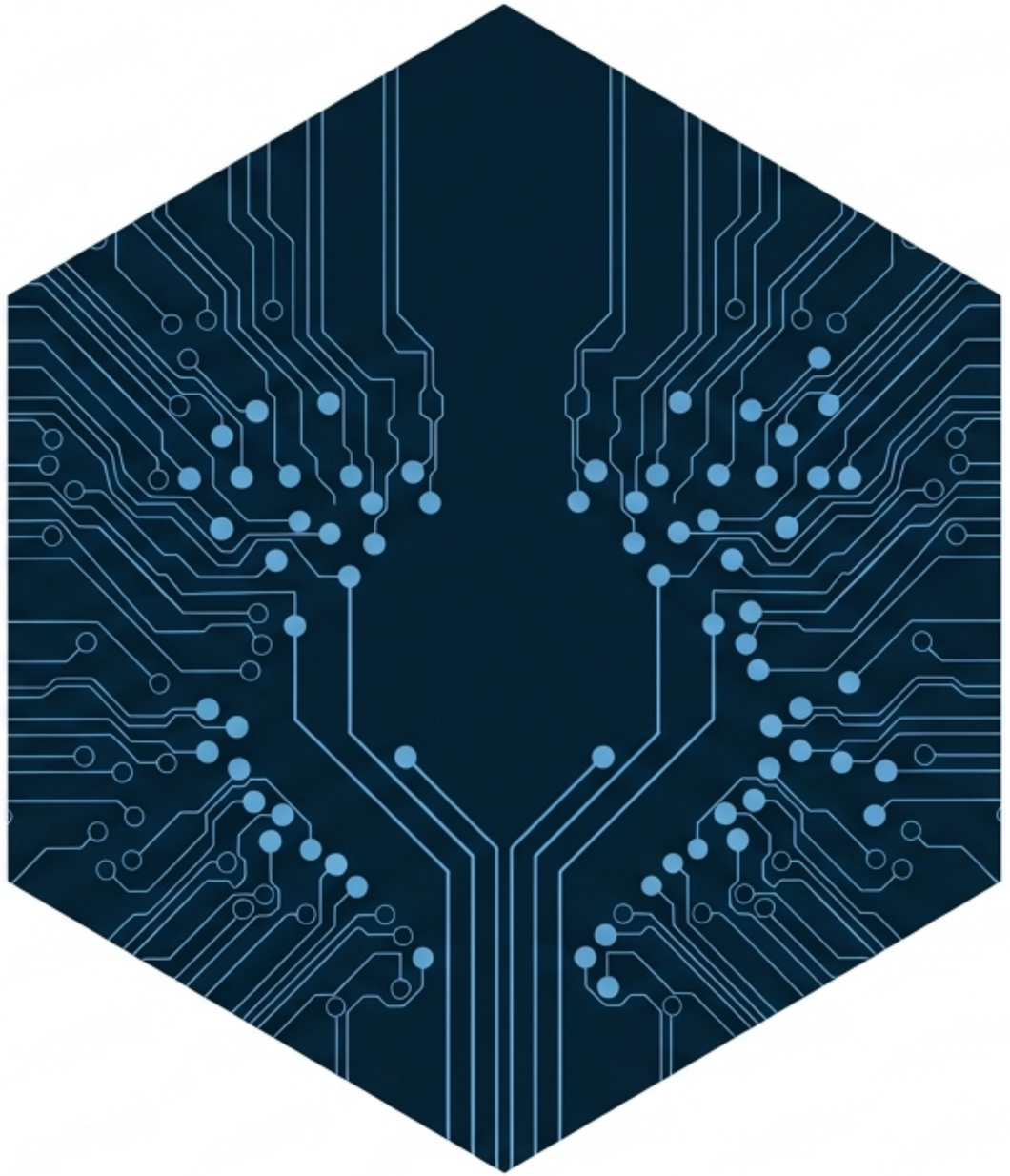
Post-Quantum Cryptography: Securing the Future

Navigating the Migration from Classical to Quantum-Resistant Standards



BASED ON CURRENT RESEARCH AND NIST 2024 STANDARDS

The Quantum Threat to Public-Key Infrastructure

Classical Security Vulnerabilities

Shor's Algorithm (1994): Breaks RSA factorisation and Elliptic Curve Cryptography (ECC) in polynomial time $O(n^3)$. Renders current PKI obsolete.

Impact: 2048-bit RSA breakable in hours.

