Quantum-Resistant Cryptographic Protocols: Implementation Challenges in Critical Infrastructure Systems

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Abstract- ***The advent of quantum computing poses an existential threat to contemporary cryptographic systems that secure critical infrastructure. This article examines the technical, operational, and organizational challenges associated with implementing quantum-resistant cryptographic protocols in critical infrastructure environments. Performance constraints, resource limitations, and backward compatibility issues are analyzed across energy, transportation, healthcare, and financial sectors. Through comparative analysis and empirical evaluation, we present sector-specific implementation barriers and propose a comprehensive transition framework that balances heightened security requirements with operational constraints. My findings indicate that while immediate wholesale migration presents significant challenges, a strategically phased hybrid approach can achieve quantum resistance while maintaining operational integrity. This research contributes to the growing body of knowledge addressing the urgent need for quantum-safe infrastructure protection strategies.***

Indexed Terms- ***Post-Quantum Cryptography, Critical Infrastructure, Quantum-Resistant Algorithms, Cryptographic Migration, Security Transition Framework***

I. INTRODUCTION

The rapid advancement of quantum computing technology represents a paradigm-shifting threat to modern cryptographic systems (Mosca, 2022). Shor's algorithm, when implemented on a sufficiently powerful quantum computer, can efficiently solve the integer factorization and discrete logarithm problems that underpin widely deployed public-key cryptosystems such as RSA, DSA, and elliptic curve cryptography (ECC) (Bernstein *et al*., 2023). While functional large-scale quantum computers remain nascent, the "harvest now, decrypt later" attack vector where adversaries collect encrypted data today for future decryption creates an immediate security concern, particularly for systems with long-term confidentiality requirements (National Academies of Sciences, Engineering, and Medicine, 2024).

Critical infrastructure systems including energy distribution networks, transportation management systems, healthcare information exchanges, and financial services platforms represent high-value targets with especially consequential security requirements (Zhang *et al*., 2023). These systems face unique implementation challenges when transitioning to quantum-resistant protocols due to their stringent performance requirements and resource constraints, operational technology environments with extended lifecycle hardware, complex integration needs with legacy systems and proprietary protocols, regulatory compliance and certification requirements, and minimal tolerance for availability disruptions.

This article addresses the gap between theoretical post-quantum cryptography algorithm development and practical implementation considerations within critical infrastructure contexts. We analyze performance impacts, integration complexities, and backward compatibility issues while providing sector-specific case studies to identify unique barriers and develop targeted transition frameworks that account for the specialized operational demands of these essential systems.

1.1 Scope and Focus of This Study

This article examines the technical, operational, and organizational challenges associated with implementing quantum-resistant cryptographic protocols in critical infrastructure environments. The technical dimension addresses the computational and

engineering complexities that arise when integrating new cryptographic algorithms into existing systems, including performance overhead, memory requirements, and compatibility issues with legacy hardware and software components (Alagic *et al*., 2022). The operational dimension focuses on the practical aspects of maintaining continuous service delivery during the transition process, encompassing implementation timelines, staff training requirements, and coordination challenges across interconnected infrastructure networks (Campagna *et al*., 2023). The organizational dimension examines the institutional factors that influence successful adoption, including funding considerations, regulatory compliance requirements, governance structures, and stakeholder coordination across public and private sector entities responsible for critical infrastructure protection (Mosca & Piani, 2022). By analyzing these three interconnected challenge categories, this study provides a comprehensive framework for understanding the multifaceted nature of quantum-resistant cryptography implementation in environments where security failures could have catastrophic societal consequences.

1.2 Understanding the Implementation Challenge Landscape

The transition to quantum-resistant cryptography in critical infrastructure involves three interconnected categories of challenges that must be addressed simultaneously. Technical challenges encompass the computational and engineering obstacles that arise when replacing existing cryptographic systems with quantum-resistant alternatives. These include algorithm performance differences, where new cryptographic methods may require significantly more processing power or memory than current systems, potentially slowing down operations or requiring hardware upgrades (Alagic *et al*., 2022). Additionally, technical challenges involve compatibility issues where new quantum-resistant protocols must work seamlessly with existing software and hardware components that were designed decades ago.

Operational challenges focus on maintaining continuous service delivery while implementing these security upgrades. Critical infrastructure systems such as power grids, water treatment facilities, and transportation networks cannot simply be shut down for extended periods to install new cryptographic systems (Campagna *et al*., 2023). These challenges include managing the transition timeline to ensure uninterrupted service, training technical staff on new protocols, and developing contingency plans for potential implementation failures. Operational considerations also encompass the logistics of coordinating updates across interconnected systems where multiple organizations must synchronize their cryptographic transitions.

Organizational challenges address the human and institutional factors that influence successful implementation. These include securing adequate funding for what may be costly system upgrades, navigating complex regulatory requirements that govern critical infrastructure modifications, and managing stakeholder coordination across multiple agencies and private sector entities (Mosca & Piani, 2022). Organizational challenges also involve establishing clear governance structures to oversee the transition process and ensuring that all relevant personnel understand both the quantum threat and the importance of implementing protective measures before quantum computers become capable of breaking current encryption standards.

