) | PLL (W) | I/O (W) |
|--------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|------------|-------------|----------|------------------|-----------|-------------------|---------|---------|
| ▼  0.168 W (70% of total) | <b>N Main</b>                                                                                                           |            |             |          |                  |           |                   |         |         |
| >  0.119 W (50% of total) |  clk_prov (clk_wiz_0)                | <0.001     | <0.001      | <0.001   | <0.001           | <0.001    | 0.119             | 0.119   | <0.001  |
| >  0.014 W (6% of total)  |  mult_32 (Multiplier_parameterized1) | <0.001     | 0.006       | 0.006    | <0.001           | 0.008     | <0.001            | <0.001  | <0.001  |
|  0.014 W (6% of total)    |  Leaf Cells (206)                    |            |             |          |                  |           |                   |         |         |
| >  0.013 W (6% of total)  |  mult_gen_32 (mult_gen_2)            | <0.001     | 0.007       | 0.007    | <0.001           | 0.007     | <0.001            | <0.001  | <0.001  |
| >  0.003 W (1% of total)  |  mult_16 (Multiplier_parameterized0) | <0.001     | 0.001       | 0.001    | <0.001           | 0.002     | <0.001            | <0.001  | <0.001  |
| >  0.003 W (1% of total)  |  mult_gen_16 (mult_gen_1)            | <0.001     | 0.001       | 0.001    | <0.001           | 0.002     | <0.001            | <0.001  | <0.001  |
| >  0.001 W (1% of total)  |  mult_8 (Multiplier)                 | <0.001     | <0.001      | <0.001   | <0.001           | <0.001    | <0.001            | <0.001  | <0.001  |
| >  0.001 W (<1% of total) |  mult_gen_8 (mult_gen_0)             | <0.001     | <0.001      | <0.001   | <0.001           | <0.001    | <0.001            | <0.001  | <0.001  |

Figure 6.1.1.2: Only LUT Multilier Power Hierarchical

The results indicates that the IP has better power utilization than the '\*' operator.



**Timing:** Critical path timing (Violating) of the design as follows:

a\_32\_reg Register -> LUT 32 IP -> product\_ip\_64 Register

Slack (VIOLATED) : -0.973ns (required time - arrival time)  
Source: a\_32\_reg[8]/C  
(rising edge-triggered cell FDRE clocked by clk\_out1\_clk\_wiz\_0 {rise@0.000ns - 10.000ns})  
Destination: product\_ip\_64\_reg[63]/D  
(rising edge-triggered cell FDCE clocked by clk\_out1\_clk\_wiz\_0 {rise@0.000ns - 10.000ns})  
Path Group: clk\_out1\_clk\_wiz\_0  
Path Type: Setup (Max at Slow Process Corner)  
Requirement: 10.000ns (clk\_out1\_clk\_wiz\_0 rise@10.000ns - clk\_out1\_clk\_wiz\_0 rise@0.000ns)  
Data Path Delay: 10.936ns (logic 6.760ns (61.812%) route 4.176ns (38.188%))  
Logic Levels: 23 (CARRY4=18 LUT2=4 LUT4=1)  
Clock Path Skew: -0.031ns (DCD - SCD + CPR)  
Destination Clock Delay (DCD): -2.062ns = ( 7.938 - 10.000 )  
Source Clock Delay (SCD): -2.457ns  
Clock Pessimism Removal (CPR): -0.425ns  
Clock Uncertainty: 0.068ns ((TSJ^2 + DJ^2)^1/2) / 2 + PE  
Total System Jitter (TSJ): 0.071ns  
Discrete Jitter (DJ): 0.116ns  
Phase Error (PE): 0.000ns

