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Design and Implementation of a 16-Bit ALU Using Structural Verilog

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Abstract: The Arithmetic Logic Unit (ALU) is a fundamental building block of all modern central processing units (CPUs). This paper presents the design and implementation of a 16-bit, 4-function ALU constructed entirely from basic logic gates, using a structural Verilog approach. The ALU supports four operations: addition, subtraction, bitwise AND, and bitwise OR, implemented via a modular, bit-sliced architecture. A single ripple-carry adder with 2's complement logic performs both arithmetic operations efficiently. Operation selection is achieved through a 2-bit control signal and a 4-to-1 multiplexer per bit slice. The system was verified using QuestaSim simulation with both normal and boundary test vectors. Unlike existing behavioral or high-level implementations, this work contributes a fully gate-level structural model that makes every interconnection explicit, enabling transparent analysis of carry propagation and delay. Performance metrics including propagation delay and hardware resource usage are analyzed. The results validate the design's functional correctness and demonstrate its potential as a scalable building block for processor architectures.

Index Terms: Arithmetic Logic Unit, Structural Verilog, Ripple Carry Adder, Bit-Sliced Architecture, 2’s Complement, Digital Logic Design, and Propagation Delay

1. Introduction

The Arithmetic Logic Unit (ALU) is an important part of digital systems and processors. It is responsible for performing basic arithmetic and logical operations such as addition, subtraction, bitwise AND, and bitwise OR. These operations are essential for data processing and decision-making in any computing system. The performance of a processor mainly depends on how efficiently the ALU is designed. A well-designed ALU can improve speed, reduce hardware usage, and make the system more reliable.

In many designs, high-level or behavioral modelling is used, which hides the internal hardware details. However, structural modeling gives a clearer view of how the circuit is actually built by showing connections between logic gates and modules. This helps in understanding how signals propagate and how delays occur in the system.

In this paper, a 16-bit ALU is designed using structural Verilog. The design is based on a modular approach where a 1-bit unit is repeated to form a complete 16-bit system. A ripple-carry adder is used to perform both addition and subtraction operations using 2’s complement method. The design is verified through simulation, and its performance is analyzed based on delay and hardware usage.

2. Literature Survey

T. L. Floyd [1] explains the fundamental concepts of digital logic design, including logic gates, combinational circuits, and binary arithmetic operations. His work describes binary addition and subtraction using two’s complement representation and the construction of multi-bit adders using cascaded 1-bit full adders. These concepts form the theoretical foundation for the arithmetic unit used in the proposed ALU design.

J. F. Wakerly [2] presents systematic methods for designing combinational logic circuits and discusses timing behavior and propagation delay in digital systems. The ripple-carry adder architecture used in this project follows the cascading full-adder structure described in his work, emphasizing modular design and scalability. Similarly, M. M. Mano and M. D. Ciletti [3] provide methodologies for digital system design using hardware description languages such as Verilog, highlighting structural modeling, modular hierarchy, and reusable design components.

Research in VLSI circuit design has also focused on optimizing arithmetic circuit performance. N. H. E. Weste and D. Harris [4] discuss CMOS-based VLSI circuit design and various adder architectures used in arithmetic logic units, including ripple-carry and carry look-ahead adders, emphasizing trade-offs between speed, area, and power consumption. I.Hassoune, D. Flandre, I. O'Connor and J. -D. Legat, [5] analyze different CMOS logic styles and compare their performance in terms of delay and power dissipation. Furthermore, Kang, Dong-In & Crago, Stephen & Suh, Jinwoo "Joseph [6] investigate power-aware design techniques for nanometer-scale VLSI circuits.

Recent studies have explored improved arithmetic architectures for higher efficiency. A. Al Share, O. Al-Khaleel, F. N. Zghoul, M. Al-Khaleel and C. Papachristou. [7] proposed an energy-efficient carry look-ahead adder architecture that enhances performance in modern VLSI systems. Al Share, O. Al-Khaleel, F. N. Zghoul, M. Al-Khaleel and C. Papachristou,. Similarly, Priyadarshini, V., Kamaraju, M. & RatnaKumari, U.V. [8] proposed a low-power ALU architecture using hybrid clock-gating techniques to minimize dynamic power consumption while maintaining computational efficiency.