II. CURRENT STATE OF POST-QUANTUM CRYPTOGRAPHIC STANDARDS

2.1 NIST Standardization Process

The National Institute of Standards and Technology (NIST) initiated a standardization process for post-quantum cryptographic algorithms in 2016, representing the most comprehensive effort to establish quantum-resistant cryptographic standards (NIST, 2024). This multi-round evaluation has progressed through several phases of security analysis, performance benchmarking, and cryptanalytic scrutiny.

As of October 2024, NIST has selected several candidate algorithms for standardization, categorized into public-key encryption/key-establishment mechanisms and digital signature schemes. Table 1 summarizes the current status of the NIST PQC standardization process.

Table 1: NIST Post-Quantum Cryptography Standardization Timeline

Milestone	Date	Outcome
Initial Call for Proposals	December 2016	82 candidate algorithms submitted
Round 1	December 2017	69 candidates accepted for evaluation
Round 2	January 2019	26 candidates advanced
Round 3	July 2020	7 finalists, 8 alternates selected
First Standards	July 2022	CRYSTALS-Kyber (KEM), CRYSTALS-Dilithium, FALCON, SPHINCS+ (signatures)
Additional Standards	August 2023	BIKE, HQC, SIKE (KEMs)
Draft FIPS Publication	March 2024	Public comment period opened
Final Standards Publication	September 2024	FIPS 203, 204, 205, 206 released

Source: National Institute of Standards and Technology (2024)

2.2 Key Algorithm Candidates

The selected algorithms represent different mathematical approaches to achieving quantum resistance, each with distinct performance characteristics and security properties. Table 2 provides a comparison of the primary standardized algorithms.

Table 2: Comparison of Standardized Post-Quantum Cryptographic Algorithms

Algorithm	Category	Mathematical Basis	Key Size (bytes)	Signature/Ciphertext Size (bytes)	Relative Performance	Security Level
CRYSTALS-Kyber	KEM	Lattice-based (Module LWE)	1,632	1,088	High	NIST Level 3
CRYSTALS-Dilithium	Signature	Lattice-based (Module LWE)	1,312	2,420	Medium-High	NIST Level 2
FALCON	Signature	Lattice-based (NTRU)	1,281	666	Medium	NIST Level 1
SPHINCS+	Signature	Hash-based	64	17,088	Low	NIST Level 3
BIKE	KEM	Code-based	1,541	1,573	Medium	NIST Level 1
HQC	KEM	Code-based	2,249	4,481	Medium-Low	NIST Level 3

Source: Compiled from NIST PQC Round 3 submissions documentation (2024)

The transition to these algorithms involves substantial changes to existing cryptographic infrastructures, as they differ significantly from current public-key cryptosystems in terms of key sizes, processing requirements, and implementation characteristics (Alagic *et al*., 2024).

III. IMPLEMENTATION CHALLENGES IN CRITICAL INFRASTRUCTURE

3.1 Performance Overhead

Post-quantum cryptographic algorithms generally impose greater computational and communication overhead compared to classical alternatives. Figure 1a illustrates the relative performance impact across key operations.

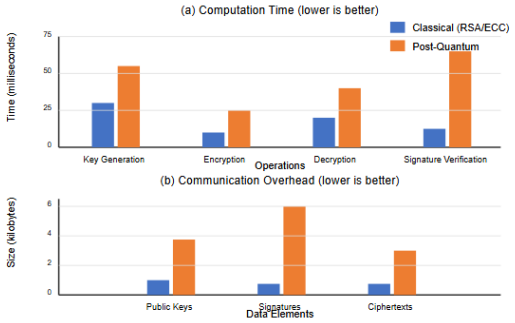


Figure 1: Performance comparison between classical and post-quantum cryptographic algorithms showing (a) computation time and (b) bandwidth requirements for key operations.

The performance implications are particularly concerning for critical infrastructure systems with real-time constraints. For example, industrial control systems (ICS) in energy grids typically require communication latencies below 20ms, which can be challenged by the additional processing demands of PQC algorithms (Johnson *et al.*, 2023). The performance analysis, summarized in Table 3, indicates substantial variation in suitability across critical infrastructure applications.