b\_32\_reg Register -> LUT 32 '\*' Logic -> product\_64 Register

Slack (VIOLATED) : -0.776ns (required time - arrival time)  
Source: b\_32\_reg[4]/C  
(rising edge-triggered cell FDRE clocked by clk\_out1\_clk\_wiz\_0 {rise@0.000ns - 10.000ns})  
Destination: product\_64\_reg[63]/D  
(rising edge-triggered cell FDCE clocked by clk\_out1\_clk\_wiz\_0 {rise@0.000ns - 10.000ns})  
Path Group: clk\_out1\_clk\_wiz\_0  
Path Type: Setup (Max at Slow Process Corner)  
Requirement: 10.000ns (clk\_out1\_clk\_wiz\_0 rise@10.000ns - clk\_out1\_clk\_wiz\_0 rise@0.000ns)  
Data Path Delay: 10.851ns (logic 5.250ns (48.381%) route 5.601ns (51.619%))  
Logic Levels: 21 (CARRY4=15 LUT3=2 LUT4=1 LUT5=1 LUT6=2)  
Clock Path Skew: 0.034ns (DCD - SCD + CPR)  
Destination Clock Delay (DCD): -2.002ns = ( 7.998 - 10.000 )  
Source Clock Delay (SCD): -2.462ns  
Clock Pessimism Removal (CPR): -0.425ns  
Clock Uncertainty: 0.068ns ((TSJ^2 + DJ^2)^1/2) / 2 + PE  
Total System Jitter (TSJ): 0.071ns  
Discrete Jitter (DJ): 0.116ns  
Phase Error (PE): 0.000ns

a\_32\_reg Register -> LUT 16 '\*' Logic -> product\_32 Register

Slack (VIOLATED) : -0.131ns (required time - arrival time)

```

Source:                a_32_reg[12]/C
                        (rising edge-triggered cell FDRE clocked by clk_out1_clk_wiz_0 {rise@0.000ns fall@0.000ns})
Destination:           product_32_reg[31]/D
                        (rising edge-triggered cell FDCE clocked by clk_out1_clk_wiz_0 {rise@0.000ns fall@0.000ns})
Path Group:            clk_out1_clk_wiz_0
Path Type:             Setup (Max at Slow Process Corner)
Requirement:           10.000ns (clk_out1_clk_wiz_0 rise@10.000ns - clk_out1_clk_wiz_0 rise@0.000ns)
Data Path Delay:       10.134ns (logic 3.673ns (36.244%) route 6.461ns (63.756%))
Logic Levels:          12 (CARRY4=7 LUT3=1 LUT4=1 LUT5=1 LUT6=2)
Clock Path Skew:       -0.038ns (DCD - SCD + CPR)
  Destination Clock Delay (DCD): -2.067ns = ( 7.933 - 10.000 )
  Source Clock Delay (SCD):      -2.455ns
  Clock Pessimism Removal (CPR): -0.425ns
Clock Uncertainty:     0.068ns ((TSJ^2 + DJ^2)^1/2) / 2 + PE
  Total System Jitter (TSJ):     0.071ns
  Discrete Jitter (DJ):          0.116ns
  Phase Error (PE):             0.000ns

a_32_reg Register -> LUT 32 '*' IP -> product_ip_32 Register
Slack (VIOLATED) :     -0.104ns (required time - arrival time)
Source:                a_32_reg[0]/C
                        (rising edge-triggered cell FDRE clocked by clk_out1_clk_wiz_0 {rise@0.000ns fall@0.000ns})
Destination:           product_ip_32_reg[31]/D
                        (rising edge-triggered cell FDCE clocked by clk_out1_clk_wiz_0 {rise@0.000ns fall@0.000ns})
Path Group:            clk_out1_clk_wiz_0
Path Type:             Setup (Max at Slow Process Corner)
Requirement:           10.000ns (clk_out1_clk_wiz_0 rise@10.000ns - clk_out1_clk_wiz_0 rise@0.000ns)
Data Path Delay:       10.107ns (logic 5.046ns (49.927%) route 5.061ns (50.073%))
Logic Levels:          14 (CARRY4=10 LUT2=4)
Clock Path Skew:       -0.038ns (DCD - SCD + CPR)
  Destination Clock Delay (DCD): -2.070ns = ( 7.930 - 10.000 )
  Source Clock Delay (SCD):      -2.458ns
  Clock Pessimism Removal (CPR): -0.425ns
Clock Uncertainty:     0.068ns ((TSJ^2 + DJ^2)^1/2) / 2 + PE
  Total System Jitter (TSJ):     0.071ns
  Discrete Jitter (DJ):          0.116ns
  Phase Error (PE):             0.000ns

```

The results indicate that 32-bit multiplication has timing violation for both. The '\*' operator seems to more close to 0 slack than the IP multiplier for 32-Bit. However, for the 16-bit violation, the IP multiplier has better slack than the '\*' operator. Using LUT multipliers ('\*' or IP) over 8-bit is not recommended because of inefficient resource utilization and timing violations.