Symmetric Key Weakening

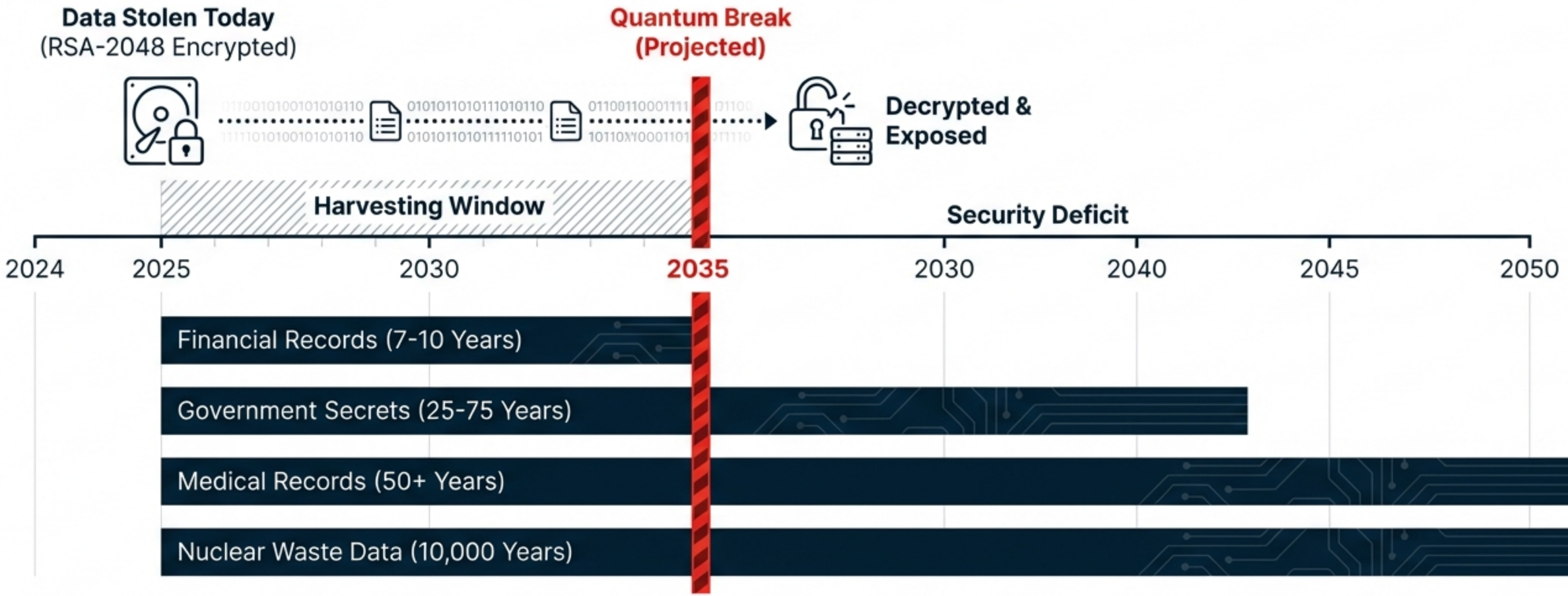
Grover's Algorithm (1996): Quadratic speedup for unstructured search. Reduces symmetric key security by half.

Impact: AES-128 effective security reduced to 64-bit.

Mitigation

AES-256 is required to maintain 128-bit quantum security.

The Immediate Crisis: Harvest Now, Decrypt Later



The Mathematical Foundations of PQC

The Standards

Lattice-Based (The Winner)

Learning With Errors (LWE).
Excellent performance, strong proofs.
Examples: Kyber, Dilithium.

Hash-Based (The Conservative)

Merkle trees.
Minimal assumptions.
Example: SPHINCS+.

Code-Based (The Veteran)

Error-correcting codes.
40+ years of confidence.
Examples: McEliece, HQC.

The Concerns

Multivariate

Rainbow (Broken 2022).
Research continues.

Isogeny-Based

SIKE (Broken 2022).
Security concerns.

The New Standards: NIST FIPS (August 2024)

Mandatory for US Government Use

FIPS 203

ML-KEM

Originally CRYSTALS-Kyber. Primary Key Encapsulation Mechanism.

FIPS 204

ML-DSA

Originally CRYSTALS-Dilithium. Primary Digital Signature Standard.

