# ALU - VERIFICATION

BHUVANESH

27bhuvanesh5@gmail.com

## INDEX

# CHAPTER 1: PROJECT OVERVIEW AND SPECIFICATION

## 1.1 Project Overview

The project focuses on the verification of a parameterized Arithmetic Logic Unit (ALU) which supports a wide range of arithmetic and logical operations. ALU are an integral part of any SOC that performs Arithmetic and logical operations. The ALU supports variety of functions including arithmetic operations such as addition, subtraction, increment, decrement, and multiplication, as well as logical operations such as AND, OR, XOR, NOT, NAND, NOR, and XNOR. In addition, it supports shift and rotate operations. The design also has comparator functions and error checking for invalid command conditions.

## 1.2 Verification Objective

The objective of the project is to:

- Verify functional correctness of all ALU operations — including arithmetic, logical, comparison, and shift/rotate — as determined by CMD and MODE.
- Ensure input protocol compliance by checking that INP_VALID reflects operand availability (2'b01, 2'b10, or 2'b11) and operations proceed only when valid.
- Verify that when only one operand is valid (INP_VALID = 2'b01 or 2'b10), the ALU waits up to 16 clock cycles for the second operand, and asserts ERR if it doesn’t arrive.
- Confirm timing behaviour, ensuring results are available after 1 or 2 clock cycles, depending on the operation.
- Apply constrained-random testing and functional coverage to explore all valid/invalid input combinations, including edge cases like overflow, underflow, and invalid rotate commands.

## 1.3 DUT Interfaces

Block diagram of parameterized ALU is shown in Figure 1.

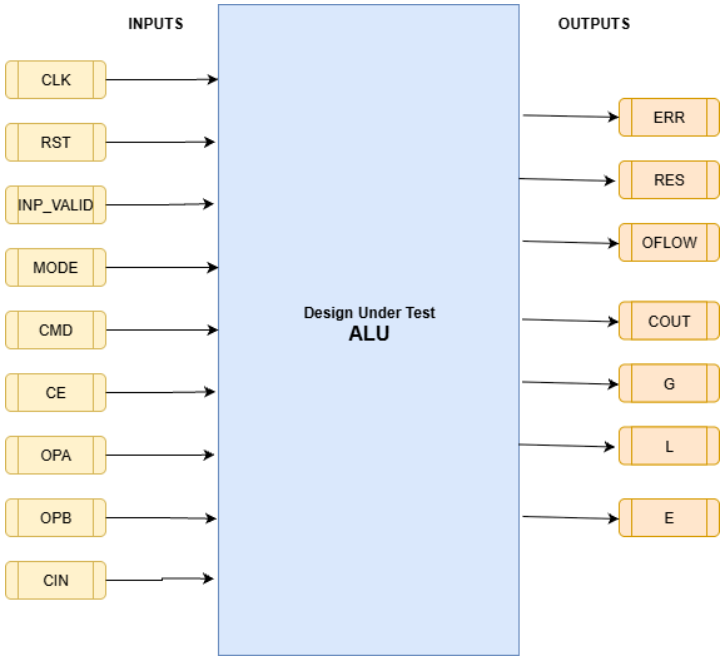


Figure 1. ALU under test

Below is the table which describes about the pins in the ALU which is design under test.

| | PIN NAME | PIN DESCRIPTION |
|---|---|---|
| INPUTS | CLK (Clock) | Synchronous clock |
| | RST (Reset) | Asynchronous reset |
| | CE (Clock Enable) | Enables the ALU to perform operations on the clock edge |
| | CDM | A 4-bit command input that specifies the operation to be performed |
| | MODE | Determines the type of operation i.e. if MODE = 1 then Arithmetic operation else Logical operation |
| | CIN (Carry In) | Used for addition/subtraction with carry/borrow |
| | OPA / OPB [Width-1:0] | Parameterized inputs for operand A and operand B |
| | INP_VALID | It is a 2-bit input which indicates validity of input operands i.e.<br>00: No operand is valid<br>01: Operand A is valid<br>10: Operand B is valid<br>11: Both operands are valid |
| OUTPUTS | ERR | Error signal for invalid operations |
| | RES [Width-1:0] | Result from the logical or arithmetic operation |
| | G, L, E | Comparator outputs indicating relationship between operands i.e. greater-than, less-than and equal-to |
| | COUT | Carry out for arithmetic operation |
| | OFLOW | Overflow flag for arithmetic operation |

Below is the table for the ALU showing specific arithmetic operation cases for given inputs, where the resulting outputs must be carefully considered as follows:

