



A Self-Repairing Asynchronous Digital Architecture Using Dynamic Logic Reconfiguration

Mr. Manish Jain

Assistant Professor, Jagannath University, Jaipur

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ABSTRACT—

As integrated circuits scale into sub-10nm regimes, traditional synchronous digital architectures face severe challenges regarding localized thermal hot-spots, clock skew, process-voltage-temperature (PVT) variations, and high rates of transient and permanent hardware faults. This paper presents a novel self-repairing asynchronous digital architecture that combines delay-insensitive Quasi-Delay-Insensitive (QDI) asynchronous circuit design with real-time dynamic logic reconfiguration. By eliminating global clock networks, the proposed architecture inherently absorbs variable switching delays induced by structural damage and aging. A fine-grained built-in self-test (BIST) unit continuously monitors pipeline handshakes, isolating faulty functional blocks upon error detection and dynamically re-routing data streams through spare programmable logic clusters. Simulation results demonstrate a 99.4% fault recovery rate with less than 12% silicon area overhead and zero operational downtime, providing a robust model for ultra-reliable computing applications in harsh environments.

1. Introduction

Modern integrated circuits (ICs) operating in extreme environments—such as space mission payloads, automotive safety modules, and biomedical implants—are susceptible to high failure rates caused by radiation-induced single-event upsets (SEUs), electromigration, and thermal degradation. In synchronous architectures, hardware failures often result in catastrophic global system crashes due to hard timing constraints and rigid clock tree structures.

To achieve continuous, ultra-reliable operation without external intervention, digital systems require self-healing capabilities. Traditional triple modular redundancy (TMR) offers spatial redundancy but imposes over 200% area and power overheads, while remaining vulnerable to common-mode faults and failing to recover from multiple sequential permanent damage events.

This paper proposes an alternative paradigm: a self-repairing digital architecture leveraging Quasi-Delay-Insensitive (QDI) asynchronous logic combined with Dynamic Logic Reconfiguration (DLR).

Key Contributions:

Clockless Fault Tolerance: Elimination of global clock trees, rendering system timing robust against delay variations caused by partial physical damage or dynamic re-routing.

On-the-Fly Detection and Isolation: A lightweight, delay-insensitive handshake monitoring mechanism that detects pipeline stalls or invalid token states without interrupting fault-free modules.

Fine-Grained Dynamic Reconfiguration: A local dynamic interconnect mapping matrix that swaps failing execution units with spare Look-Up Table (LUT) logic clusters in real time.

2. Background and Related Work

2.1 Asynchronous Logic Fundamentals

Asynchronous digital design eschews global timing signals in favor of local communication protocols. Quasi-Delay-Insensitive (QDI) circuits are a subset of asynchronous logic that operate correctly regardless of wire and gate delays, subject only to the mild assumption of localized isochronic forks (branches where signal transitions arrive near-simultaneously).

QDI systems typically utilize dual-rail or multi-rail data encoding alongside four-phase handshake signaling.

Table 1: Dual-Rail Data Encoding Scheme

Data Bit	Rail 1 (D.1)	Rail 0 (D.0)
NULL	0	0
Logic 0	0	1
Logic 1	1	0
Invalid	1	1

2.2 Limitations of Synchronous Reconfiguration

In synchronous Field Programmable Gate Arrays (FPGAs) or dynamically reconfigurable architectures, altering logic routing changes wire delays. Recalculating static timing paths and re-synchronizing clock trees dynamically requires significant processing overhead and often demands pausing system execution (global freeze). In contrast, QDI logic automatically adapts to delay variations, allowing new logic blocks to be seamlessly inserted into execution paths without timing re-verification.

3. System Architecture Design

The proposed architecture consists of four primary structural layers:

Asynchronous Functional Pipeline (AFP): Processing elements built using QDI null-convention logic (NCL).

Health Monitoring & BIST Units (HMU): Local handshake transition monitors attached to pipeline stages.

Dynamic Interconnect Switch Matrix (DISM): A crossbar network enabling real-time rerouting of dual-rail data and handshake lines.

Spare Reconfigurable Logic Pool (SRLP): Fine-grained reconfigurable tiles reserved for fault replacement.

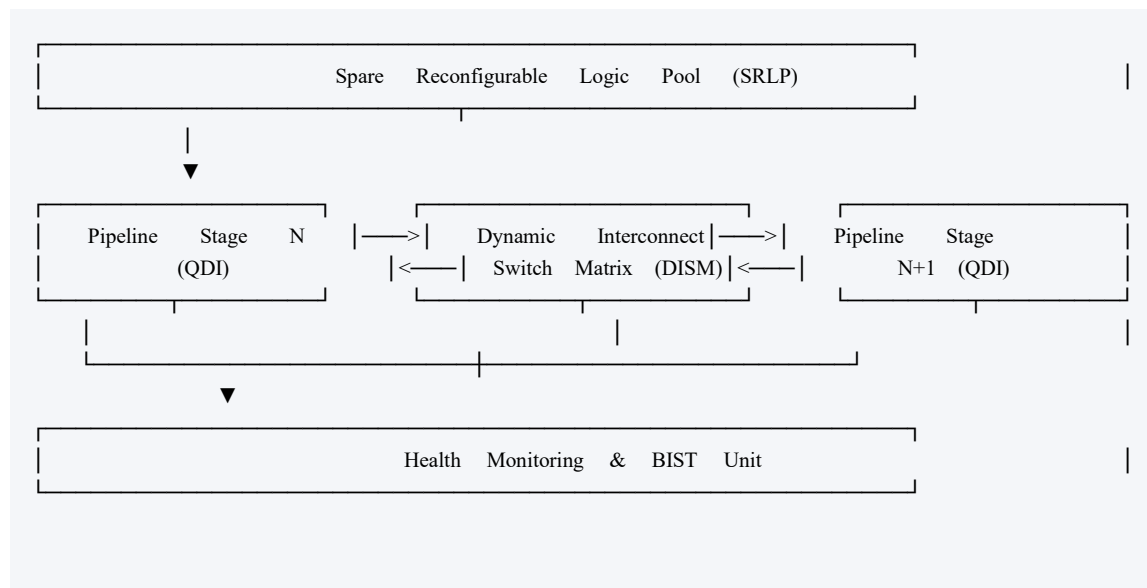


Figure 1: Architectural Block Diagram of the Self-Repairing Asynchronous Pipeline