### 6.1.2 Second Case

In this case, we will use the '\*' operator and Multiplier IP (No Stages) to multiply two numbers, using DSPs.

The modules used are below:

```
(* USE_DSP="yes", keep_hierarchy = "yes" *) module Multiplier_Dsp #(parameter A_WIDTH = 8,
    B_WIDTH = 8)(input wire clk,
    input wire [A_WIDTH-1:0] a,
    input wire [B_WIDTH-1:0] b,
    output reg [A_WIDTH+B_WIDTH-1:0] product
);

    always @(clk) begin
        product <= a * b;
    end
endmodule

module Main_Dsp(
input wire clk, input wire [31:0] raw_a_32, input wire [31:0] raw_b_32, input wire rst, output reg [63:0] product
);

    wire AHundredMHz_clk;
    wire TwoHundredMHz_clk;
    wire locked;

    reg [31:0] a_32;
    reg [31:0] b_32;
    reg [15:0] product_16;
    reg [31:0] product_32;
    reg [63:0] product_64;
    reg [15:0] product_ip_16;
    reg [31:0] product_ip_32;
    reg [63:0] product_ip_64;

    clk_wiz_0 clk_prov_1(.clk_out1(AHundredMHz_clk), .clk_out2(TwoHundredMHz_clk), .reset(rst), .locked(locked));

    wire [15:0] product_w_16;
    wire [31:0] product_w_32;
    wire [63:0] product_w_64;
    wire [15:0] product_ip_w_16;
    wire [31:0] product_ip_w_32;
    wire [63:0] product_ip_w_64;

    Multiplier_Dsp #(.A_WIDTH(8), .B_WIDTH(8)) mult_dsp_8(.clk(AHundredMHz_clk), .a(a_32[7:0]), .b(b_32[7:0]), .product(product_w_16));
    Multiplier_Dsp #(.A_WIDTH(16), .B_WIDTH(16)) mult_dsp_16(.clk(AHundredMHz_clk), .a(a_32[15:0]), .b(b_32[15:0]), .product(product_w_32));
    Multiplier_Dsp #(.A_WIDTH(32), .B_WIDTH(32)) mult_dsp_32(.clk(AHundredMHz_clk), .a(a_32[31:0]), .b(b_32[31:0]), .product(product_w_64));
```

```

mult_gen_3 mult_gen_dsp_8(a_32[7:0], b_32[7:0], product_ip_w_16);
mult_gen_4 mult_gen_dsp_16(a_32[15:0], b_32[15:0], product_ip_w_32);
mult_gen_5 mult_gen_dsp_32(a_32[31:0], b_32[31:0], product_ip_w_64);

always @(posedge AHundredMHz_clk or posedge rst) begin
    if (rst) begin
        product_16 <= 16'b0;
        product_32 <= 32'b0;
        product_64 <= 64'b0;
        product_ip_16 <= 16'b0;
        product_ip_32 <= 32'b0;
        product_ip_64 <= 64'b0;
    end
    else begin
        product_16 <= product_w_16;
        product_32 <= product_w_32;
        product_64 <= product_w_64;
        product_ip_16 <= product_ip_w_16;
        product_ip_32 <= product_ip_w_32;
        product_ip_64 <= product_ip_w_64;
        fake_out[0] <= product_16[15];
        fake_out[1] <= product_32[31];
        fake_out[2] <= product_64[63];
        fake_out[3] <= product_ip_16[15];
        fake_out[4] <= product_ip_32[31];
        fake_out[5] <= product_ip_64[63];
        a_32 <= raw_a_32;
        b_32 <= raw_b_32;
    end
end
endmodule

