Asian Deans' Forum 2026

THE RISING STARS

Women in Engineering Workshop

SEP 13 - 15 | HKUST, Hong Kong

Reliable Digital Information: From Error-Correcting Codes to Hardware

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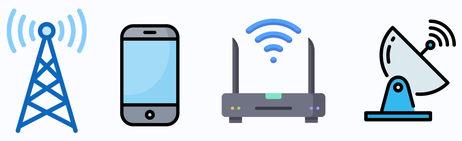
1 WHY RELIABLE DIGITAL INFORMATION MATTERS?

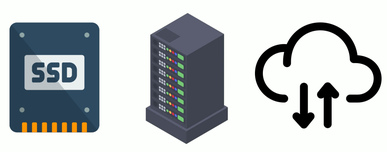
Reliable digital information is everywhere

COMMUNICATION



- 5G control information
- Wi-Fi / Optical links
- IoT and connected devices
- Remote and autonomous systems

STORAGE



- SSD / Flash memory
- Data centers
- Cloud storage

COMMON NEED

- Errors can occur in both transmission and storage.
- Reliable delivery is essential for our daily life and future systems.
- Strong error protection must be achieved with practical cost.

2 WHAT ARE ERROR-CORRECTING CODES?

Where channel coding sits & How it recovers corrupted bits

1. Complete communication system — channel coding highlighted

Source → Source Encoder → **Channel Encoder** → Modulation + TX → **Noisy Channel** → RX + Demodulation → **Channel Decoder** → Source Decoder → Sink

Channel encoder adds redundancy; channel decoder uses it to correct errors.

2. Repetition coding through a noisy channel — one complete example

Information Bits: 1 0 1 — original bits

→ **Channel Encoder**: repeat every bit 3 times: 1 1 1 0 0 0 1 1 1 (1 → 111, 0 → 000)

→ **Channel / Storage**: bits may flip or be erased: 1 1 **0** 0 **?** 0 1 **0** 1 (error, erasure, error)

→ **Majority-vote Decoder**: one decision per group: 110 → 1, 0?0 → 0, 101 → 1

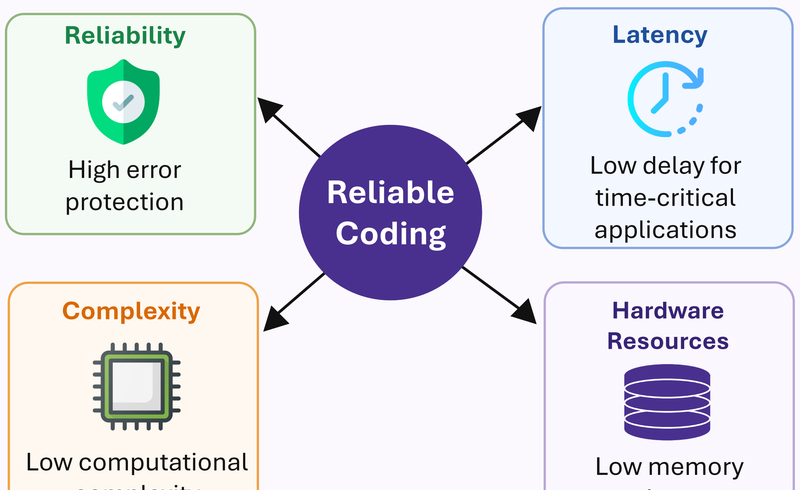
→ **Recovered bits**: 1 0 1

Split the received sequence into groups of three; majority vote recovers each original bit.

Redundancy allows the receiver to reconstruct the original 0s and 1s even when the channel changes or erases part of the message.

3 THE CHALLENGE

High reliability must be achieved without excessive cost



Our question:

How can we improve reliability without making decoding impractical?

4 MY RESEARCH: ALGORITHMIC APPROACHES

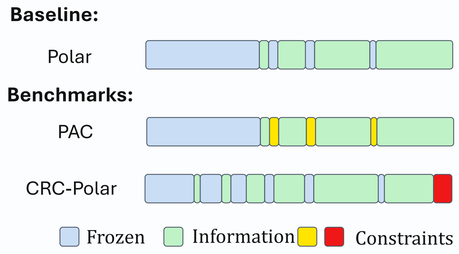
Understand code behavior, design stronger codes, and scale to longer blocks

Code Analysis

Analyze code structures to identify the properties that determine error-correction performance.

Baseline: Polar

Benchmarks: PAC, CRC-Polar



Distance properties predict error-correction performance

$$P_e^{ML} \le A_{d_{min}} Q\left(\sqrt{2 \cdot d_{min} \cdot R \cdot E_b/N_0}\right)$$

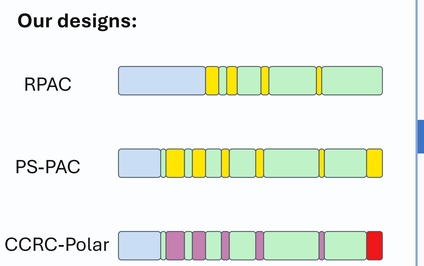
- Larger minimum distance (d_{min} ↑)
- Fewer harmful codewords ($A_{d_{min}}$ ↓)
- Explain and guide better code designs

Challenge: Bounds in d_{min} & $A_{d_{min}}$

Better Code Designs

Use structural insights to construct stronger and more flexible codes.