FIPS 205

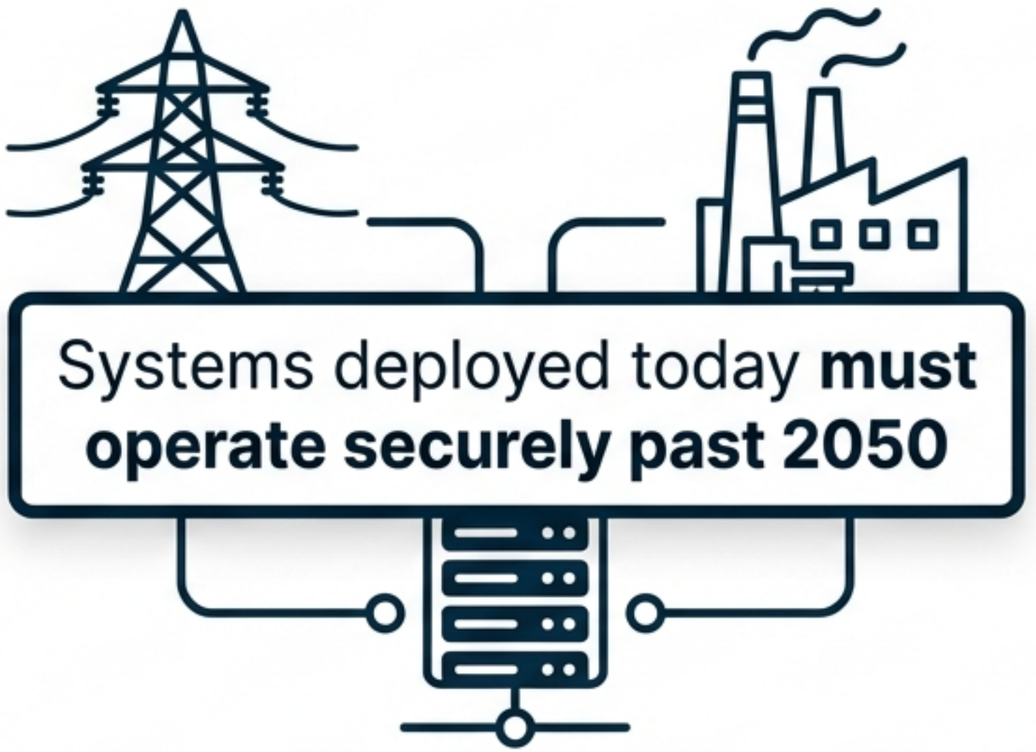
SLH-DSA

Originally SPHINCS+. Stateless Hash-Based Signatures (Fallback).

Critical Infrastructure & Industrial IoT

Long Lifecycle Challenges

- Power Grid / SCADA: 30-50 year operational lifetime.
- Nuclear Facilities: Extreme security duration.
- Constraint: Limited CPU/memory makes ‘heavy’ crypto difficult.



Based on: Cybersecurity in Critical Infrastructures: A Post-Quantum Cryptography Perspective (IEEE IoT Journal, June 2024)

Financial Systems & The Digital Economy

Banking & Payments

7-10 year retention makes current ACH transfers vulnerable to “Harvest Now” attacks.

Blockchain & Crypto

Bitcoin/Ethereum rely on ECDSA signatures. Urgent need for quantum-resistant wallet addresses to prevent asset theft.

