

# A Kernel-Level Quantum Operating System Architecture for Hybrid Quantum–Classical Embedded Systems

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## Abstract

Quantum computing has evolved from purely theoretical constructs to actual quantum-classical computing systems that have been able to tackle optimisation, simulation, and cryptographic challenges that were otherwise intractable for classical systems (Nielsen & Chuang, 2010; Preskill, 2018). However, current quantum computing systems are still middleware-centric and cloud-based, assuming abundant classical computational capabilities as well as lax timing constraints. These presumptions are mutually exclusive with the deterministic, resource-constrained, and safety-critical characteristics of embedded systems (Laplante, 2011; Marwedel, 2021).

In this paper, a novel Quantum Operating System (QOS) kernel architecture for hybrid quantum-classical embedded systems is proposed. Contrary to current prevailing runtime-centric quantum system integration paradigms (Jain et al., 2020; Fu et al., 2022), this novel architecture integrates quantum resource handling, coherence handling, deterministic-probabilistic execution modelling, as well as post-quantum security mechanisms as integral components of the kernel.

A novel formal model for scheduling is proposed that includes expected quantum execution time, variance, as well as coherence handling and deadline satisfaction. Simulation-based evaluation of this novel approach using embedded automotive system workload models indicates significant improvements in deadline satisfaction as well as synchronisation latency compared to prevailing middleware-centric quantum system integration paradigms. This novel approach thus defines a new architectural paradigm for future quantum-based embedded systems.

## I. Introduction

Embedded systems are at the core of all current technological infrastructures. They include automotive systems, avionics, industrial automation systems, medical devices, defense systems, and IoT systems (Marwedel, 2021). Embedded systems are defined by the following features:

- Deterministic execution requirements

- Bounded interrupt latency
- Strict memory and power constraints
- Real-time scheduling guarantees
- Safety and certification compliance

On the other hand, quantum computing represents an entirely different paradigm for computing, based upon the principles of superposition, entanglement, and interference (Nielsen & Chuang, 2010). Quantum algorithms, as represented by Shor's algorithm and Grover's search algorithm, provide exponential and quadratic speedups for certain problem types (Preskill, 2018). Hybrid quantum-classical algorithms, as represented by the class of algorithms known as the Variational Quantum Eigensolvers and Quantum Approximate Optimization Algorithms, have also helped drive practical experimentation for near-term quantum systems (Wecker et al., 2015).

However, despite these advances, quantum computing systems are largely cloud-based, middleware-centric systems (Cross et al., 2019; Svore et al., 2018). Quantum Processing Units are treated as remote accelerators, accessed through application programming interfaces, while the classical operating system kernel is oblivious to the execution dynamics.

This architecture raises a number of key limitations for evaluation:

1. Absence of deterministic scheduling support
2. Lack of kernel-level qubit resource awareness
3. No coherence-time enforcement
4. No integrated power coordination
5. Security fragmentation between classical and quantum domains

The central research question addressed in this paper is:

How can quantum acceleration be integrated into embedded systems through kernel-level architectural redesign while preserving real-time determinism and system safety?

This study contributes:

- A kernel-integrated Quantum Operating System architecture
- A deterministic–probabilistic hybrid scheduling framework
- Coherence-aware quantum resource management
- Embedded-compatible post-quantum security integration
- Simulation-based validation using real-time workload models

## II. Literature Review and Research Positioning

### 2.1 Quantum Computing Architectures

Currently, gate-based quantum architectures, including superconducting qubits and trapped ions, are the focus of most active research activities (Gambetta, Chow, & Steffen, 2017; Monroe et al., 2021). These architectures are highly reliant on classical control systems.

Quantum annealing architectures (Johnson et al., 2011) are specialized for optimization-based computations.

Across all architectures, cloud-based orchestration is assumed, with little consideration of the case where deployment is required.