Recent advancements in digital system design and verification have focused on improving performance, power efficiency, and reliability. Punith Kumar M B and Sreekantesha H N [9] proposed the design and verification of an SPI master core using Universal Verification Methodology (UVM), highlighting enhanced reusability and efficient detection of functional errors in communication interfaces. Similarly, Meghana Jain H K and Punith Kumar M B [10] carried out verification of the Advanced Peripheral Bus (APB) V2.0 protocol, ensuring reliable data transfer and compliance with AMBA standards in embedded systems.

In the domain of low-power VLSI design, D. M. Harris and S. L. Harris [11] Harris and Harris presented the architecture and design principles of Arithmetic Logic Units (ALUs) and datapaths using Verilog HDL. Their work provides a strong foundation for implementing efficient and modular 16-bit ALUs using structural Verilog.. Further, R T et al. [12] introduced a 4-bit carry save adder employing MTCMOS-based ripple carry architecture with 10T full adders, achieving reduced leakage power and enhanced speed in nanoscale technologies.

Moreover, high-performance computing architectures have seen significant innovation, as demonstrated by D Im and H J Yoo [13], who proposed a dense-sparse bit-slice architecture (LUTein) for efficient tensor processing, improving computational density and scalability. Additionally, Punith Kumar M B and Sahana Raj B S [14] implemented a high-speed 8-bit Vedic multiplier on FPGA using a barrel shifter, demonstrating optimized hardware utilization and faster arithmetic operations suitable for real-time applications. A. Al Share et al. [7] proposed a high-speed Carry Look-Ahead Decimal Adder (CLDA) using CMOS technology to reduce carry propagation delay and improve arithmetic performance. Their work demonstrates the importance of optimized adder architectures in designing high-speed ALUs. [15]

However, many existing studies focus on high-performance or low-power ALU architectures using complex adder designs. In contrast, this work focuses on a simple and modular ripple-carry-based ALU implemented using structural Verilog, which emphasizes clarity, scalability, and ease of implementation for digital system design.

3. Tasks Performed

Problem Statement: Design and Implementation of 16-BIT ALU using Structural Verilog.

Problem Description: The problem is to design and build a 16-bit Arithmetic Logic Unit from scratch. The system must be able to perform four distinct operations on two 16-bit inputs (A and B) selected by a 2-bit control signal (S [1: 0]).

The specific challenges include:

- Designing a scalable 1-bit “slice” that can be replicated 16 times.
- Implementing both addition and subtraction efficiently, ideally using a single adder structure.
- Correctly implementing and interpreting 2’s complement arithmetic for subtraction and signed results.

Deliverables

- 16-bit ALU design supporting addition, subtraction, AND, and OR operations.
- Modular 1-bit ALU slice design scalable to 16 bits.
- Operation selection logic using a 2-bit control signal.
- Functional verification through simulation and test cases.

Table 1. 2-bit Control Signal Mapping for ALU Operations

S[1: 0]	Operation	Description
00	AND	Bitwise AND of A and B
01	OR	Bitwise OR of A and B
10	ADD	$A + B$ (ripple-carry adder)
11	SUB	$A - B$ (2's complement)

4. Implementation Details

The system is built from four main parallel computation units that perform all operations simultaneously. The 2-bit select lines [1: 0] are used at the very end to pick the desired result. For each of the 16 bits (from i=0 to i=15), the circuit performs:

1. $Ai. Bi$
2. $Ai \mid Bi$
3. $Ai + Bi$ (as part of a 16-bit adder)
4. $Ai - Bi$ (as part of the same 16-bit adder)

The four results for each bit are fed into a 4-to-1 MultiThe four results for each bit are fed into a 4-to-1 Multiplexer (MUX), as shown in Fig. 1.

