APPROXIMATE COMPUTING FOR IMAGE



/SIGNAL PROCESSING

RECENT ADVANCEMENTS IN MACHINE LEARNING USING EDGE AI

Report submitted to GITAM (Deemed to be University) as a partial fulfillment of the requirements for the award of the Degree of

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NOV 2025

# DECLARATION

We declare that the project work contained in this report is original and it has been done by us under the guidance of my project guide.

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# Chapter 1: Introduction

## Overview of the problem statement

In modern digital systems, there is an increasing demand for high-performance computing while maintaining low power consumption and minimal hardware resources. Traditional computing techniques aim for exact calculations, which can be resource-intensive and sometimes unnecessary, especially in applications like image processing, machine learning, and multimedia where slight errors are tolerable.

This project addresses the challenge of optimizing computational efficiency by introducing **approximate computing techniques**, where controlled imprecision is used to reduce power consumption, area, and processing time without significantly affecting output quality. The focus is on designing hardware modules that leverage approximate arithmetic, such as **approximate adders**, to achieve these efficiency gains.

## Objectives and goals

1. **To study and implement approximate computing techniques** in digital hardware design.
2. **To design and simulate approximate arithmetic units**, particularly adders, for use in image processing tasks.
3. **To analyze the trade-offs** between accuracy, power consumption, area, and performance in hardware design.
4. **To evaluate the effectiveness of approximate computing** by comparing it with conventional exact computing in terms of energy efficiency and output quality.
5. **To provide a framework for applying approximate computing techniques** in real- world applications where minor inaccuracies are acceptable.

# Chapter 2 : Literature Review

### A Novel Design of Power-Efficient and Accurate Approximate Multiplier using Approximate Compressors and Approximate Adders

**Date of Conference:** 28-30 May 2025 **Date Added to IEEE *Xplore*:** 02 July 2025 **ISBN Information:**

**DOI:** [10.1109/ICCRTEE64519.2025.11053053](https://doi.org/10.1109/ICCRTEE64519.2025.11053053)

**Publisher:** IEEE

**Conference Location:** Virudhunagar, India

Authors : Koneru Lakshmi Sowjanya; Pallavi Yampalaku; Kodali Prakash

Approximate multipliers represent a burgeoning paradigm shift in approximate computing. They achieve significant reductions in power consumption, area, and delay at the expense of some computational fidelity. Approximate computing is widely used for better performance in image processing, neural networks, and wireless communication. This paper proposes a novel approximate multiplier architecture that uses approximate compressors and approximate adders (half and full) to achieve appreciable power savings. An error compensation mechanism ensures acceptable accuracy bounds, this approach simplifies complex arithmetic operations while maintaining computational efficiency. The proposed designs are implemented using Verilog HDL, and their functionality is verified through simulation and synthesis using the Xilinx Vivado tool. In the baseline design, the proposed designs, design 1 and design 2, reduced power consumption by 59.16% and 65.93% and have an average accuracy of 93. 14% and 91. 98%, respectively.

* **Approximate multipliers**: The design combines **approximate compressors** and **approximate adders** to build a multiplier that aims to be both power-efficient and reasonably accurate. [J-GLOBAL](https://jglobal.jst.go.jp/en/public/202502247224610076?utm_source=chatgpt.com)
* **Trade-off between error & efficiency**: The authors likely explore how much error is

introduced vs. how much power (and maybe area/delay) is saved. The “accurate

approximate multiplier” suggests they try to keep error low while getting significant

savings. [J-GLOBAL](https://jglobal.jst.go.jp/en/public/202502247224610076?utm_source=chatgpt.com)

* **Implementation & evaluation**: It being a conference proceedings paper of 6 pages likely includes design details, results (simulation / perhaps synthesis), showing the savings in power and possibly comparisons with exact multiplier(s) or prior approximate ones. The conference (ICCRTEE) is recent (2025), so it might use fairly up-to-date process or tools. [J-GLOBAL](https://jglobal.jst.go.jp/en/public/202502247224610076?utm_source=chatgpt.com)
* **Local / regional contribution**: The authors are from institutions in Andhra Pradesh, India.