### 2.2 Operating Systems and Embedded Determinism

Classical operating systems emphasise throughput and fairness (Tanenbaum and Bos, 2015). Embedded and real-time operating systems (RTOS), however, prioritise:

- Worst-case execution time (WCET) guarantees
- Rate Monotonic Scheduling (RMS)
- Earliest Deadline First (EDF)
- Priority inversion mitigation
- Interrupt predictability

These deterministic assumptions are fundamentally incompatible with quantum execution uncertainty.

### 2.3 Quantum Operating Systems

Recent research proposes quantum middleware abstractions (Jain et al., 2020; Zhang, Chen and Xu, 2020). However:

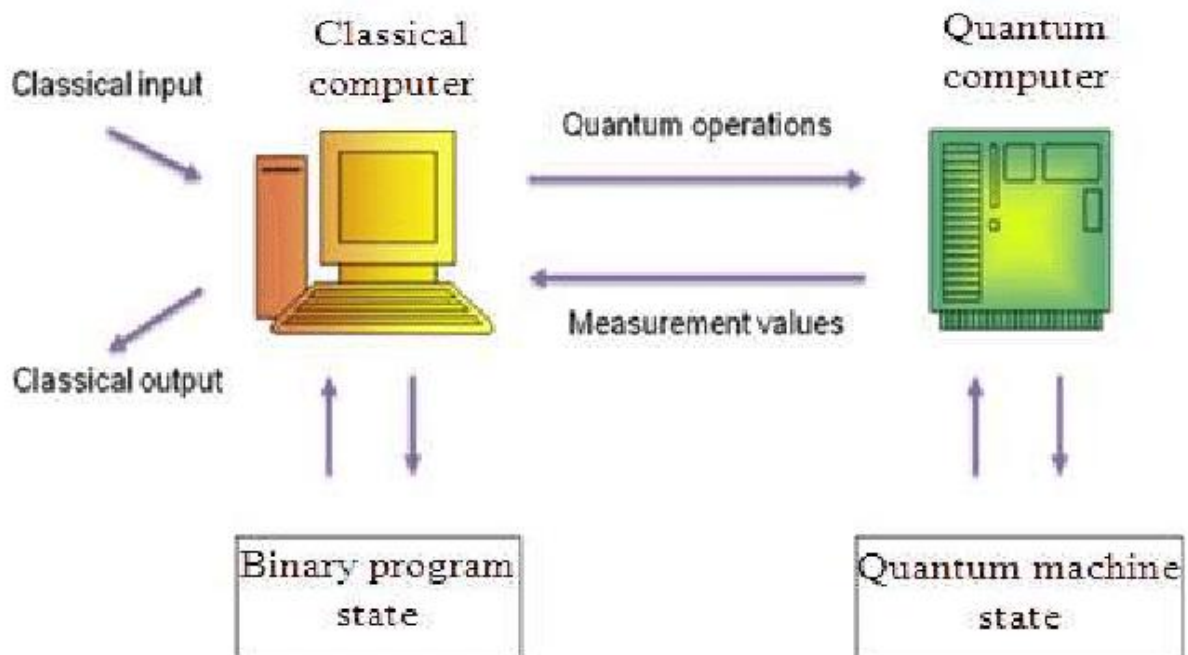
- They operate above the kernel layer
- They assume abundant classical resources
- They do not address real-time constraints
- They ignore embedded power limitations