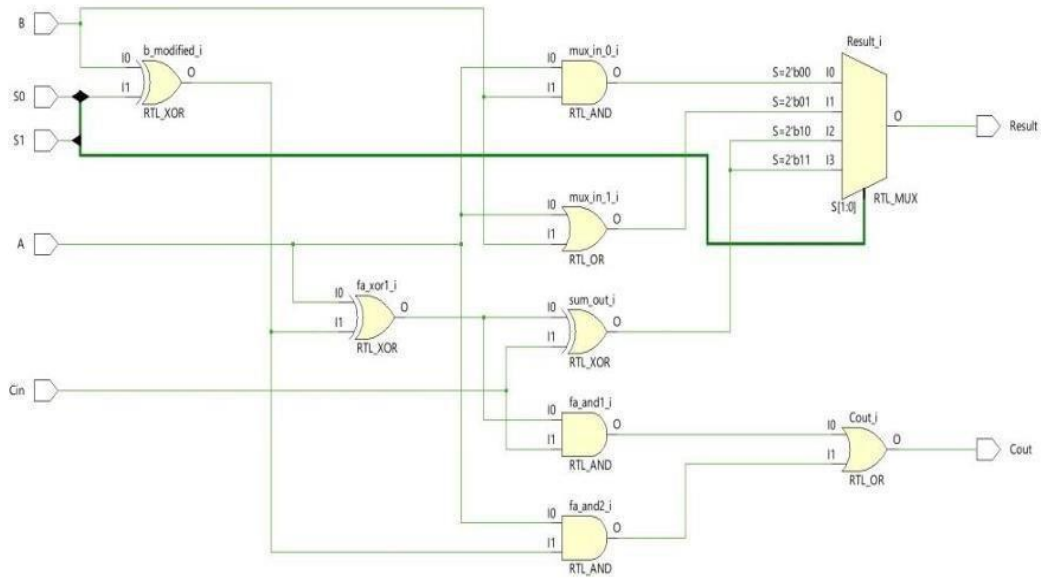

Fig. 1. 1-Bit ALU Slice

Fig. 1. illustrates the structural architecture of a 1-bit ALU slice used in the proposed 16-bit ALU design. Each slice performs both arithmetic and logical operations on the corresponding bits of input operands A and B. The logical operations AND and OR are implemented using basic logic gates, while arithmetic operations are performed using a full adder structure consisting of XOR and AND gates to generate the sum and carry outputs. The input B passes through an XOR gate controlled by the signal S_0, enabling conditional inversion of B during subtraction operations. The Cin input represents the carry from the previous lower-order bit in the ripple-carry chain. A 4-to-1 multiplexer, controlled by the select signals S_1S_0, chooses the required operation result among AND, OR, ADD, and SUB outputs. The selected result forms the output of the ALU slice, while the generated carry (Cout) propagates to the next higher-order slice. This modular bit-slice architecture allows the design to be easily scaled to a 16-bit ALU.

4.1. Functional Units

4.1.1. Logics Unit (for I0 and I1)

This is the most straightforward part of the design.

- 16-bit AND: 16 2-input AND gates take Ai and Bi as input. The 16 results are wired to the I0 inputs of their respective MUXes.
- 16-bit OR: 16 2-input OR gates take Ai and Bi as input. The 16 results are wired to the I1 inputs of their respective MUXes.

4.1.2. Arithmetic Unit (for I2 and I3)

This is the most important part of the ALU. A single 16-bit Ripple-Carry Adder is used to perform both addition and subtraction. This is achieved by using the [0] selector line as a control signal. The design relies on 2's complement arithmetic,

Where

$$A - B = A + B + 1 \quad (1)$$

- 16-bit Ripple-Carry Adder: This is built from 16 1-bit Full Adders chained together. The Cout of bit i becomes the Cin of bit $i + 1$.
- Controlled Inverter (B-Input): Before B is fed to the adder, each Bi bit passes through an XOR gate. The other input to this XOR gate is the [0] selector line.
- The "+1" Control (Carry-In): The Cin of the very first Full Adder (bit 0) is wired directly to the [0] selector line.