| Command number | Command Operation | Description | ALU Behaviour / Operation | Flags Affected |
|---|---|---|---|---|
| 0 | ADD | Unsigned Addition | RES = OPA + OPB | COUT, OFLOW |
| 1 | SUB | Unsigned Subtraction | RES = OPA - OPB | COUT, OFLOW |
| 2 | ADD_CIN | Addition with Carry-In | RES = OPA + OPB + CIN | COUT, OFLOW |
| 3 | SUB_CIN | Subtraction with Borrow (Carry-In) | RES = OPA - OPB - CIN | COUT, OFLOW |
| 4 | INC_A | Increment A | RES = OPA + 1 | OFLOW |
| 5 | DEC_A | Decrement A | RES = OPA - 1 | OFLOW |
| 6 | INC_B | Increment B | RES = OPB + 1 | OFLOW |
| 7 | DEC_B | Decrement B | RES = OPB - 1 | OFLOW |
| 8 | CMP | Compare A and B | Sets G, L, E based on comparison | G, L, E |
| 9 | INC_A_B_MUL | Increment A and B, then multiply | RES = (OPA + 1) * (OPB + 1) | - |
| 10 | SHL_A_MUL_B | Left shift A by 1, then multiply with B | RES = (OPA << 1) * OPB | - |
| 11 | ADD_SIGNED | Signed Add, sets all relevant flags | RES = OPA + OPB with signed consideration | COUT, OFLOW, G, L, E |
| 12 | SUB_SIGNED | Signed Subtract, sets all relevant flags | RES = OPA - OPB with signed consideration | COUT, OFLOW, G, L, E |

The designed ALU supports various logical operations when the signal MODE is deasserted which includes AND, OR, NAND, NOR, XOR, XNOR, NOT_A, NOT_B, SHR1_A, SHL1_A, SHR1_B, SHL1_B, ROL_A_B (Rotate Left A by bits specified in B), ROR_A_B (Rotate Right A by bits specified in B)

Below is the table for the ALU showing specific logical operation cases for given inputs, where the resulting outputs must be carefully considered as follows:

| Command number | Command Operation | Description | ALU Behaviour / Operation | Flags Affected |
|---|---|---|---|---|
| 0 | AND | Bitwise AND between A and B | RES = OPA & OPB | - |
| 1 | NAND | Bitwise NAND between A and B | RES = ~ (OPA & OPB) | - |
| 2 | OR | Bitwise OR between A and B | RES = OPA \| OPB | - |
| 3 | NOR | Bitwise NOR between A and B | RES = ~ (OPA \| OPB) | - |
| 4 | XOR | Bitwise XOR between A and B | RES = OPA ^ OPB | - |
| 5 | XNOR | Bitwise XNOR between A and B | RES = ~ (OPA ^ OPB) | - |
| 6 | NOT_A | Bitwise NOT of A | RES = ~OPA | - |
| 7 | NOT_B | Bitwise NOT of B | RES = ~OPB | - |
| 8 | SHR1_A | Shift Right A by 1 | RES = OPA >> 1 | - |
| 9 | SHL1_A | Shift Left A by 1 | RES = OPA << 1 | - |
| 10 | SHR1_B | Shift Right B by 1 | RES = OPB >> 1 | - |
| 11 | SHL1_B | Shift Left B by 1 | RES = OPB << 1 | - |
| 12 | ROL_A_B | Rotate Left A by bits specified in B | Rotate A left by the lowest bits of B needed to cover the operand width; set ERR if any higher bits of B, are nonzero. | ERR |

| | | | | |
|---|---|---|---|---|
| 13 | ROR_A_B | Rotate Right A by bits specified in B | Rotate A right by the lowest bits of B needed to cover the operand width; set ERR if any higher bits of B, are nonzero. | ERR |