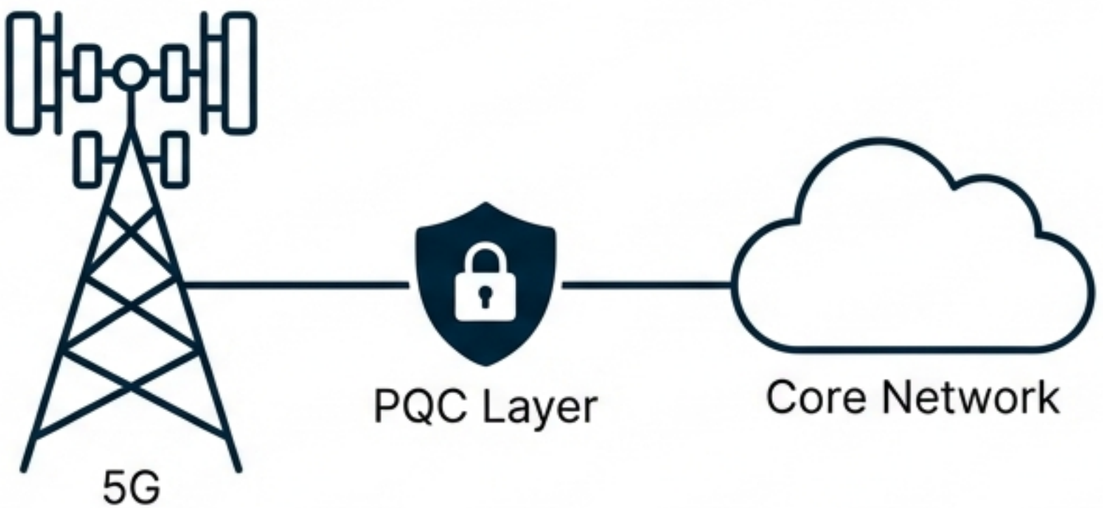
High-Frequency Trading

Requires data integrity speeds that PQC must match to maintain market stability.

Telecommunications & Open RAN Integration

Integration Challenges & Requirements

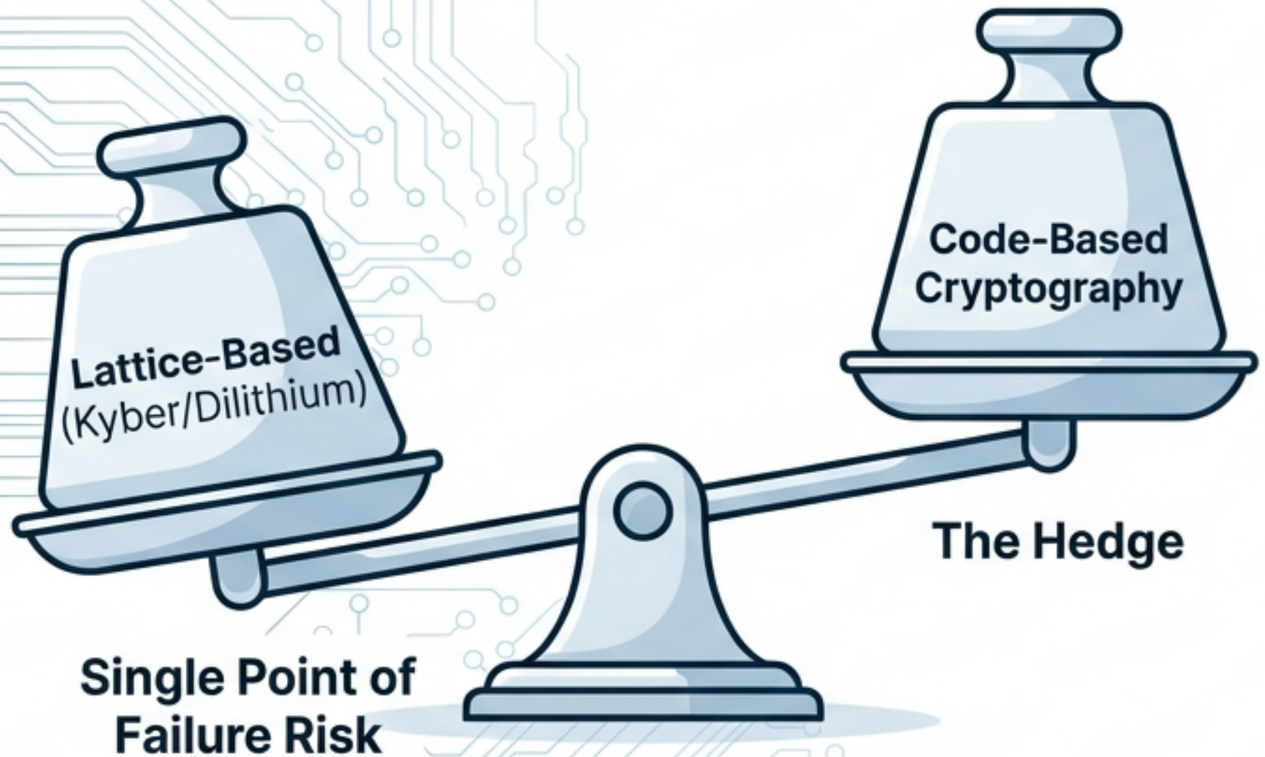
- **Key Challenge:** Integrating PQC into Open RAN interfaces without latency degradation.
- **Application:** Protecting 5G/6G Backhaul and Fronthaul.
- **Government Requirement:** Classified communications need 25-75 year protection.



Research Source: Introducing Post-Quantum algorithms in Open RAN interfaces (Otero-García et al., Jan 2025)

The Strategic Value of Mathematical Diversity in Inter Tight Deep Navy (#051C2C)

The **risk of a monoculture**: Do not rely solely on Lattice-based schemes.