Our designs: RPAC, PS-PAC, CCRC-Polar



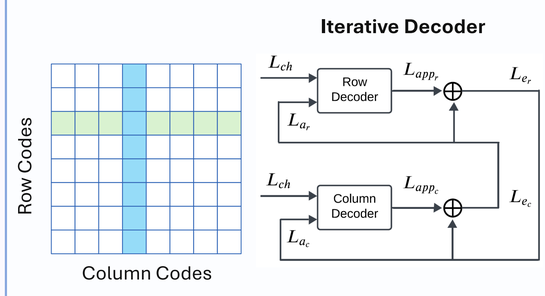
- Additional constraints
- Improved distance properties
  → Remove bounds: d_{min} ↑, $A_{d_{min}}$ ↓
- Stronger error-correction performance
- Flexible code rates and lengths

Larger-Scale Systems

Build longer codes from short component codes using product-code structures.

Challenge: Direct decoding of long codes can require substantial latency and memory.

- Build long codes from short component codes
- Product polar codes



- Iterative Row Decoder ⇄ Column Decoder
- Practical decoding complexity
- Maintain strong performance

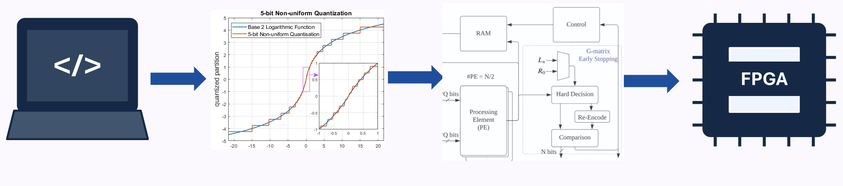
5 FROM ALGORITHMS TO HARDWARE

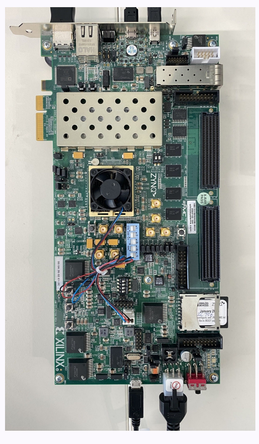
Translate decoding algorithms into practical FPGA implementations

Why FPGA?

- ✓ Real-world environment for practical validation
- ✓ Explore quantization and memory trade-offs
- ✓ Bridge the gap between theory and deployment
- ✓ Evaluate practical decoder architectures

Decoder Algorithm → **Quantization Design** → **Architecture Design** → **FPGA Implementation**





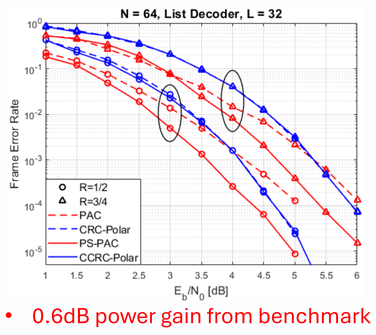
What we evaluate

Latency · Throughput · Memory Usage · Error Correction performance · Power Efficiency · Area Resources

6 SELECTED RESULTS (Highlights)

Short Codes (High Reliability)

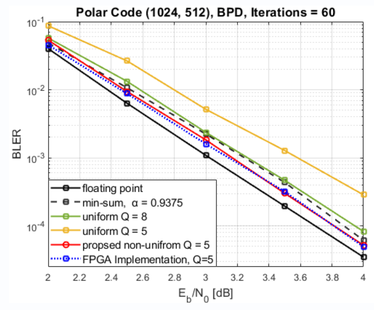
- Better performance for short-to-moderate code lengths



- 0.6dB power gain from benchmark
- Adaptive to a broad range of code lengths and code rates

Hardware-Efficient Decoding (Reduced memory)

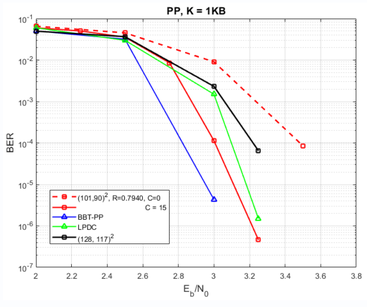
- Non-uniform Quantization, Q = 5
- Look-up table based hardware design



- Reduce 37.5% memory
- 0.2dB power gain compared to Q = 8

Product Codes (Longer Lengths)

- Irregular coding tree
- Construct required length directly



- Reliable performance is maintained for longer and flexible block lengths.

Results demonstrate gains in code performance, memory efficiency, and scalability to longer blocks.

7 TAKE-AWAY MESSAGE

Everyday systems generate and exchange digital information. → Error-correcting codes protect information from errors in the real world. → Stronger code designs, scaled and implemented efficiently, enable reliable and practical systems. → This research contributes to future digital systems that are reliable, efficient, and ready for real-world impact.

Better Codes • Scalable Designs • Efficient Hardware = Reliable Digital Systems

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