# CHAPTER 2: TESTBENCH ARCHITECTURE AND METHODOLOGY

## 2.1 TESTBENCH ARCHITECTURE

### GENERAL TESTBENCH ARCHITECTURE

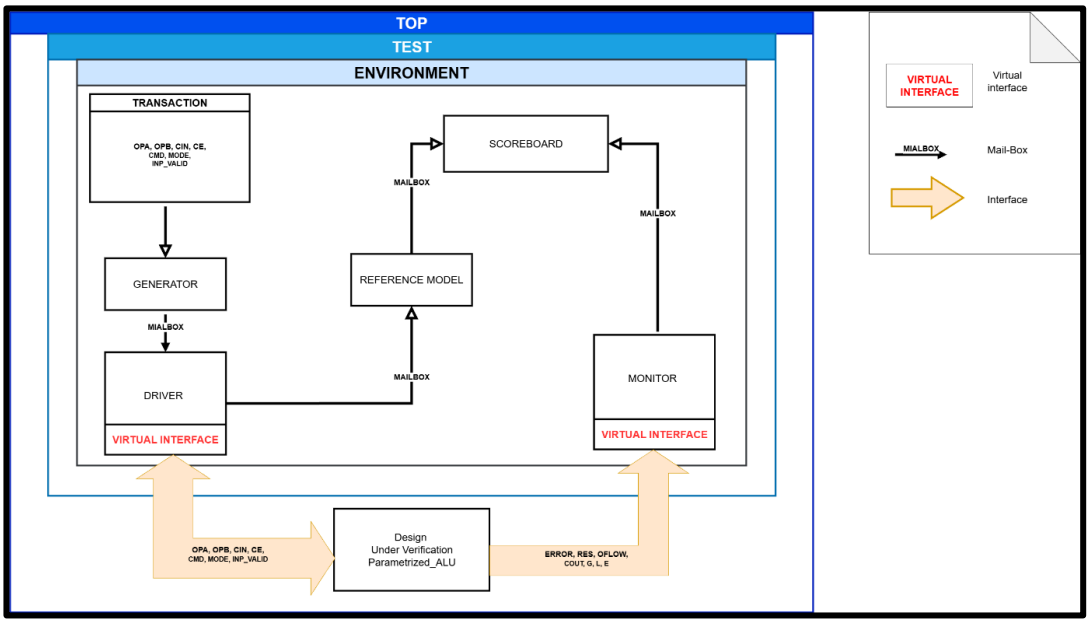


Figure 1. General Testbench Architecture

### ALU TESTBENCH ARCHITECTURE

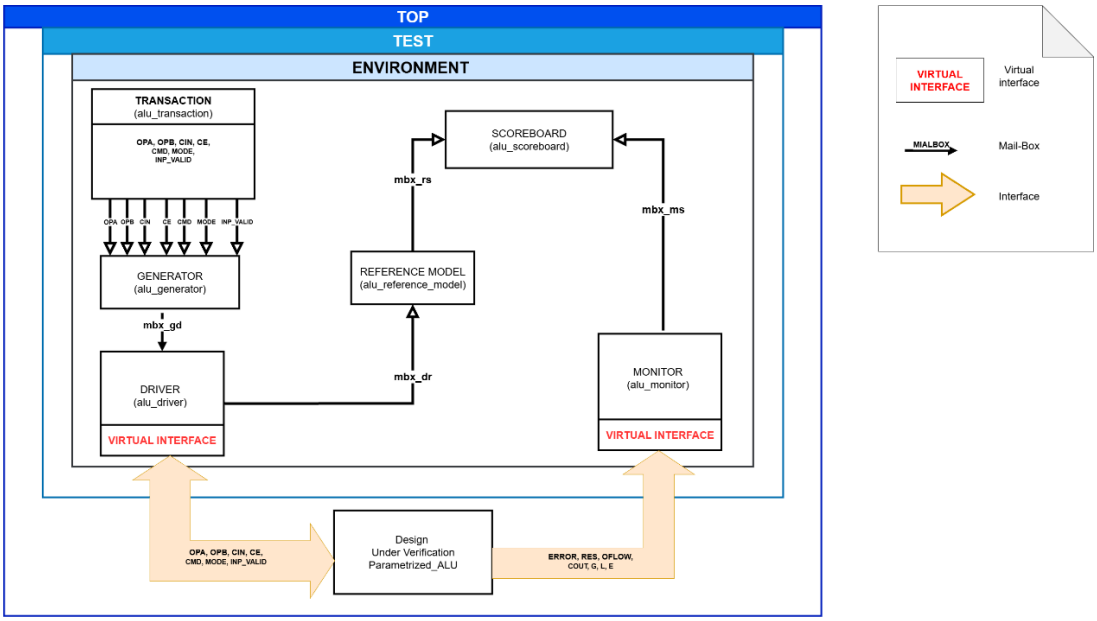


Figure 2. ALU Testbench Architecture

## 2.2 Component Details and Flowchart

The ALU testbench architecture consist as follows:

**Transaction Class:**

- All the inputs and outputs used by the ALU (like OPA, OPB, CIN, CE, CMD, MODE, and INP_VALID) are included in the transaction class.
- Clock and reset signals are excluded since they are generated in the Top module.
- The transaction class can also contain constraints on the input values to generate meaningful scenarios (e.g., valid operand ranges, operation types).

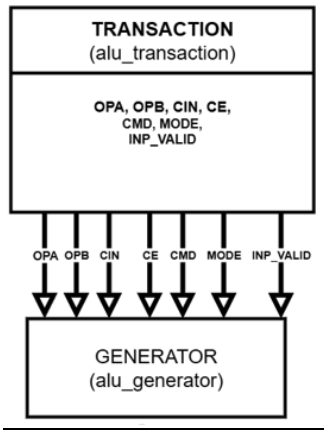


Figure 3. ALU_Transaction block

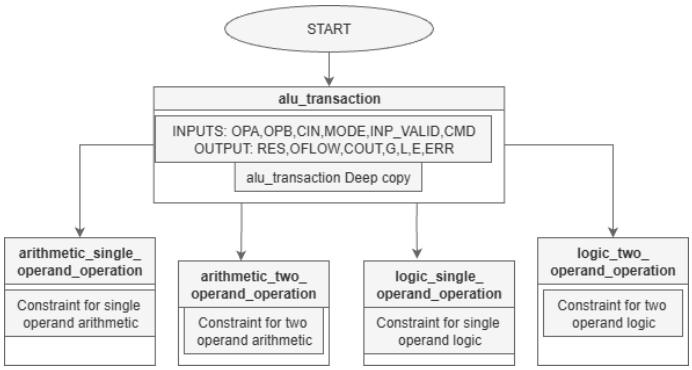


Figure 4. Flowchart of ALU_Transaction Class

**Generator:**

- This component creates random input combinations for the ALU, respecting the constraints defined in the transaction class.
- It generates transactions and sends them to the driver using a mailbox.
- The generator helps cover different kinds of operations and edge cases.