This indicates perhaps more accessible tools / synthesis resources; but still contributes to the global literature.

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### Analysis of various Approximate adders in Ripple Carry Adder design.

This paper evaluates different approximate adder architectures when applied to the **Ripple Carry Adder (RCA)** structure. The authors investigate how various approximation techniques (such as truncation of lower significant bits, use of simplified approximate full adders, and carry chain modification) affect the performance of RCAs. The comparison is based on metrics like **power consumption, delay, area utilization, and error distance**. The study shows that approximate RCA designs achieve significant reductions in power and delay compared to exact RCAs, at the cost of minor accuracy

degradation.

### Relevance to Project:

Since my project also involves approximate arithmetic (using approximate adders for energy-efficient computing), this paper provides an important benchmark. It demonstrates that ripple carry adders, though inherently slower in exact designs, can become competitive in low-power applications when approximate logic is used. The analysis helps identify trade-offs between accuracy and hardware efficiency, which is directly relevant to evaluating approximate computing techniques in my work.

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### FAU: Fast and error-optimized approximate adder units on LUT-Based FPGAs

* **Authors:** Jorge Alfonso Echavarria Gutiérrez; Stefan Wildermann; Andreas Becher; Jürgen Teich; Daniel Ziener [UT Research Information+1](https://research.utwente.nl/en/publications/fau-fast-and-error-optimized-approximate-adder-units-on-lut-based?utm_source=chatgpt.com)
* **Conference:** *Proceedings of the 2016 International Conference on Field- Programmable Technology (FPT)*, Xi’an, China [UT Research Information+1](https://research.utwente.nl/en/publications/fau-fast-and-error-optimized-approximate-adder-units-on-lut-based?utm_source=chatgpt.com)
* **Pages:** 213-216 [CRIS](https://cris.fau.de/publications/123069364/?utm_source=chatgpt.com)
* **DOI:** 10.1109/FPT.2016.7929536

Here are the main ideas and contributions of this work:

### Approximate Adder Units Optimized for LUT-Based FPGAs

The paper designs adder structures that exploit FPGA architecture (especially LUTs and segmented carry chains) to obtain speed (reduced critical path) and error trade-offs. [CRIS](https://cris.fau.de/publications/123069364/?utm_source=chatgpt.com)

### Exploitation of Unused LUT Inputs and FPGA-Specific Features

They notice that in many FPGAs some LUT inputs might be unused (depending on logic structure), which can be harnessed to build approximate logic without using more resources. This helps reduce resource usage or maintain resources while improving speed. [CRIS](https://cris.fau.de/publications/123069364/?utm_source=chatgpt.com)

### Smaller Average Error than Some Previous Approximate Adders

They compare their FAU designs vs prior approximate adders, showing FAU gives smaller average error under typical input distributions. They also introduce (or use) a “stochastic error calculus” that takes into account non-uniform input distributions (i.e. inputs aren’t always equally likely) for more realistic error estimation. [CRIS](https://cris.fau.de/publications/123069364/?utm_source=chatgpt.com)

### Reduced Critical Path Delay vs Accurate Logic

One of their claims is that in LUT-based FPGAs, their approximate adder units can achieve lower delay (i.e. faster operation / higher max clock frequency) than even some dedicated accurate logic. This is a strong result for approximate designs in FPGA domain.

### Analysis

* **RCA vs FAU Structure**:

Traditional RCAs propagate carry through each bit, which yields long latency. FAU designs exploit FPGA carry chains and LUT-based features to shorten delay. In your report, you can contrast how RCAs are simple, but FAU’s design may be able to beat

RCA in terms of delay for certain approximations.

### Error Metrics & Input Distributions:

FAU’s use of stochastic error models (non-uniform inputs) is important. Many earlier approximate adder papers assume uniform random inputs. In real applications (images, sensor data, etc.), distributions may be skewed. You can highlight this as an advance.

### Resource Usage Tradeoffs:

Since FAU is tuned for LUT usage, resource (LUT count), power, etc., can differ significantly. Use their data to compare resource vs error vs delay tradeoffs in your own designs.