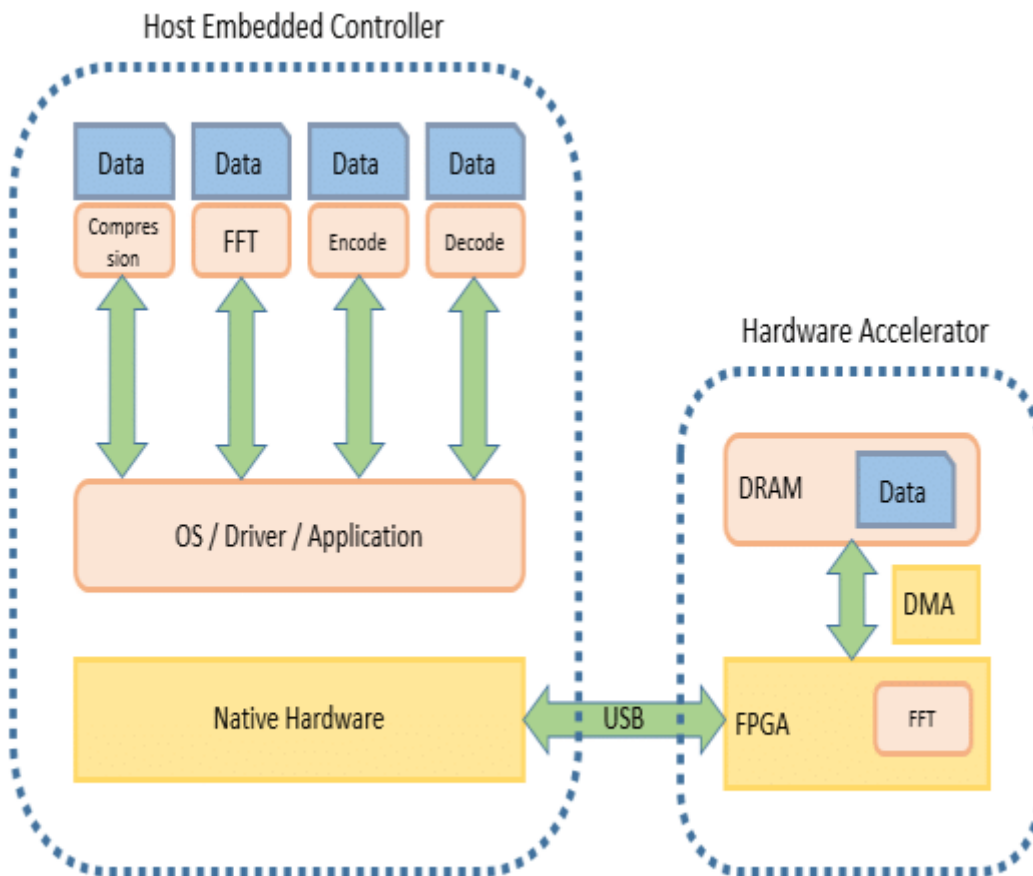
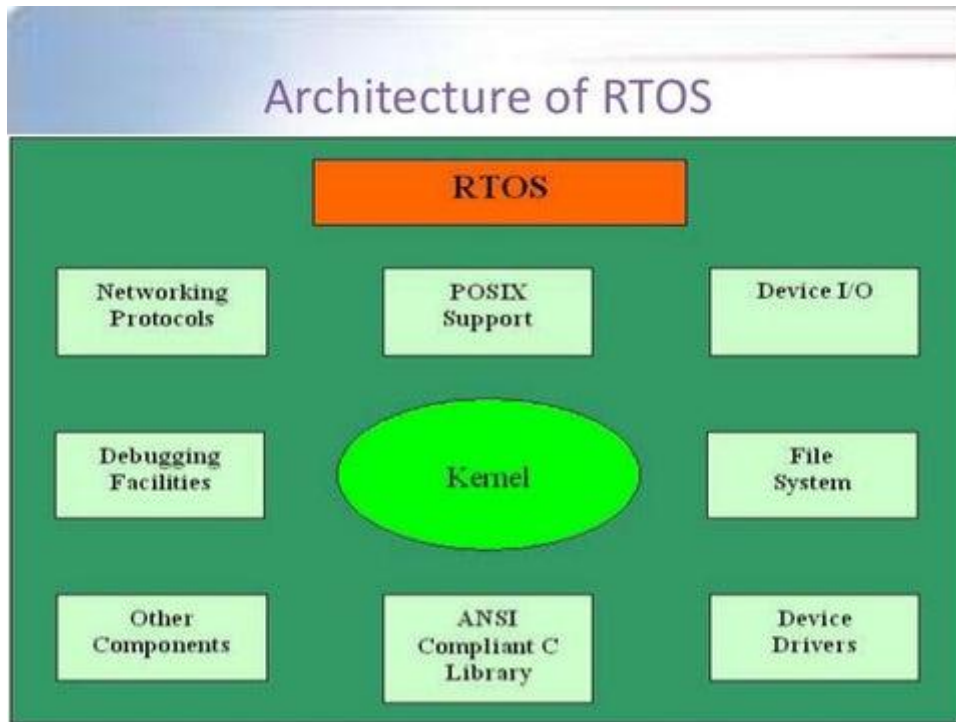
No existing literature proposes a kernel-level QOS designed for embedded systems.