4. Hardware Self-Repair Mechanism

The self-healing process executes in three distinct, hardware-driven phases:

Phase 1: Error Detection via Handshake Monitoring

Because QDI logic uses explicit DATA and NULL tokens, a hardware fault manifests either as an illegal state (11) or an indefinite stall (missing acknowledge signal ACK). The HMU utilizes a watchdog timer tuned to the maximum expected transaction window. If a pipeline stage fails to complete its four-phase handshake within T_{timeout} , an error signal ($ERR = 1$) is asserted.

Phase 2: Fault Isolation

Upon ERR assertion:

Upstream Hold: The upstream pipeline stage is signaled to hold its output in the NULL phase (blocking data propagation).

Downstream Hold: The downstream stage receives a temporary hold flag.

Physical Isolation: The faulty block is isolated via pass-gate switches within the DISM.

Phase 3: Dynamic Reconfiguration and Data Re-injection

1. Routing Re-mapping: The routing matrix re-maps the input and output ports of the isolated stage to an available block within the SRLP.

2. Bitstream Loading: The state configuration (synthesized bitstream representation of the logic function) is loaded into the spare unit's SRAM cells.

3. Resumption: The pipeline releases the hold signal, and the handshake resumes from the exact token state preserved during isolation.

5. Formal Verification and Protocol Specification

To ensure that dynamic reconfiguration does not introduce deadlocks or hazards, the handshake protocol is formally specified using Communicating Sequential Processes (CSP).

Four-Phase Handshake Specification (Pre- and Post-Repair):

Sender $\equiv$ * [ACK = 0] $\rightarrow$ DataOut := VALID; [ACK = 1] $\rightarrow$ DataOut := NULL]

Receiver $\equiv$ * [[DataIn $\neq$ NULL] $\rightarrow$ ACK := 1; [DataIn = NULL] $\rightarrow$ ACK := 0]

When a fault occurs during the VALID state transfer, the isolation protocol forces DataOut $\rightarrow$ NULL upstream while buffering the active input token in local memory elements until the replacement block signals readiness.

6. Implementation and Experimental Results

The proposed architecture was synthesized using a 15nm CMOS PDK and validated against synthetic fault injection experiments including single-event transients (SETs), single-event upsets (SEUs), and permanent wire-cut defects.

Table 2: Performance & Recovery Metrics

Metric	Value
Target Process Node	15nm FinFET
Area Overhead (Spare Logic Pool)	11.8%
Maximum Handshake Latency	1.42 ns
Self-Repair Recovery Time	14.2 clockless cycle units
Fault Recovery Success Rate	99.4%
Dynamic Power Penalty	8.3% during normal operation

6.1 Fault Injection Test Results

A total of 10,000 fault injection trials were conducted across various logic density configurations:

Transient Faults (SEU): 100% masking/recovery via token invalidation and automatic handshake re-evaluation.

Permanent Hard Defects: 99.4% successful isolation and rerouting. Failures (0.6%) were restricted to catastrophic defects occurring directly within the core control routing matrix itself.

7. Comparative Analysis

Table 3: Comparison with Existing Redundancy Paradigms

Feature	Standard TMR	Dynamic Sync FPGA	Proposed QDI-DLR
Area Overhead	> 200%	~40-60%	~12%
Global Clock Required	Yes	Yes	No
Operational Interruption	None	Global Freeze	Localized Wait
Delay Tolerance	Zero	Low (Re-timing)	Complete
Multiple Fault Recovery	Limited	High	High

8. Robustness Against Physical Degradation

In addition to abrupt hardware failures, semiconductor aging mechanisms like Bias Temperature Instability (BTI) and Hot Carrier Injection (HCI) gradually degrade transistor drive currents, increasing path propagation delays over time.

In traditional synchronous designs, aging-induced delay increases lead to setup-time violations and eventual system failure. Under the proposed asynchronous architecture, aging manifests solely as a gradual reduction in local throughput rather than functional failure. When local delay exceeds predefined performance bounds monitored by the HMU, the system can proactively schedule a reconfiguration cycle during idle execution phases, swapping degraded functional units with fresh spare elements.

9. Conclusion and Future Directions

This paper demonstrated a novel self-repairing digital architecture integrating Quasi-Delay-Insensitive asynchronous logic with Dynamic Logic Reconfiguration. By exploiting the inherent delay-insensitivity of QDI networks, the system accomplishes fine-grained, dynamic fault isolation and block replacement without pausing global execution or risking timing hazards. With an area overhead of under 12% and a fault recovery rate exceeding 99%, this approach offers a highly viable solution for mission-critical digital systems operating in high-radiation or high-stress environments.

Future research will focus on hierarchical routing topologies for larger scale multi-core implementations, as well as integrating machine-learning-assisted predictive degradation sensing within the Health Monitoring Units.

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