### Comparisons You Could Do:

* Compare FAU vs simple approximate RCA (LOA, truncated, etc.) in terms of max frequency achieved (because FAU shows good delay improvements).
* Look at error vs degree of approximation (how many LSBs approximate). FAU likely shows that approximating more bits increases error but gives more speed/resource gains.

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# Chapter 3 : Strategic Analysis and Problem Definition

## SWOT Analysis

### Strengths:

* + Reduces **power consumption and delay** by using approximate adders and multipliers.
  + Suitable for **VLSI/FPGA implementation** in energy-constrained devices.
  + Applicable to **image processing, AI, DSP, and IoT applications**.
  + Allows **trade-off between accuracy and hardware efficiency**, enabling flexible designs.

### Weaknesses:

* + Accuracy loss may limit usage in **critical systems** (medical devices, aerospace).
  + Design complexity increases with **error analysis and verification**.
  + Initial learning curve for **FPGA/ASIC tools and approximate design methods**. **Opportunities**:
  + Growing demand for **low-power, high-speed arithmetic units** in embedded and portable devices.
  + Extendable to **complex operations** like MAC units, convolution engines, and DSP blocks.
  + Research scope in **error-tolerant systems, AI accelerators, and edge computing**. **Threats**:

Competing exact architectures, rapid tech changes, excessive errors, limited industrial adoption.

### Review 1 : Approximate vs Exact Adders

**Exact Adders**

* + 100% accurate.
  + Higher power, larger area, slower (long carry chains).
  + Used in accuracy-critical systems.

### Approximate Adders

* + Slightly inaccurate but faster and energy-efficient.
  + Lower power, smaller area, simpler logic.
  + Suitable for AI, image/video processing, IoT.

**Key Insight:** Approximate adders trade **accuracy for speed and efficiency**, making them ideal for resource-constrained or high-performance applications, while exact adders remain essential for critical computations.

### Review 2: Approximate Multipliers

**Exact Multipliers**

* + Fully accurate.
  + High power, area, and delay.
  + Used in accuracy-critical systems.

### Approximate Multipliers

* + Slightly inaccurate but faster and energy-efficient.
  + Lower power, smaller area, simpler hardware.
  + Suitable for AI, image/video processing, and signal processing.

**Key Insight:** Approximate multipliers trade **accuracy for speed and efficiency**, making them ideal for resource-constrained or high-performance applications.

## Problem statement

Traditional arithmetic units, such as adders and multipliers, are designed to produce **exact**

**results**, but they consume significant **power, area, and delay**, especially in high-performance or energy-constrained applications like **AI, image processing, and IoT devices**.

The challenge is to design **approximate adders and multipliers** that **reduce power consumption, area, and delay** while maintaining **acceptable accuracy**. The goal is to achieve a **balance between performance and error**, enabling efficient computation in applications where minor inaccuracies are tolerable.

# Chapter 4 : Methodology

## Description of the approach

* + **Literature Study:** Understanding existing approximate adder and multiplier designs and their trade-offs in **power, delay, and accuracy**.

### Design Phase: Developing approximate adders and multipliers

* + **Implementation:** Coding the designs in **Verilog/SystemVerilog** for simulation and hardware evaluation.
  + **Testing & Simulation:** Verifying functional correctness, and evaluating **performance metrics** such as **power, area, delay, and error** using FPGA/EDA tools.
  + **Analysis:** Comparing approximate designs with exact designs to study **trade-offs and efficiency improvements**.

## Tools and techniques utilized

* + **Hardware Description Languages:** Verilog / SystemVerilog for RTL design.

### EDA Tools:

* + **Xilinx Vivado** – for FPGA-based implementation and verification.
  + **Simulation Tools:** Vivado
  + **Analysis Tools:** Power and area estimation using **tool-specific reports** (Vivado Power Analyzer)

## Design considerations

1. **Error Tolerance:** Only minor errors in LSBs are acceptable; MSBs are kept accurate for reliability.
2. **Power Efficiency:** Optimizing logic to reduce **switching activity** and **resource usage**.
3. **Hardware Resources:** Ensuring designs fit within FPGA LUT and slice constraints.
4. **Scalability:** Supporting multiple bit-widths for adders/multipliers.
5. **Application Suitability:** Targeting **image processing, AI inference, and signal processing** where slight inaccuracies are tolerable.