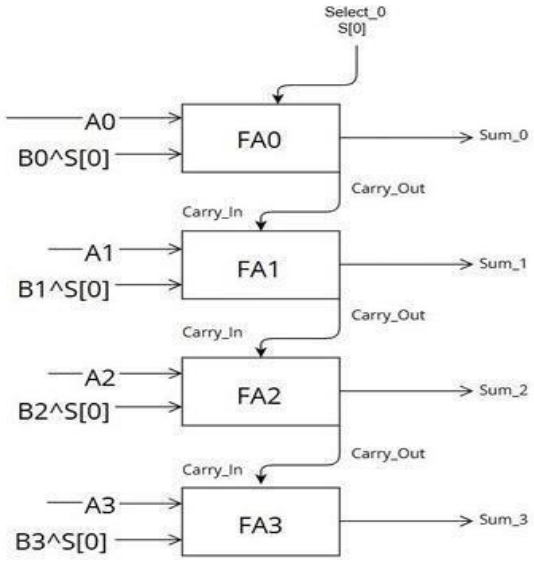

Fig. 2. 4-Bit Ripple Carry Adder

4.2. The Magic of the **[0]** *Signal*

This single wire performs two different jobs depending on the operation:

Case 1: ADD ([1: 0] = 10)

- [1] = 1 tells the MUX to select an arithmetic result (either I2 or I3).
- [0] = 0 is fed to the XOR gates. The XOR gates calculate $Bi \oplus 0$, which just equals Bi. The B operand passes through unchanged.
- [0] = 0 is fed to the first Cin. The adder calculates with an initial carry of 0.
- The final operation is $A + B + 0$.

This is standard addition. The result is wired to the I2 inputs of the MUXes.

Case 2: SUBTRACT([1: 0] = 11)

- [1] = 1 tells the MUX to select an arithmetic result.
- [0] = 1 is fed to the XOR gates. The XOR gates calculate $Bi \oplus 1$, which equals Bi (NOT B). The B operand is inverted.
- [0] = 1 is fed to the first Cin. The adder calculates with an initial carry of 1.
- The final operation is

$$A + B + 1 \quad (2)$$

This is the exact formula for 2's complement subtraction. The same result from the same adder is wired to the I3 inputs of the MUXes.