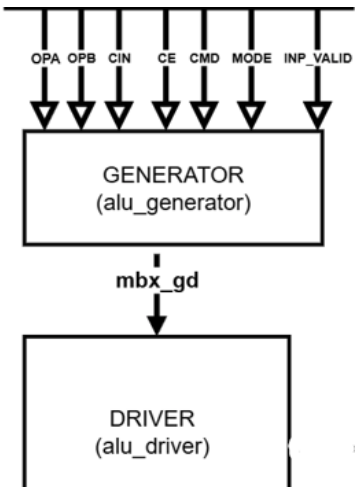


Figure 5. ALU_Generator Block

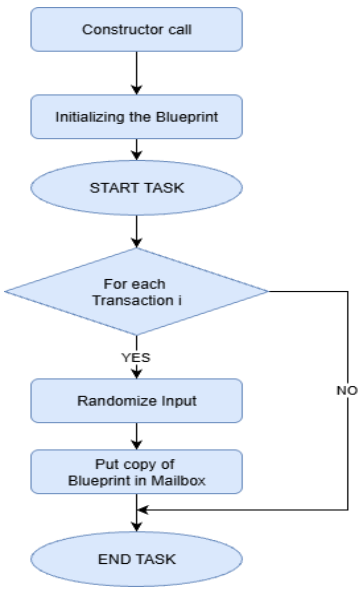


Figure 6. Flowchart of ALU_Generator

**Driver:**

- The driver receives transactions from the generator and applies them to the ALU inputs using a virtual interface.
- It translates the high-level transaction data into signal activity on the ALU pins.
- It also forwards the same transactions to the reference model, which is used for checking expected behaviour.

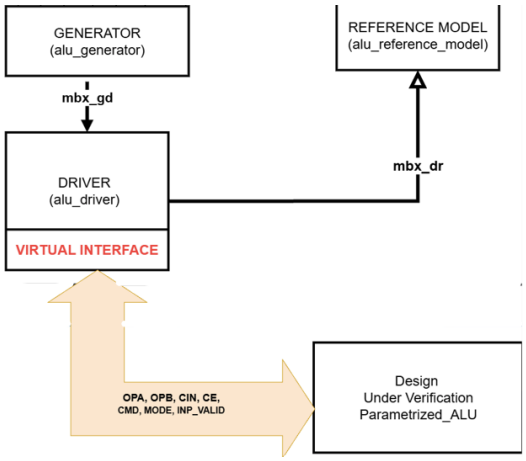


Figure 7. ALU_Driver Block

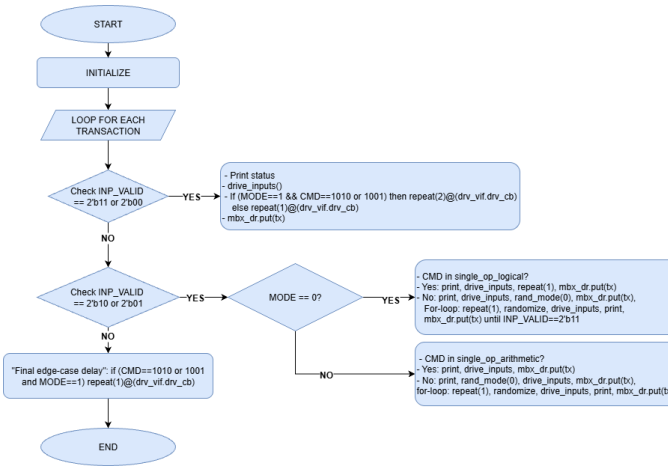


Figure 8. Flowchart of ALU_Driver

**Monitor:**

- The monitor observes the outputs of the ALU (like RES, COUT, OFLOW, ERR, G, L, and E) using a virtual interface.
- It converts these low-level signals into a high-level transaction and sends them to the scoreboard through a mailbox.