- **Historical Confidence**: McEliece (1978) unbroken for 45+ years.
- **Security Foundation**: Syndrome Decoding Problem (NP-complete).
- **Independence**: Mathematically distinct from Lattice.

The Performance Bottleneck: HQC

Hamming Quasi-Cyclic - NIST Round 4 Candidate

High Security

Small keys, IND-CCA2 secure, based on well-understood error-correcting codes.

Low Speed

Significant performance bottleneck compared to Kyber. Standard implementations are much slower, limiting real-world enterprise adoption.

Research Breakthrough: OptHQC Optimization

OptHQC: Optimize HQC for High-Performance Post-Quantum Cryptography
(Dong, Feng, & Wang, Dec 2025)

3.6x

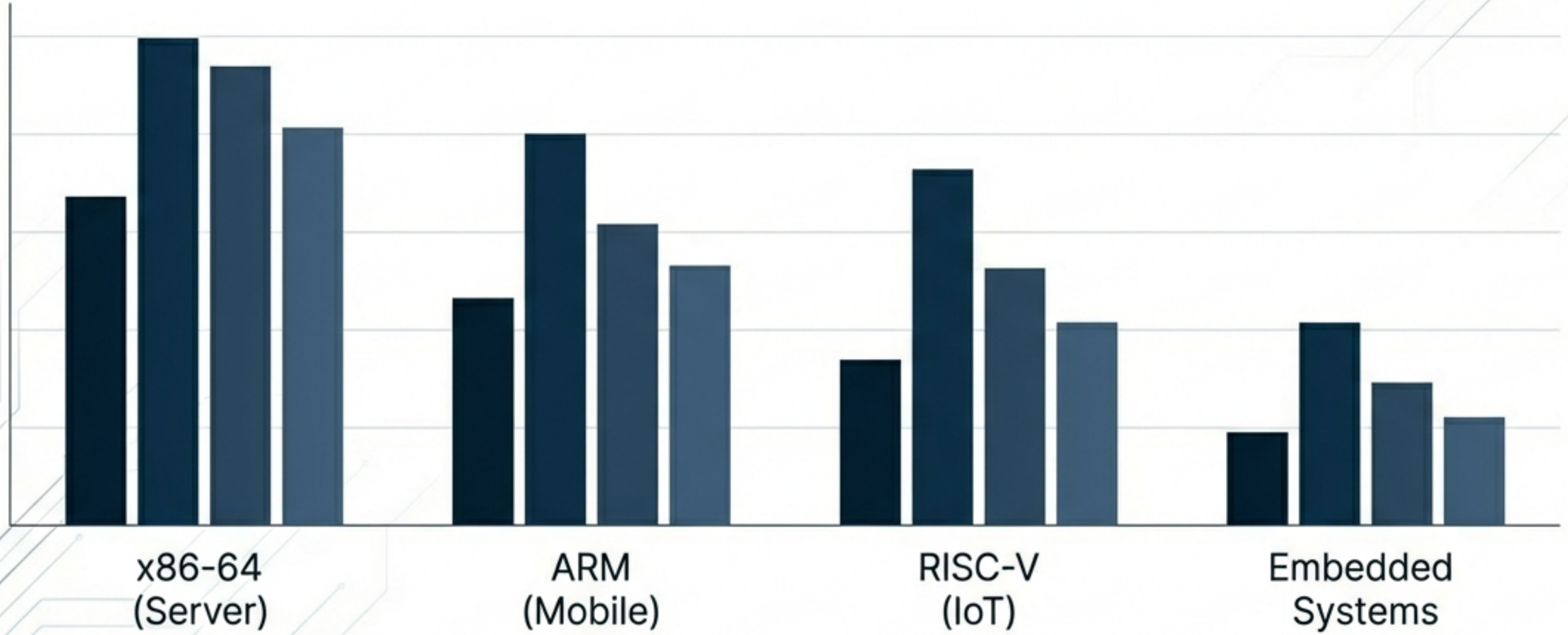
Speedup achieved in HQC operations

Methodology: Algorithm optimization for high-performance computing.

Result: Code-based cryptography becomes a viable, competitive alternative to Lattice schemes.