```

The results of the second case are shown below: **Utilization:**

| Name                                            | ^1 | Slice LUTs<br>(20800) | Slice Registers<br>(41600) | Slice<br>(8150) | LUT as Logic<br>(20800) | DSPs<br>(90) | Bonded IOB<br>(106) | BUFCTRL<br>(32) | PLLE2_ADV<br>(5) |
|-------------------------------------------------|----|-----------------------|----------------------------|-----------------|-------------------------|--------------|---------------------|-----------------|------------------|
| ▼ N Main_Dsp                                    |    | 48                    | 106                        | 50              | 48                      | 12           | 72                  | 2               | 1                |
| > [I] clk_prov_1 (clk_wiz_0)                    |    | 0                     | 0                          | 0               | 0                       | 0            | 0                   | 2               | 1                |
| [I] mult_dsp_8 (Multiplier_Dsp)                 |    | 0                     | 0                          | 0               | 0                       | 1            | 0                   | 0               | 0                |
| [I] mult_dsp_16 (Multiplier_Dsp_parameterized0) |    | 0                     | 0                          | 0               | 0                       | 1            | 0                   | 0               | 0                |
| [I] mult_dsp_32 (Multiplier_Dsp_parameterized1) |    | 47                    | 0                          | 12              | 47                      | 4            | 0                   | 0               | 0                |
| > [I] mult_gen_dsp_8 (mult_gen_3)               |    | 0                     | 0                          | 0               | 0                       | 1            | 0                   | 0               | 0                |
| > [I] mult_gen_dsp_16 (mult_gen_4)              |    | 0                     | 0                          | 0               | 0                       | 1            | 0                   | 0               | 0                |
| > [I] mult_gen_dsp_32 (mult_gen_5)              |    | 0                     | 0                          | 0               | 0                       | 4            | 0                   | 0               | 0                |

Figure 6.1.2.1: DSP Multilier Utilization Hierarchical

The submodules that has 'gen' in their names are IP multipliers built with only DSPs. The

results indicate that the IP has better resource utilization than the '\*' operator for only 32-bit multiplication. Otherwise same.

## Power:

| Utilization                 | Name                                        | Clocks (W) | Signals (W) | Data (W) | Clock Enable (W) | Logic (W) | DSP (W) | Clock Manager (W) | PLL (W) | I/O (W) |
|-----------------------------|---------------------------------------------|------------|-------------|----------|------------------|-----------|---------|-------------------|---------|---------|
| ▼ 0.133 W (65% of total)    | <b>Main_Dsp</b>                             |            |             |          |                  |           |         |                   |         |         |
| > 0.119 W (59% of total)    | clk_prov_1 (clk_wiz_0)                      | <0.001     | <0.001      | <0.001   | <0.001           | <0.001    | <0.001  | 0.119             | 0.119   | <0.001  |
| ■ 0.006 W (3% of total)     | Leaf Cells (180)                            |            |             |          |                  |           |         |                   |         |         |
| > ■ 0.004 W (2% of total)   | mult_dsp_32 (Multiplier_Dsp_parameterized1) | <0.001     | 0.001       | 0.001    | <0.001           | <0.001    | 0.003   | <0.001            | <0.001  | <0.001  |
| > ■ 0.003 W (2% of total)   | mult_gen_dsp_32 (mult_gen_5)                | <0.001     | <0.001      | <0.001   | <0.001           | <0.001    | 0.003   | <0.001            | <0.001  | <0.001  |
| > ■ <0.001 W (<1% of total) | mult_dsp_16 (Multiplier_Dsp_parameterized0) | <0.001     | <0.001      | <0.001   | <0.001           | <0.001    | <0.001  | <0.001            | <0.001  | <0.001  |
| > ■ <0.001 W (<1% of total) | mult_gen_dsp_16 (mult_gen_4)                | <0.001     | <0.001      | <0.001   | <0.001           | <0.001    | <0.001  | <0.001            | <0.001  | <0.001  |
| > ■ <0.001 W (<1% of total) | mult_dsp_8 (Multiplier_Dsp)                 | <0.001     | <0.001      | <0.001   | <0.001           | <0.001    | <0.001  | <0.001            | <0.001  | <0.001  |
| > ■ <0.001 W (<1% of total) | mult_gen_dsp_8 (mult_gen_3)                 | <0.001     | <0.001      | <0.001   | <0.001           | <0.001    | <0.001  | <0.001            | <0.001  | <0.001  |

Figure 6.1.2.2: DSP Multilier Power Hierarchical

For 32-bit, IP multiplier has better power utilization than the '\*' operator. Otherwise, they are similar.