5. Design and Development of Solution

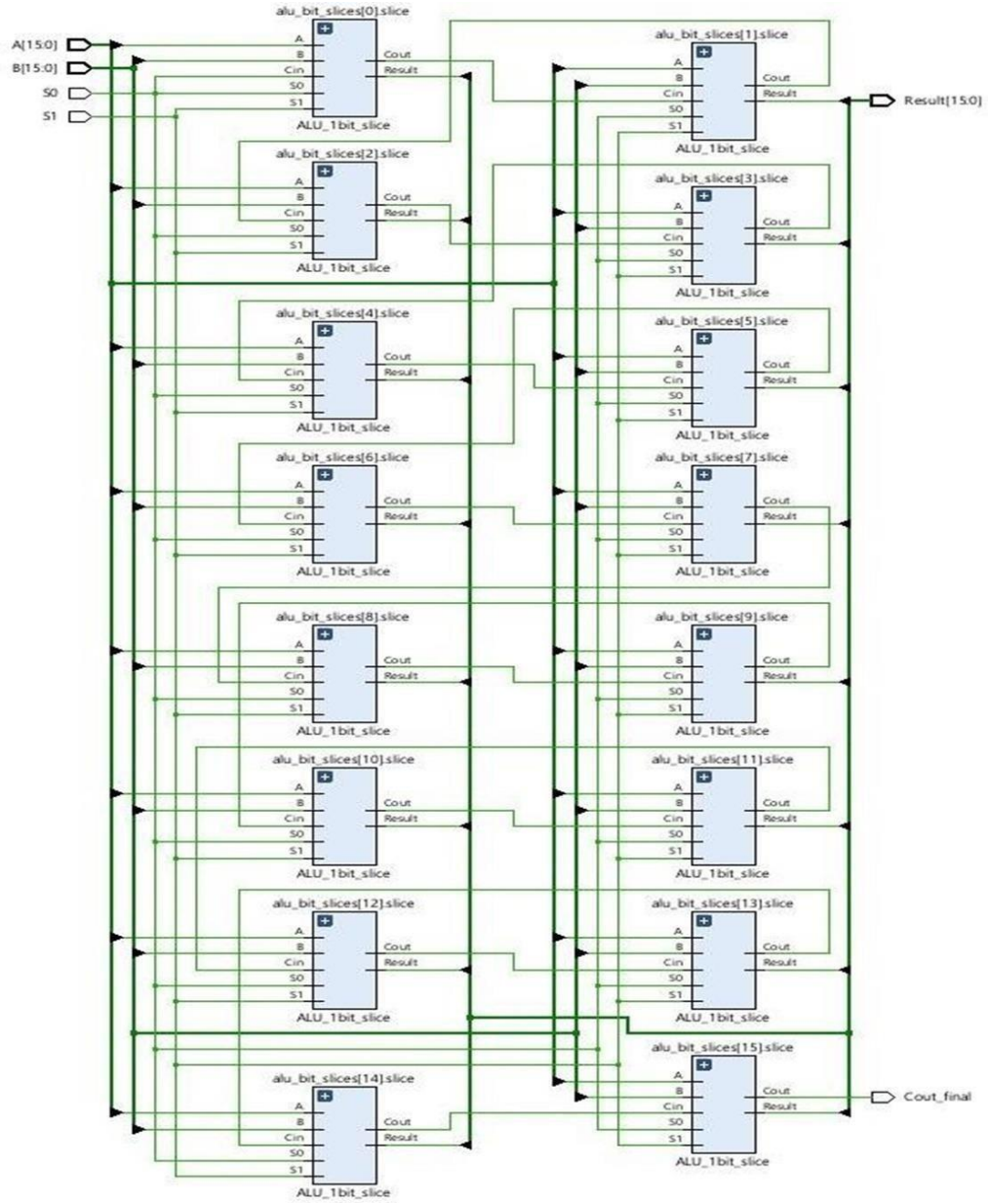

Fig. 3. 16-Bit ALU Schematic

Input Operand Blocks

The ALU accepts two 16-bit input operands, [15: 0] and [15: 0]. Each bit of these operands is routed to its corresponding 1-bit ALU slice. This parallel distribution allows all bits to be processed simultaneously while maintaining bit-wise independence.

Control Signal Block

The control signals S1 and S0 determine the operation performed by the ALU. These signals are broadcast to all 1-bit ALU slices to ensure consistent operation selection across the entire 16-bit word. Based on these signals, the ALU performs addition, subtraction, bitwise AND, or bitwise OR.

1-Bit ALU Slice Blocks

Each modular slice processes a single bit of the operands, performing logic and arithmetic operations in parallel. A selection multiplexer then outputs the result based on the control signals. This "bit-slice" architecture ensures the design is easily scalable to 16 bits.

Carry Propagation Block

The carry-out from each 1-bit ALU slice is connected to the carry-in of the next higher-order slice. This ripple-carry mechanism ensures correct carry propagation during arithmetic operations. The initial carry-in is applied to the least significant slice, and the carry propagates through all slices as required.

Result Combination Block

The result output from each 1-bit slice forms one bit of the final 16-bit result. These individual outputs are combined in order to generate the complete Result[15:0] vector, representing the outcome of the selected operation.

Final Carry Output Block

The carry-out produced by the most significant 1-bit slice represents the final carry or borrow of the 16-bit operation. This output can be used to indicate overflow or borrow conditions in arithmetic computations.

Propagation Delay Analysis

The worst-case path in a ripple-carry adder traverses all 16 full adders in series. Each full adder introduces a gate delay of approximately 2 gate-delays (Tg) for the carry path. The total carry-propagation delay is therefore approximately

$$2x16xTg = 32Tg \tag{3}$$

In contrast, a 16-bit carry look-ahead adder achieves an

$$(\log, 16) = 4 \tag{4}$$

level delay, illustrating the trade-off accepted in this implementation in favour of reduced hardware cost.