# Chapter 5 : Implementation

## Description of how the project was executed

### Design of Approximate Adders and Multipliers

* Selected approximate adder types
* Defined bit-widths and approximation levels to balance **accuracy, power, and speed**. **Coding in Hardware Description Language (HDL)**
* Implemented the designs in **Verilog**
* Structured the modules for **modular testing**, including parameterizable adders/multipliers.

### Simulation and Verification

* Testbenches were created to apply **random and corner-case input vectors**.

### Synthesis and Implementation on FPGA / EDA Tools

* Synthesized the design in **Xilinx Vivado**

### Evaluated power, delay, and area reports. Comparison with Exact Designs

* Compared approximate designs with exact adders/multipliers to **analyze trade-offs** in

**error, power, area, and delay**.

## Challenges faced and solutions implemented

|  |  |
| --- | --- |
| **Challenge** | **Solution** |
| Balancing **accuracy vs. power/delay** in approximate designs | Adjusted **number of LSBs approximated** and selected suitable approximate adder/multiplier types. |
| Verification of functional correctness | Developed **comprehensive testbenches** with random and corner-case inputs. |
| High **power consumption in** | Optimized logic, simplified carry chains, and reduced |

|  |  |
| --- | --- |
| **initial designs** | switching activity. |
| FPGA resource constraints | Modified design parameters to **fit LUTs, slices, and carry chains** efficiently. |
| Analysis of **error patterns** | Implemented scripts to calculate **mean error, error distance, and worst-case error**. |

# Chapter 6: Results

## 1 Outcomes

* Approximate adders and multipliers reduce power and improve speed.
* Minor accuracy loss in lower-order bits, acceptable for image processing.

## Interpretation of results

* Significant power and delay reduction with controlled approximation.
* Errors mainly in LSBs, minimal effect on overall output quality.

## Comparison with existing literature or technologies

* Lower power and faster than exact circuits.
* Slight accuracy trade-off aligns with trends in recent approximate computing studies.
* Efficient for applications like image processing and multimedia.

# Chapter 7: Conclusion

* The implementation of approximate adders and multipliers in this project demonstrates that controlled approximation can significantly **reduce power consumption** and **increase computational speed** compared to exact arithmetic circuits. Although there is a small loss of accuracy, it is mostly confined to the **least significant bits (LSBs)**, which has a negligible effect on overall output quality. This trade-off between accuracy and efficiency makes approximate computing particularly suitable for applications like **image processing, multimedia, and machine learning**, where perfect precision is not critical.
* Furthermore, the results indicate that approximate circuits can be integrated into larger hardware systems to achieve **energy-efficient designs** without compromising performance. The study also highlights the potential for **further improvements**, such as adaptive approximation techniques and hardware optimization strategies, which can enhance both **efficiency and reliability**. Overall, approximate computing presents a promising approach for developing **low-power, high-performance hardware systems** in modern computing applications.

# Chapter 8 : Future Work

For future work, the use of **approximate computing in image convolution** can be further explored to enhance performance and efficiency:

* **Adaptive Approximation:** Develop techniques that dynamically adjust the level of approximation based on the image content or processing requirements to balance **accuracy and power savings**.
* **Hardware Acceleration:** Implement approximate convolution engines on **FPGA or ASIC platforms** to evaluate real-world performance and energy efficiency.
* **Integration with AI/ML:** Combine approximate convolution with **deep learning models** for faster and more energy-efficient image processing in applications like object detection or recognition.
* **Error Optimization:** Design **error-correction or compensation mechanisms** to reduce visual artifacts while maintaining low power consumption.
* **Large-Scale Image Processing:** Extend the approach to **high-resolution images and video processing**, analyzing trade-offs between speed, power, and accuracy.

# References

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