**Timing:** Critical path timing (Violating) of the design as follows:

```
Slack (VIOLATED) :      -0.644ns (required time - arrival time)
Source:                a_32_reg[10]_replica/C
                        (rising edge-triggered cell FDRE clocked by clk_out1_clk_wiz_0 {rise@0.000ns - fall@0.000ns})
Destination:          product_ip_64_reg[63]/D
                        (rising edge-triggered cell FDCE clocked by clk_out1_clk_wiz_0 {rise@0.000ns - fall@0.000ns})
Path Group:            clk_out1_clk_wiz_0
Path Type:              Setup (Max at Slow Process Corner)
Requirement:           10.000ns (clk_out1_clk_wiz_0 rise@10.000ns - clk_out1_clk_wiz_0 rise@0.000ns)
Data Path Delay:        10.540ns (logic 9.436ns (89.525%) route 1.104ns (10.475%))
Logic Levels:           4 (DSP48E1=4)
Clock Path Skew:        -0.020ns (DCD - SCD + CPR)
  Destination Clock Delay (DCD): -2.061ns = ( 7.939 - 10.000 )
  Source Clock Delay (SCD):      -2.454ns
  Clock Pessimism Removal (CPR): -0.412ns
Clock Uncertainty:      0.068ns ((TSJ^2 + DJ^2)^1/2) / 2 + PE
  Total System Jitter (TSJ):     0.071ns
  Discrete Jitter (DJ):          0.116ns
  Phase Error (PE):              0.000ns
```

```
Slack (VIOLATED) :      -0.068ns (required time - arrival time)
Source:                b_32_reg[6]_replica/C
                        (rising edge-triggered cell FDRE clocked by clk_out1_clk_wiz_0 {rise@0.000ns - fall@0.000ns})
Destination:          product_64_reg[63]/D
                        (rising edge-triggered cell FDCE clocked by clk_out1_clk_wiz_0 {rise@0.000ns - fall@0.000ns})
Path Group:            clk_out1_clk_wiz_0
Path Type:              Setup (Max at Slow Process Corner)
Requirement:           10.000ns (clk_out1_clk_wiz_0 rise@10.000ns - clk_out1_clk_wiz_0 rise@0.000ns)
Data Path Delay:        10.043ns (logic 7.611ns (75.785%) route 2.432ns (24.215%))
Logic Levels:           10 (CARRY4=7 DSP48E1=2 LUT2=1)
Clock Path Skew:        -0.019ns (DCD - SCD + CPR)
```

```

Destination Clock Delay (DCD):    -2.061ns = ( 7.939 - 10.000 )
Source Clock Delay      (SCD):    -2.455ns
Clock Pessimism Removal (CPR):    -0.412ns
Clock Uncertainty:      0.068ns  ((TSJ^2 + DJ^2)^1/2) / 2 + PE
Total System Jitter     (TSJ):    0.071ns
Discrete Jitter         (DJ):     0.116ns
Phase Error             (PE):     0.000ns

```

The results indicate that 32-bit multiplication has timing violation for both. The '\*' operator seems to more close to 0 slack than the IP multiplier for 32-Bit. When other met max delay paths are inspected, the IP multiplier data path delay is larger than '\*' in general. For a no stage multiplication using DSP a '\*' operator might be the choice for better slack given a bit more area is used.

Given the results using DSP blocks are much more efficient than using LUTs for multiplication for larger bit arrays. If the design intends to use no pipeline, the '\*' operator might be the choice for better slack and usage simplicity as the results are close with no stage IP.

## 6.2 Slack / Clock / Pipeline Relationship Investigation

In this part we will try to answer following questions:

1. Can we assume that if we increase clock period by X seconds, slack will increase by X seconds?
2. How does Multiplier IP stages effect slack? (Even delay paths between stages or not)
3. Using the information from first two questions, can we fine tune the clock period given to IP multiplier to have a single clock cycle result in the top module?
4. Why does the IP setup suggests a stage level? Is it related to the maximum clock speed of the device?

### 6.2.1 First Question

In this part, we will try to understand the relationship between slack and clock period. We will try to increase the clock period by X seconds and see if the slack increases by X seconds. We will use the same module from the dsp part of the multiplication part using only IP Multiliers.

The clock period was set to 10ns and worst slack was around -0.644ns. New clock period will be:

$$\text{Closest integer} = \left\lfloor \frac{1}{10\text{ns} + 0.644} + \frac{1}{2} \right\rfloor = 93896714 \approx 93.75\text{MHZ}$$

The hypothesis is that if we set the clock period to 10.667ns, the slack will be positive close to 0. The results are shown below:

|               |        |
|---------------|--------|
| -----         |        |
| required time | 8.073  |
| arrival time  | -8.073 |
| -----         |        |
| slack         | -0.001 |

It failed again. It is observed that the slack is close to 0. The hypothesis is close to be correct. The slack is increased by 0.649ns when the clock period is increased by 0.667ns. Given the phase error and jitter of the clock it is more safe to increase the clock period more than required.