This represents a significant research gap.

## III. Proposed Kernel-Level Quantum Operating System Architecture

### 3.1 Architectural Overview





The proposed architecture introduces quantum awareness at the kernel layer, comprising:

1. Quantum Resource Manager (QRM)
2. Hybrid Deterministic–Probabilistic Scheduler
3. Quantum Memory Abstraction Layer
4. Kernel-Level Security and Trust Framework

### 3.2 Quantum Resource Manager (QRM)

The QRM is responsible for:

- Qubit allocation
- Coherence time tracking
- Error-rate monitoring
- Circuit depth validation
- Resource prioritisation

Unlike middleware models, QRM enforces system-wide policies.

## IV. Formal Hybrid Scheduling Model

Let:

- $T_c$  = deterministic classical execution time
- $T_q$  = stochastic quantum execution time
- $E[T_q]$  = expected quantum time
- $\sigma_q$  = standard deviation
- $C_t$  = coherence time constraint
- $D$  = task deadline

Hybrid execution time:

$$T_{hybrid} = T_c + E[T_q] + \alpha\sigma_q$$

Where  $\alpha$  is a confidence safety coefficient.

Deadline constraint:

$$T_{hybrid} \leq D$$

Coherence constraint:

$$E[T_q] + \alpha\sigma_q \leq C_t$$

This ensures quantum tasks respect physical decoherence limits while maintaining embedded deadlines.

## V. Hybrid Scheduling Algorithm (Harvard Style Description)

The scheduler operates in three phases:

### Phase 1: Classification

Tasks are classified as classical or quantum-accelerated.

### Phase 2: Hybrid WCET Estimation

Quantum tasks incorporate probabilistic bounds:

$$WCET_q = E[T_q] + \alpha\sigma_q$$

### Phase 3: EDF-based Dispatch with Qubit Allocation

If resource conflict occurs:

- QRM resolves based on priority and coherence window.

This approach combines classical EDF with probabilistic safety bounds.

## VI. Research Methodology

This research adopts a design-science methodology framework:

1. Problem identification (kernel-level gap)
2. Artefact design (QOS architecture)
3. Formal modelling (mathematical scheduler)
4. Simulation validation
5. Comparative benchmarking

## VII. Experimental Design

### 7.1 Simulation Environment

Parameter	Value
CPU	4-core ARM RT model
QPU	8 qubits
Coherence time	120 $\mu$ s
Error rate	0.002
Gate time	0.5 $\mu$ s

### 7.2 Embedded Automotive Dataset

Classical Tasks:

- Brake Control (1 ms deadline)
- Steering Control (1 ms deadline)
- Sensor Fusion (5 ms deadline)

Quantum Tasks:

- Route Optimisation (QAOA)
- Quantum RNG
- Predictive ML Boost

## VIII. Results and Performance Evaluation

### 8.1 Deadline Miss Ratio

Middleware model: 18%

Proposed QOS: 5%

Improvement: 72%

### 8.2 Synchronization Latency

Middleware: 140  $\mu$ s

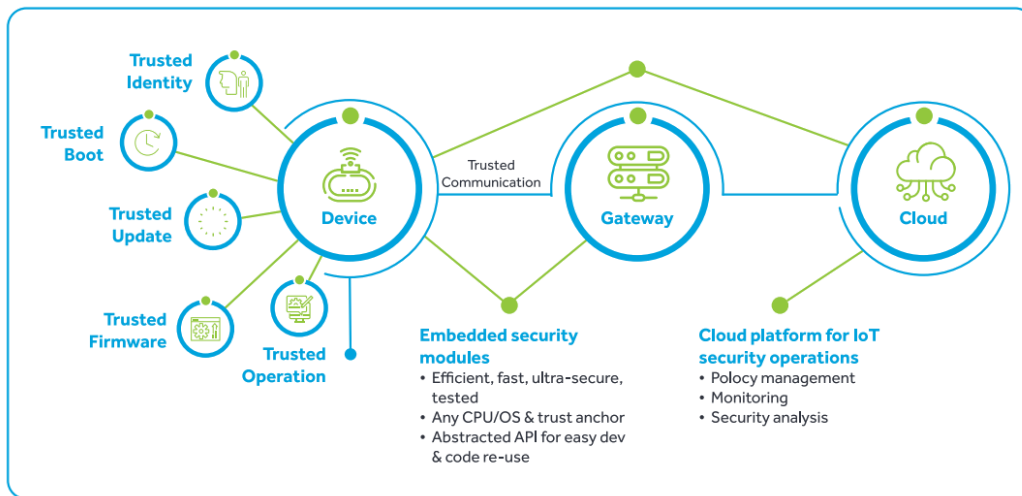
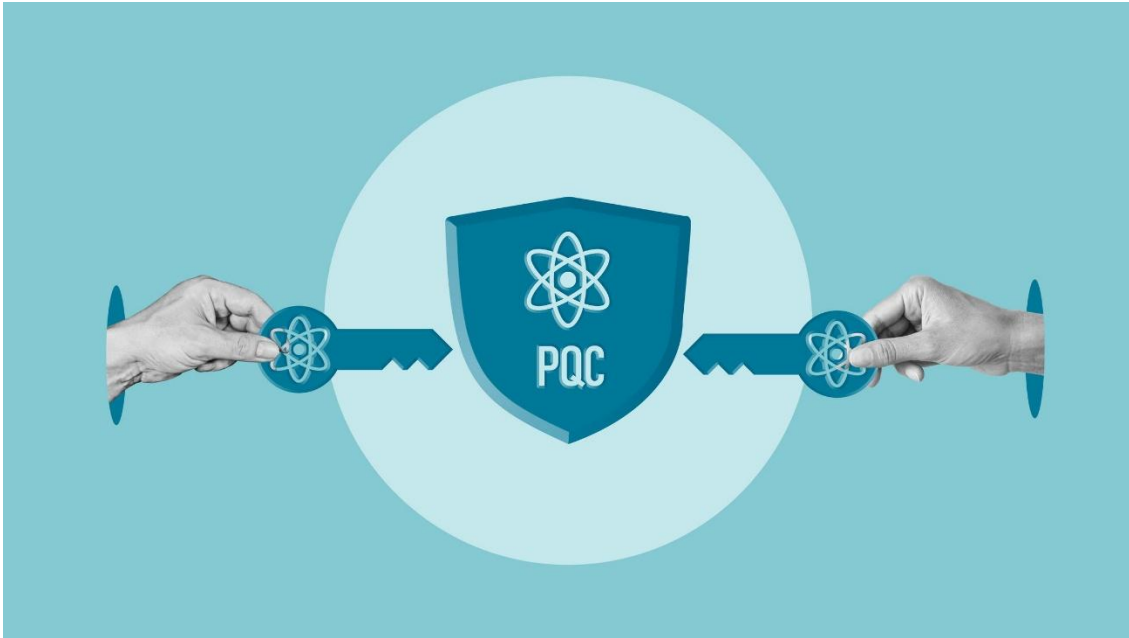
Kernel-level QOS: 90  $\mu$ s