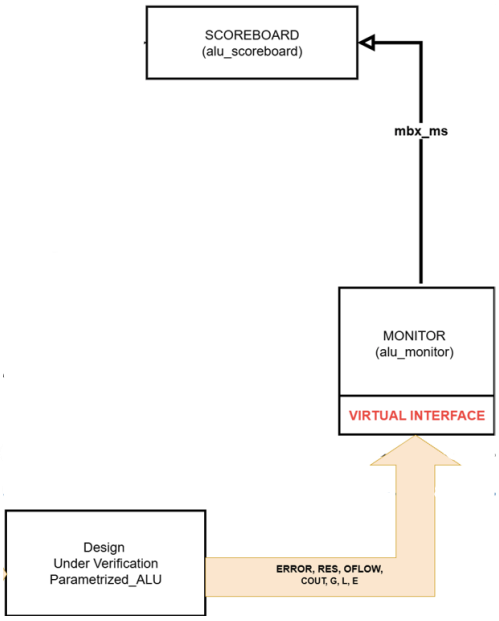


Figure 9. ALU_Monitor Block

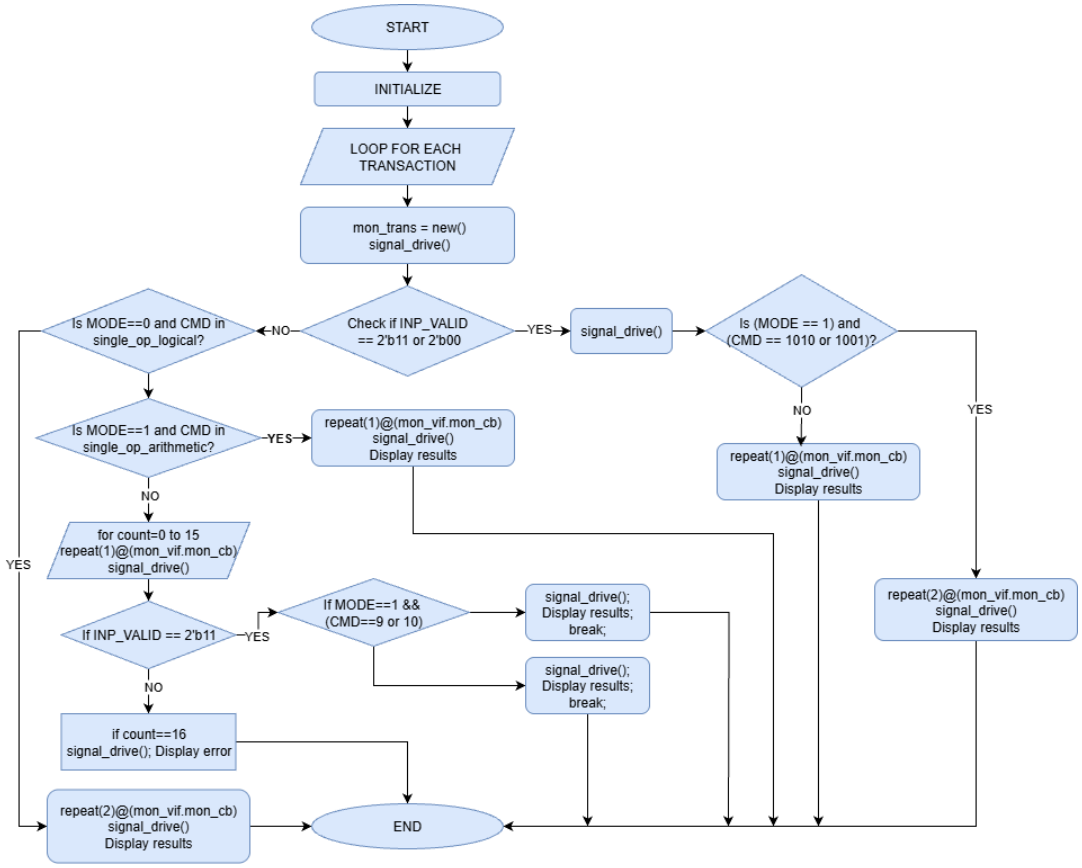


Figure 10. Flowchart of ALU_Monitor

**Reference Model:**

- This is the ideal or “golden” model of the ALU, implemented at a high level.
- It performs the same operation as the real ALU using the input transaction and produces the expected output.
- The input to the reference model comes from the driver, and its output is passed to the scoreboard for comparison.