Real-World Performance Benchmarks

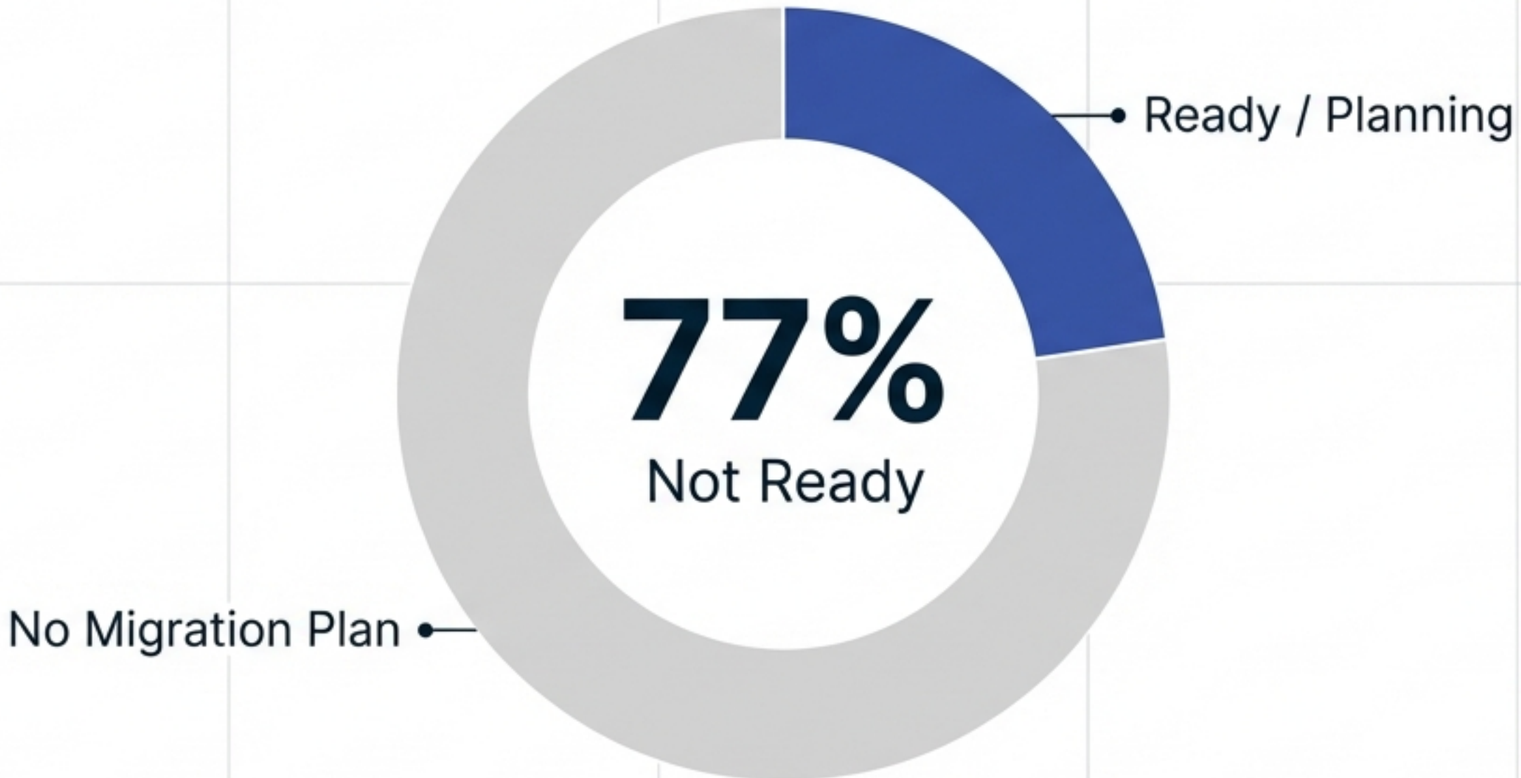
Testing PQC Across Heterogeneous Environments



Source: A Practical Performance Benchmark of Post-Quantum Cryptography (MDPI, May 2025)

The Readiness Gap

Are Enterprises Ready for Quantum-Safe Cybersecurity?



Key Barriers

- Legacy system complexity.
- IoT performance constraints.
- Certificate Authority (CA) infrastructure updates.

Survey of 500+ Organizations (arXiv, Sep 2025)

The Migration Roadmap (2024-2035)

The Window is Closing

We need crypto that outlasts the data.

1 Inventory

Identify long-lived data (GDPR, HIPAA, Secrets).

2 Assess

Test crypto-agility and hybrid implementations.

3 Adopt

Integrate FIPS 203, 204, and 205 into procurement.

Migration takes 10-15 years. **The time to start is now.**