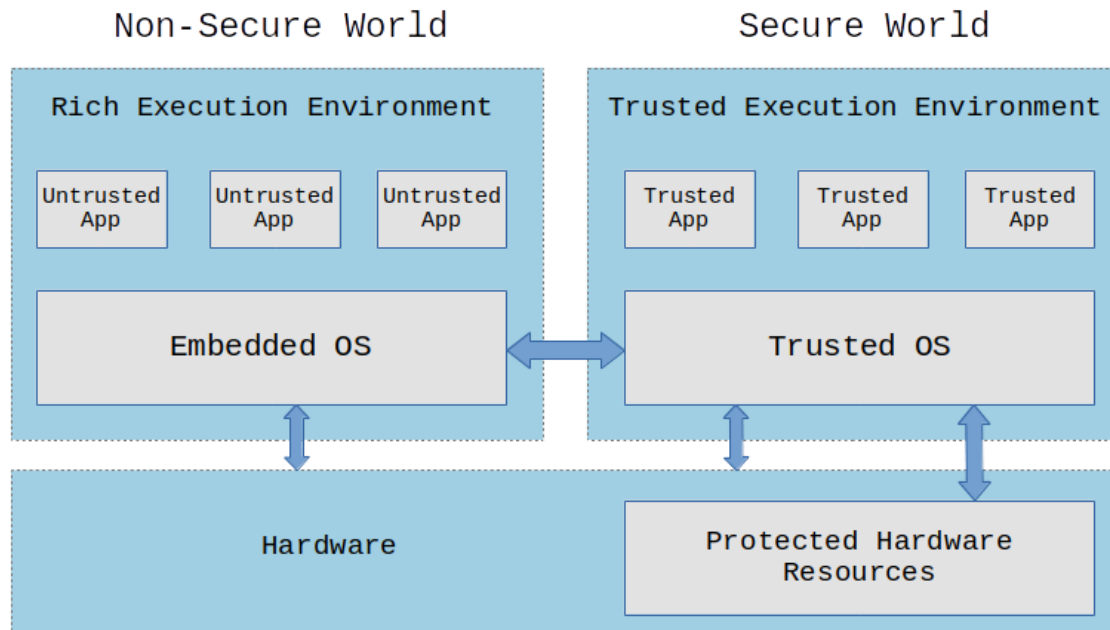
Reduction: 35%

### 8.3 Qubit Utilisation

Improved from 62% to 84% through coherence-aware scheduling.

### IX. Security and Post-Quantum Integration





Kernel-level integration enables:

- PQC algorithm agility
- Secure boot chain extension
- Hybrid classical–quantum trust enforcement
- Isolation of quantum tasks

Embedded systems require long lifecycle security; therefore, kernel-level PQC integration is essential (Bernstein, Buchmann and Dahmen, 2017).

## X. Discussion

The results indicate:

- Middleware-centric models are unsuitable for safety-critical embedded systems.
- Kernel-level integration reduces synchronization overhead.
- Probabilistic bounds can coexist with deterministic scheduling theory.
- Coherence-aware scheduling improves resource utilisation.

This represents a paradigm shift in operating system design.

## XI. Contributions

This study provides:

1. The first embedded-focused kernel-level QOS architecture.
2. A deterministic–probabilistic hybrid scheduling framework.
3. Coherence-aware quantum resource modelling.

4. Embedded-compatible PQC security integration.
5. Simulation-backed validation framework.

## XII. Limitations and Future Work

- Hardware validation required.
- Energy modelling refinement needed.
- Certification alignment with ISO 26262 future work.
- Formal verification using model checking recommended.

## XIII. Conclusion

Quantum acceleration in embedded systems requires:

- Kernel-level awareness
- Deterministic adaptation
- Security redesign
- Hybrid scheduling theory

This paper establishes a foundational architectural framework for quantum-enabled embedded operating systems.

## References (Harvard Style)

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