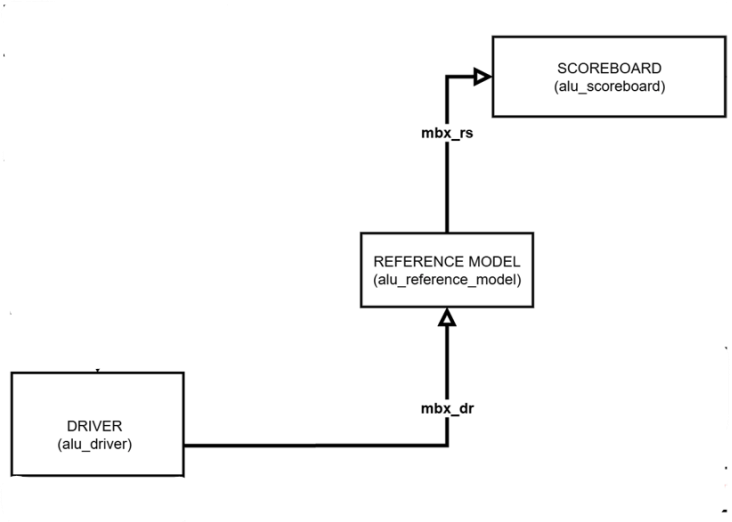


Figure 11. ALU_Reference_Model Block

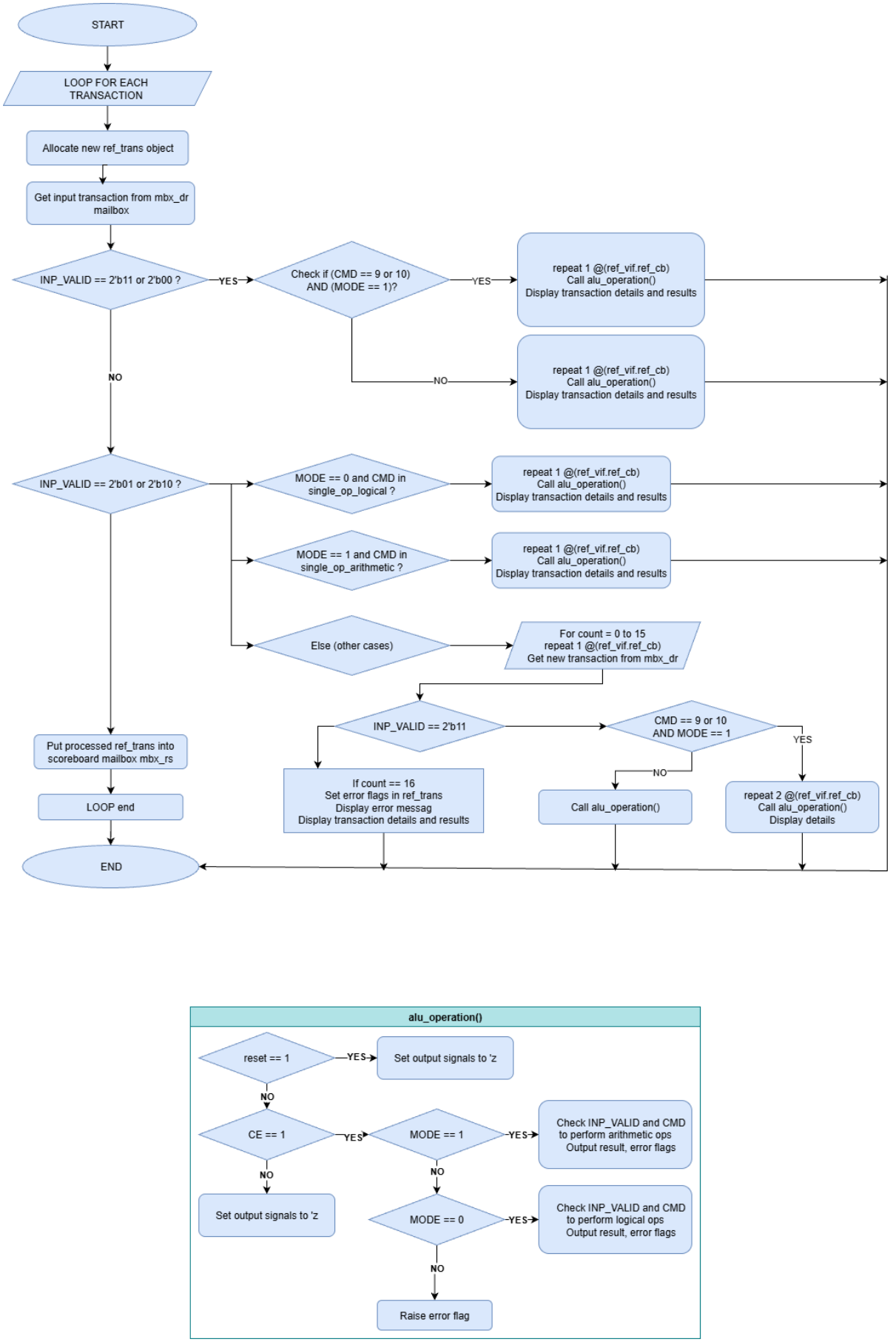


Figure 12. ALU_Reference_Model Block

**Scoreboard:**

- The scoreboard compares the expected output from the reference model with the actual output from the monitor.
- If the values match, the test passes; otherwise, it logs a mismatch and raises an error.
- The scoreboard is central to identifying bugs or mismatches in ALU functionality.

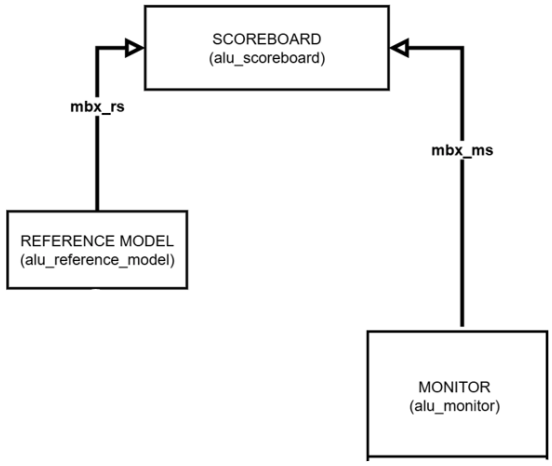


Figure 13. ALU_ScoreBoard

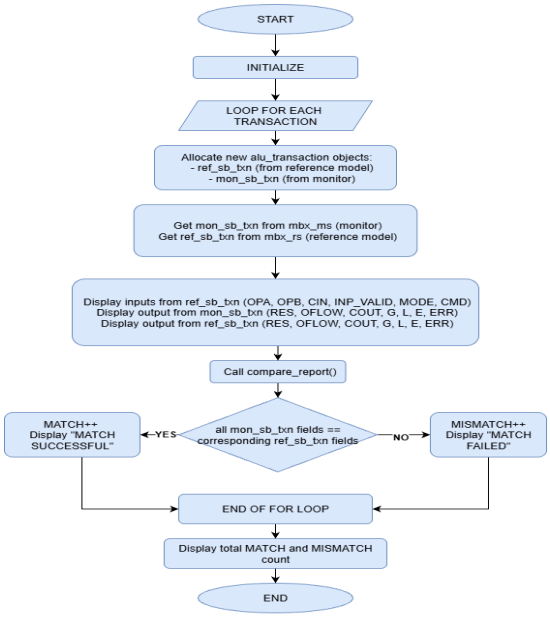


Figure 14. Flowchart of ALU_Scoreboard

**Environment:**

- The environment contains all the above components: generator, driver, monitor, reference model, and scoreboard.
- It handles their construction, configuration, and connection using mailboxes and virtual interfaces.
- The environment acts as a container for building the full testbench.