Table 2. Estimated Gate Count for 16-Bit ALU

Component	Gate Type	Count
AND unit	AND-2	16
OR unit	OR-2	16
B-Inverter (XOR)	XOR-2	16
Full adder - sum	XOR-2	32
Full adder - carry	AND-2 / OR-2	32/16
MUX (4-to1)	AND/OR/NOT	$\approx 16 * 10$
Total	-	$\approx$ 288 gate-equivalents

The estimates confirm that a ripple-carry ALU is area-efficient, requiring far fewer gates than a carry look-ahead counterpart (~480 gate-equivalents for the adder stage alone), at the cost of higher delay. This trade-off is acceptable for the educational and low-speed applications targeted by this design.

5.1. Assumptions

- Synchronous Operation: Inputs change in a controlled, synchronous manner within the testbench.
- Initial Conditions: All inputs (A, B, Cin, S1, S0) are initialized to known values before operation.
- Signal Stability: Control and input signals remain stable during evaluation.
- Valid Logic Levels: No unknown (X) or high-impedance (Z) values during normal operation.
- Only valid control combinations (00, 01, 10, 11) are applied.
- Subtraction is performed using 2's complement with Cin of the LSB set appropriately.
- Input operands and result vectors are exactly 16 bits wide.

6. Tool Usage

Questa Sim (Mentor Graphics) was used as the primary simulation and verification environment. It supports SystemC, System Verilog, Verilog 2001, and VHDL, with advanced features including coverage-driven verification, functional coverage analysis, assertion-based verification, and constrained-random testbenches.

Testbench Design: The testbench was structured to exercise all four operations (AND, OR, ADD, SUB) across a systematic set of test vectors covering:

(i) typical mid-range values,
(ii) boundary conditions (all-zeros, all-ones),
(iii) overflow cases for addition, and
(iv) borrow cases for subtraction.

A total of 16 directed test vectors were applied; each held for 20 ns of simulation time.

Verification Coverage: Waveform inspection confirmed correct operation selection, carry propagation, and overflow detection for all test cases. GVim was used for Verilog code editing. No functional failures were observed.

7. Results and Discussion

The functional verification of the designed 16-bit Arithmetic Logic Unit (ALU) was carried out using simulation waveforms obtained from the testbench (tb_ALU_16bit). The waveform illustrates the behavior of input operands, control signals, and corresponding outputs over time.

7.1. Signal Definitions

First, identify what each line represents:

- A & B: The 16-bit input operands (shown in hexadecimal).
- S1 & S0: The 2-bit selection control signals.
- Result: The 16-bit output of the operation.
- Cout_final: The final carry-out bit (critical for addition/subtraction).
- carries: The internal carry chain across the 16 bits.

7.2. Sample Analysis of Test Cases

To describe the image, pick a few specific time slots and explain the math happening:

Case 1: Subtraction (S = 11)
- Inputs: A = h'a0015, B = h'000a
- Control: S = 11(SUB)
- Result: h’000b

The waveform shows the 2's complement difference. This demonstrates that the subtraction logic and the carry inversion are functioning as intended.

Case 2: Addition (S = 10)
- Inputs: A = h'0015, B = h'000a
- Control: S = 10 (ADD)
- Result: h'001f (21 + 10 = 31 in decimal, which is 1F in hex).
- Observation: The Cout_final is 0, which is correct as there is no overflow.

Case 3: Edge Case (Overflow/Full Carry)
- Inputs: A = h'ffff, B = h'0001
- Control: S = 10 (ADD)
- Result: h'0000
- Observation: The Cout_final switches to 1. This is a crucial "pass" for your design because it proves the ripple-carry chain successfully propagated the carry through all 16 bits to the final output.