Trying again with 93.333MHZ, 10.71ns:

|               |        |
|---------------|--------|
| required time | 8.117  |
| arrival time  | -8.076 |
| slack         | 0.041  |

Slack is tested again with other clocks as data path delay is changing with the clock When the results are combined (Note that the non ip parts are removed therefore the the slack at 100MHZ is different than the previous results):

Table 6.1: Timing Analysis at Different Clock Frequencies

| Path Delay | Clk frq (MHz) | Period (ns) | Slack  |
|------------|---------------|-------------|--------|
| 11.093     | 50            | 20.000      | 8.657  |
| 10.538     | 93.333        | 10.714      | 0.041  |
| 10.535     | 93.750        | 10.535      | -0.001 |
| 10.373     | 100           | 10.000      | -0.495 |
| 10.361     | 200           | 5.000       | -5.488 |

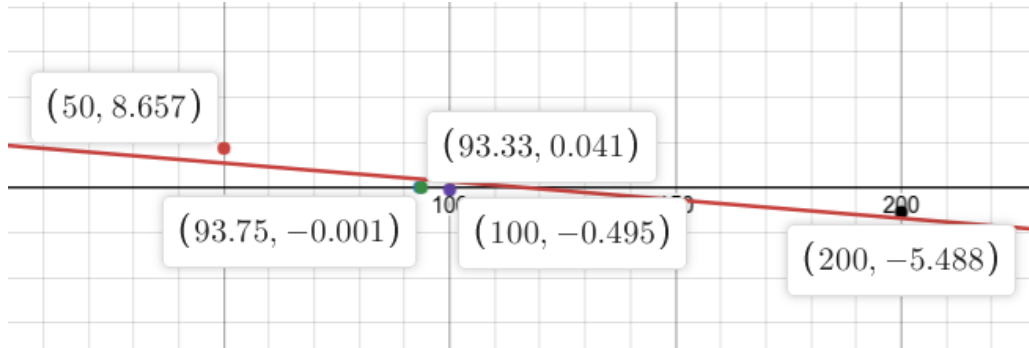


Figure 6.2.1.1: Frequency vs Slack Graph

By looking and plotting the data we can see that the data path delay and thus the slack values are not linearly related to the clock period. As frequency increases, change of the path delay decreases. By doing this analysis we can conclude that there is no linear relationship between slack and clock period, but there is a relation close to linear at higher clock speeds as data path delay tends to be constant.



### 6.2.2 Second Question

The second question requires us to find how does Multiplier IP pipelines multiple stages. To find a relationship, we will use critical path and how it is reduced after each stage. Same module will be used with different stages of IP multipliers.

During this test we will use 10ns clock period. It has initially Worst Slack as -0.495ns. The two paths that are critical are:

- any a or b register to IP (it can have a weird name like `mult_gen_dsp_32/U0/i_mult/gDSP.gDSP_only.iDSP/use_prim.appDSP[1].bppDSP[1].use_dsp.use_dsp48e1.iDSP48E1/PCIN[0]`) which refers to a flip flop inside the DSP block)
  - any path from IP to output register
  - any path from IP register to IP register
1. **Stage 0:** Slowest path is from `a_32[i]` register to the product register through the IP. **The max data path delay is 10.373 ns.**
  2. **Stage 1:** Slowest path is from `a_32[i]` register to a dsp register register inside the IP. **Data path delay is 8.503.** Searching a path from an IP to output register, **the longest path is 1.119ns** and it is in the 32-bit multiplier. It suggests that the IP doing most of the job in the first cycle.
  3. **Stage 2:** Slowest path is from a dsp register inside the IP to a dsp register register inside the IP (`mult_gen_dsp_32/U0/i_mult/gDSP.gDSP_only.iDSP/use_prim.appDSP[0].bppDSP[0].use_dsp.use_dsp48e1.iDSP48E1/PCIN[0]`) to `mult_gen_dsp_32/U0/i_mult/gDSP.gDSP_only.iDSP/use_prim.appDSP[1].bppDSP[1]`). **Data path delay is 6.633..** It suggests that most of the job is done in the intermediate cycle. In the first cycle the maximum data path is to the 32-bit multiplier IP and **Its data path delay is 2.815.** The maximum data path delay from the IPs to output register is 1.180ns and in the 32-bit multiplier.
  4. **Stage 3:** From timing report couldn't detect pipelining paths due to hidden information, but intermediate maximum data path delay is **4.208ns**. Input to the IP paths has maximum delay **2.815 ns**. The maximum data path delay from the IPs to output register is **1.119ns**. These are the maximum delay paths and they are inside the 32-bit multiplier IP.