**Test:**

- This is where different test cases are defined (e.g., testing addition, subtraction, overflow, rotate, etc.).
- The test instantiates the environment and runs specific scenarios.
- It is written inside a class and helps run both directed and randomized tests.

# CHAPTER 3: VERIFICATION RESULT AND ANALYSIS

## 3.1 ERROR IN THE DUT

- The increment operation on operand A (OPA) is incorrect according to the specification
- The operation of increment and decrement on operand B (OPB) is incorrect according to the specification
- CMD 13 performs a left rotation instead of the required right rotation, leading to incorrect output
- When OPB[7:4] ≠ 0 in CMD 13, the ERR flag is not set, failing to indicate an invalid input condition
- RES is declared with a hardcoded width [8:0] instead of using parameter DW, breaking scalability
- The design does not verify INP_VALID = 2'b11 before executing dual-operand commands, allowing operations with missing operands
- For single-operand operations, the design accepts both operands instead of ignoring the unused one
- There is no priority handling when one operand arrives late (beyond 16 cycles) the later operand should overwrite the earlier one but does not
- The ALU does not flag an error when only one operand is present for operations that require both
- The command (CMD) is not validated against the required number of operands before execution, leading to unexpected behaviour
- Connection width does not match the declared port width for RES, causing simulation or synthesis issues

## 3.2 COVERAGE REPORT

Below is the coverage report obtained on verifying the ALU design.

**Input Coverage:**

Figure 15. shows the input coverage for the ALU

Scope: /alu_pkg/alu_driver

**Covergroup type:**

**drv_cg**

| Summary | Total Bins | Hits | Hit % |
|---|---|---|---|
| Coverpoints | 30 | 29 | 96.66% |
| Crosses | 104 | 58 | 55.76% |

Search:

| CoverPoints | Total Bins | Hits | Misses | Hit % | Goal % | Coverage % |
|---|---|---|---|---|---|---|
| A_cp | 3 | 3 | 0 | 100.00% | 100.00% | 100.00% |
| B_cp | 3 | 3 | 0 | 100.00% | 100.00% | 100.00% |
| CIN_cp | 2 | 2 | 0 | 100.00% | 100.00% | 100.00% |
| CMD_cp | 16 | 15 | 1 | 93.75% | 93.75% | 93.75% |
| INP_VALID_cp | 4 | 4 | 0 | 100.00% | 100.00% | 100.00% |
| MODE_cp | 2 | 2 | 0 | 100.00% | 100.00% | 100.00% |

Search:

| Crosses | Total Bins | Hits | Misses | Hit % | Goal % | Coverage % |
|---|---|---|---|---|---|---|
| CMD_x_INP_VALID | 64 | 28 | 36 | 43.75% | 43.75% | 43.75% |
| MODE_x_CMD | 32 | 22 | 10 | 68.75% | 68.75% | 68.75% |
| MODE_x_INP_VALID | 8 | 8 | 0 | 100.00% | 100.00% | 100.00% |

Figure 15. Input Coverage for ALU

**Output Coverage:**

Figure 16. shows the output coverage for the ALU

Scope: /alu_pkg/alu_monitor

**Covergroup type:**

**mon_cg**

| Summary | Total Bins | Hits | Hit % |
|---|---|---|---|
| Coverpoints | 10 | 8 | 80.00% |
| Crosses | 0 | 0 | 0.00% |

Search:

| CoverPoints | Total Bins | Hits | Misses | Hit % | Goal % | Coverage % |
|---|---|---|---|---|---|---|
| COUT_CP | 2 | 2 | 0 | 100.00% | 100.00% | 100.00% |
| EQUAL | 1 | 0 | 1 | 0.00% | 0.00% | 0.00% |
| ERROR | 2 | 2 | 0 | 100.00% | 100.00% | 100.00% |
| GREATER | 1 | 0 | 1 | 0.00% | 0.00% | 0.00% |
| LESSER | 1 | 1 | 0 | 100.00% | 100.00% | 100.00% |
| OF_LOW | 2 | 2 | 0 | 100.00% | 100.00% | 100.00% |
| RESULT | 1 | 1 | 0 | 100.00% | 100.00% | 100.00% |

Figure 16. Output Coverage for ALU

## Assertion Coverage:

Figure 17. shows the assertion coverage for the ALU

**Assertions Coverage Summary:**

Search:

| Assertions | Failure Count | Pass Count | Attempt Count | Vacuous Count | Disable Count | Active Count | Peak Active Count | Status |
|---|---|---|---|---|---|---|---|---|
| /top/intrf/assert__CE_ASSERT | 0 | 16 | 139 | 123 | 0 | 0 | 16 | Covered |
| /top/intrf/assert__TIMEOUT_16Clk | 0 | 0 | 139 | 139 | 0 | 0 | 5 | ZERO |
| /top/intrf/assert__VALID_INPUTS_CHECK | 0 | 123 | 139 | 16 | 0 | 0 | 1 | Covered |
| /top/intrf/assert__VERIFY_RESET | 0 | 0 | 139 | 139 | 0 | 0 | 0 | ZERO |
| /work.alu_if/assert__CE_ASSERT | 0 | 16 | 139 | 123 | 0 | 0 | 16 | Covered |
| /work.alu_if/assert__TIMEOUT_16Clk | 0 | 0 | 139 | 139 | 0 | 0 | 5 | ZERO |
| /work.alu_if/assert__VALID_INPUTS_CHECK | 0 | 123 | 139 | 16 | 0 | 0 | 1 | Covered |
| /work.alu_if/assert__VERIFY_RESET | 0 | 0 | 139 | 139 | 0 | 0 | 0 | ZERO |