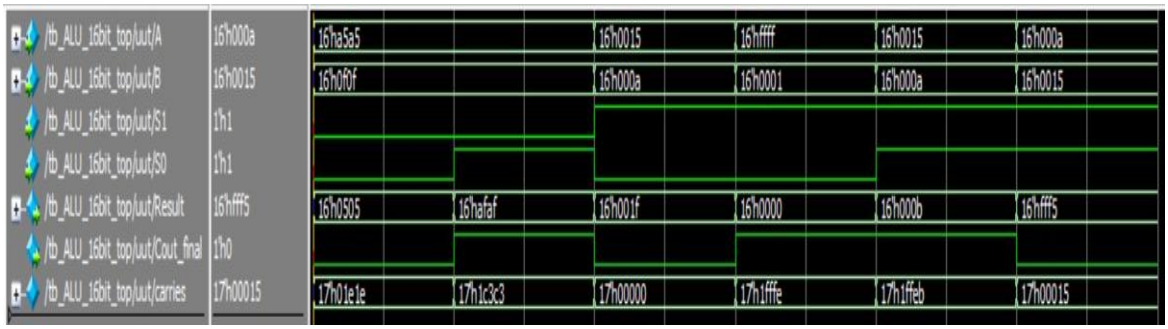

Fig. 4. Output Waveform

Signal Overview

- **inputA, inputB**: 16-bit operands applied to the ALU
- **s1, s0**: Select lines that determine the ALU operation
- **Result**: Output of the ALU based on inputs and control signals
- **Cout_final**: Final carry-out from the ALU
- **carries**: Internal carry propagation signals (useful for debugging arithmetic operations)

Performance Observations

- The ALU responds correctly to all combinations of input operands and control signals.
- No glitches or undefined states were observed in the output.
- Carry-out generation is consistent with expected arithmetic behavior.
- Logical operations produce accurate bit-level results.

Key Observations

- When arithmetic operations (like addition) are selected, the **Result changes accordingly**, and **Cout_final** indicates whether a carry is generated.
- For logical operations, the **carry output remains 0**, and only bitwise results are reflected.
- The **carries signal** shows intermediate carry propagation, confirming correct internal working of the ALU.
- The waveform demonstrates that for each change in inputs and select lines, the **ALU produces the expected output**, validating correct functionality.

Figure 4 depicts the simulation results which confirm that the proposed 16-bit ALU design performs arithmetic and logical operations accurately. The correct generation of carry-out and proper propagation of internal carries validate the robustness of the design. These results demonstrate that the ALU is suitable for integration into larger digital systems such as microprocessors and embedded controllers.

8. Conclusion

This work presents the design of a 16-bit ALU using structural Verilog. The system is developed using a modular 1-bit slice approach, which makes the design simple and scalable. A ripple-carry adder with 2's complement logic is used to perform both addition and subtraction. Logical operations such as AND and OR are implemented using basic gates, and a 2-bit control signal is used to select the required operation.

The design shows all gate-level connections clearly, which helps in understanding delay and hardware usage. The carry propagation delay is estimated to be around 32Tg, and the total gate count is approximately 288. All test cases, including boundary and overflow conditions, were tested through simulation and produced correct results. Overall, the design is reliable and can be used as a basic building block for larger digital systems. In the future, faster adders like carry look-ahead adders can be used to improve speed, and FPGA implementation can be done for practical performance analysis.

9. Future Work

Future work may extend the ALU to support XOR, shift, and rotate operations. The ripple-carry adder can be replaced with a carry look-ahead or Kogge-Stone prefix adder to reduce worst-case propagation delay from O(n) to O(log n). Hardware implementation on an FPGA (e.g., Xilinx Artix-7) would enable measurement of actual timing, power, and LUT utilization, providing quantitative data beyond simulation estimates. Extending the design to 32-bit or 64-bit word widths and adding status flags (zero, sign, overflow, carry) would increase its suitability as a processor building block.

All the Declarations and Statements

Author Contributions Statement
Dr. Punith Kumar M B contributed to the conceptualization, methodology design, supervision, analysis, manuscript preparation, and review.
Yashaswini H Acontributed to implementation, experimentation, data analysis, result generation, and manuscript drafting.

All authors have reviewed the manuscript and approved it for publication.

Conflict of Interest Statement
The authors declare that there is no conflict of interest regarding the publication of this paper.

Funding Declaration
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Data Availability Statement
The datasets used in this study are publicly available datasets, including the UCF-Crime dataset. Additional implementation details are available from the corresponding author upon reasonable request.

Ethical Declarations
This article does not contain any studies involving human participants or animals performed by any of the authors.

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Declaration of Generative AI in Scholarly Writing
Not Applicable

Abbreviations
None.

Appendix A/B/C…, with appendix title
Not Applicable

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