From this information we can come up with a table:

Input refers to the delay from the input register to the IP, intermediate step/s refers to the delay inside the IPs, and output refers to the delay from the IP to the output register. A few things can be inferred from the table:

- The maximum delay path is reduced after each stage by around 2ns.
- Stages are not divided equally. An intermediate step is doing most of the job, or first one if it is a stage 0 and stage 1 IP.
- After 2 stages data path that gets input and gives output stays similar as job is done in the intermediate steps.

|             | Critical Path Delays (ns) |                     |        |
|-------------|---------------------------|---------------------|--------|
| # of Stages | Input                     | Intermediate Step/s | Output |
| 0           | Combinational*            |                     | 10.373 |
| 1           | 8.503                     | -                   | 1.119  |
| 2           | 2.815                     | 6.633               | 1.180  |
| 3           | 2.815                     | 4.208               | 1.119  |

Table 6.2: Critical Path Delays

To be sure that the data path delay is reduced by 2ns after each stage, the reports for 4 stages and check the data path delays is checked. The maximum delay path in the ip and the whole system reduced to 2.428 as expected. At 5th stage, intermediate step path delays are below input and output path delays and **almost all of their delays are net delay**, so we can't say at every stage 2ns reduced.

### 6.2.3 Third Question

The investigation indicates that we can't assume that the stages are equally divided and we cannot multiply clock by 2 as we increase the pipeline stages by one.

### 6.2.4 Fourth Question

Another mystery that why and how the optimum stage level of multiplier ip suggested by Vivado. The hypothesis is that it is related to the minimum clock period that the device, Basys3, can handle. Basys3 can handle maximum **450MHZ** clock frequency as documented, which corresponds to 2.222ns. The IP suggests a stage level to be 6 for 32-bit unsigned multiplier. We will check:

- The maximum delay path and the slack in the IP at stage level suggested.
- If it is below 2.222ns and we have slack around 8ns, we will check slack given the clock period is 2.222ns because given clock related time delays data path delay doesn't directly mean time required.
- To finalize the hypothesis, we will check again at stage level 5 if it is failing timing.

**Checking at Stage Level 6:** The result showed that the worst data path delay in the whole system is 2.585ns. Minimum slack is 6.852. However, higher clock speeds can make the dsp even faster as we already found. Therefore it is worth to check the slack at 2.222ns clock period.

**Checking at 2.222ns Clock Period:** The results indicate that the design got faster. The worst path delay is 1.802. However, due to clock effects it is slightly negative, -0.045ns. Which means that we can try to work with 400MHZ clock.

**Checking at 2.5ns Clock Period:** After decreasing frequency to 400MHZ, worst slack is:

Slack (MET) : 0.014ns (required time - arrival time)  
-----

|               |        |
|---------------|--------|
| required time | -0.667 |
| arrival time  | 0.681  |
| -----         |        |
| slack         | 0.014  |

This test indicted that the optimum suggested stage level is related to the maximum clock speed of the device. The IP suggests a stage level that can handle the maximum clock speed of the device. Due to clock uncertainty it is same to use a smaller clock period than the maximum clock speed of the device as slack report showed. The report showed clock uncertainty and adds it to time domain to find the slack:

|                     |         |                                   |
|---------------------|---------|-----------------------------------|
| Clock Uncertainty:  | 0.057ns | $((TSJ^2 + DJ^2)^{1/2}) / 2 + PE$ |
| Total System Jitter | (TSJ):  | 0.071ns                           |
| Discrete Jitter     | (DJ):   | 0.090ns                           |
| Phase Error         | (PE):   | 0.000ns                           |

This is why at 450MHZ clock period, the slack was negative. The clock uncertainty is 0.057ns and the slack was -0.045ns.