Figure 17. Assertion Coverage Summary for ALU

## Overall Coverage:

Figure 18. shows the overall coverage for the ALU

**Coverage Summary by Type:**

| Total Coverage: | | | | | 74.21% | **69.49%** |
|---|---|---|---|---|---|---|
| **Coverage Type** | **Bins** | **Hits** | **Misses** | **Weight** | **% Hit** | **Coverage** |
| Covergroups | 144 | 95 | 49 | 1 | 65.97% | **80.50%** |
| Statements | 570 | 422 | 148 | 1 | 74.03% | **74.03%** |
| Branches | 186 | 136 | 50 | 1 | 73.11% | **73.11%** |
| FEC Conditions | 66 | 37 | 29 | 1 | 56.06% | **56.06%** |
| Toggles | 310 | 258 | 52 | 1 | 83.22% | **83.22%** |
| Assertions | 4 | 2 | 2 | 1 | 50.00% | **50.00%** |

Figure 18. Overall Coverage for ALU

## Output waveform:

Figure 19. shows the output waveform from the interface in the ALU testbench architecture

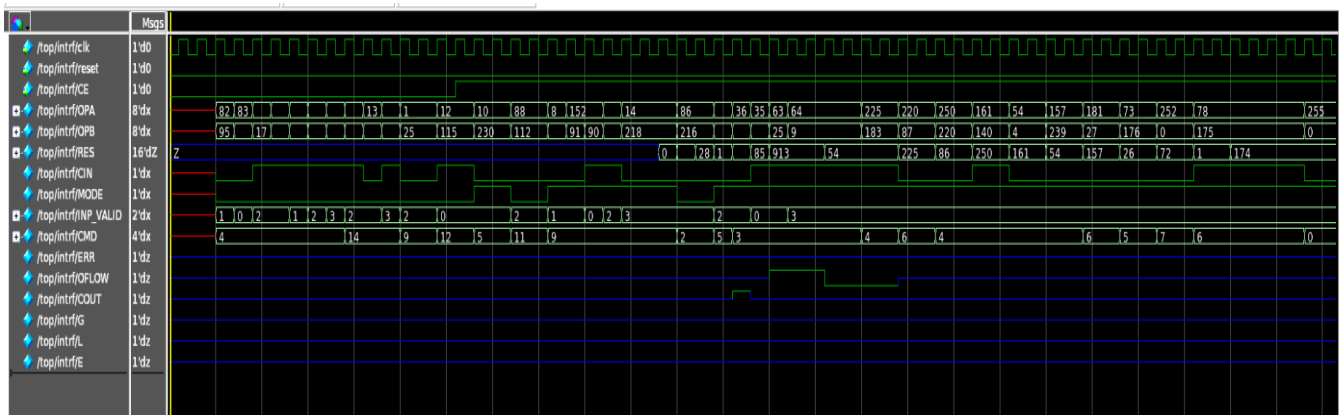


Figure 19. Output waveform from the interface in the ALU testbench architecture

## Conclusion

The testbench for the ALU design helped identify whether the design functioned correctly. The testbench was organized into separate parts—generator, driver, monitor, reference model, and scoreboard—making it easier to test and debug each section of the design.

Several issues were found during simulation, such as incorrect handling of specific commands, missing error detection, and lack of parameterization, which reduced design flexibility. These problems were clearly visible due to the structured approach of the testbench.

## Future Scope

- The design is not fully parameterized; while DW (data width) and CW (command width) are declared as parameters, internal hardcoded values like bit widths (e.g., [8:0] for RES) should instead use parameter expressions to ensure scalability.
- The current implementation of CMD 13 performs a left-rotation instead of the required right-rotation; this must be corrected to match the expected behaviour.
- In CMD 13, when OPB [7:4] ≠ 0, the error flag (ERR) is incorrectly set to 0; it should be set to 1 to indicate an invalid rotation input, as per specification.
- The ALU does not enforce that both operands must be present (INP_VALID = 2'b11) for dual-operand commands like ADD, SUB, and MUL; operand validity checking should be enforced before processing.
- Single-operand operations such as INC_A or DEC_A do not restrict the design from accepting both operands; logic should be added to accept only the necessary operand(s).
- There is no priority logic to handle timing violations when one operand is delayed by more than 16 cycles; the later operand should overwrite the earlier one as per the requirement.
- Error handling is missing when invalid operand sequences are received (e.g., only one operand present when two are required); the design should flag an error in such cases.
- The design does not validate if the provided command (CMD) matches the expected number of operands before execution; this validation logic should be incorporated.

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## Test Plan

Click on the link to access the test plan of the ALU : ALU_TEST_PLAN

## Functional Coverage Plan

Click on the link to access the coverage plan of the ALU : ALU_COVERAGE_PLAN

## Assertions Plan

Click on the link to access the assertion plan of the ALU : ALU_ASSERTION_PLAN