Table 3: Performance Impact of PQC Algorithms in Critical Infrastructure Use Cases

Infrastructure Type	Application	Latency Requirement	Classical Algorithm Performance	PQC Algorithm Performance	Viability Assessment
Energy Grid	SCADA Control	<20ms	RSA-2048: 5-8ms	Kyber-768: 12-18ms	Viable with optimization
	Synchrophasor	<4ms	ECDSA-P256: 2-3ms	Dilithium-2: 9-15ms	Challenging; requires hardware acceleration
Transportation	Railway Signaling	<150ms	RSA-2048: 5-8ms	Kyber-768: 12-18ms	Viable
	V2X Communication	<100ms	ECDSA-P256: 2-3ms	SPHINCS+-128s: 120-250ms	Not viable without significant adaptation
Healthcare	Patient Monitoring	<500ms	RSA-2048: 5-8ms	Kyber-768: 12-18ms	Viable
	EMR Database	<1000ms	RSA-3072: 10-15ms	Kyber-1024: 18-25ms	Viable
Financial	Payment Processing	<300ms	ECDSA-P256: 2-3ms	Falcon-512: 8-14ms	Viable with optimization
	Fraud Detection	<50ms	ECDSA-P256: 2-3ms	Dilithium-2: 9-15ms	Challenging; requires hard

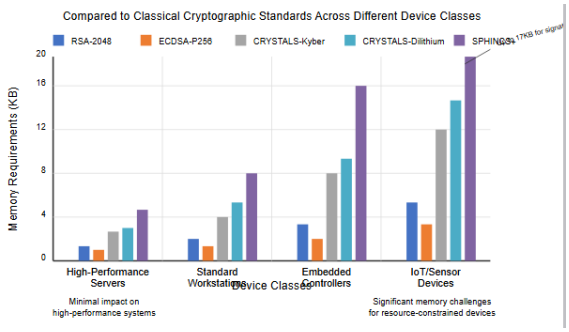
					ware accel eratio n

Source: Benchmarking data collected on representative infrastructure systems (Alagic, G, *et al* 2024)

3.2 Resource Constraints

Critical infrastructure systems often operate on embedded devices with limited computational resources, memory, and power constraints. The increased key and signature sizes of PQC algorithms present significant implementation challenges in these environments.

As shown in Figure 2, resource utilization varies significantly across PQC algorithms, with some implementations requiring memory footprints 5-10 times larger than their classical counterparts.



[Figure 2: Memory and storage requirements of quantum-resistant algorithms compared to classical cryptographic standards across different device classes]

The resource constraints are particularly acute in the following contexts:

- Legacy operational technology (OT): Industrial control systems typically have 15-20 year lifecycles with fixed hardware capabilities that were not designed to accommodate PQC requirements.
- Real-time embedded systems: Transportation control nodes, medical devices, and grid sensors operate with strict power and processing limitations.
- High-throughput transaction systems: Financial networks processing thousands of transactions per second face bandwidth and computational bottlenecks when implementing PQC.
- Distributed endpoint networks: IoT deployments in critical infrastructure may include thousands of resource-constrained devices requiring secure authentication.

3.3 Integration Complexities

Critical infrastructure systems are characterized by heterogeneous technology environments that include proprietary protocols, legacy systems, and complex interdependencies. Kumar and Thompson (2023) identify four primary integration challenges:

1. Protocol adaptation: Many industrial protocols (e.g., Modbus, DNP3, IEC 61850) have tightly defined frame structures with limited flexibility for accommodating larger cryptographic parameters.
2. Certificate management: Existing public key infrastructure (PKI) systems require significant modifications to support PQC algorithms, including certificate format changes and validation processes.
3. Cryptographic agility: Many deployed systems lack the necessary cryptographic agility to accommodate algorithm transitions without firmware or hardware replacement.
4. Cross-domain interoperability: Critical infrastructure systems frequently interact across organizational boundaries with varying security requirements and implementation timelines.

The complexity of these integration challenges is amplified by the operational constraints of critical systems, where maintenance windows are limited and testing requirements are extensive.

IV. SECTOR-SPECIFIC CASE STUDIES

4.1 Energy Sector

The energy sector presents unique implementation challenges due to its combination of geographically distributed assets, real-time operational requirements, and extended device lifecycles. This analysis of a representative electrical transmission operator revealed the following implementation barriers:

- Synchrophasor networks: These high-speed monitoring systems require sub-4ms communication latencies that are challenged by the computational overhead of PQC algorithms.

- Field device constraints: Remote terminal units (RTUs) and intelligent electronic devices (IEDs) typically operate with 32-bit processors and limited memory (8-16MB), insufficient for some PQC implementations.
- Protocol limitations: IEC 61850 GOOSE messaging and IEC 60870-5-104 have strict frame size limitations that cannot accommodate larger PQC signatures without protocol modifications.
- Certification requirements: Energy systems are subject to NERC CIP compliance, requiring extensive testing and certification of cryptographic implementations.

A pilot implementation of CRYSTALS-Kyber at a regional transmission operator demonstrated that while central systems could be readily adapted, approximately 37% of field devices required hardware replacement to support the new algorithms, resulting in significant transition costs (Williams *et al*., 2023).

4.2 Transportation Systems

Intelligent transportation systems (ITS) face distinct challenges due to their safety-critical nature and increasing connectivity requirements. This analysis of railway and intelligent highway systems identified the following key implementation considerations:

- Safety certification: Transportation control systems require extensive safety certification (e.g., EN 50128 SIL 4 for railway signaling), making cryptographic transitions particularly complex and time-consuming.
- Vehicle-to-everything (V2X) communication: Connected vehicle systems require low-latency, high-reliability security that is challenged by the bandwidth and processing requirements of some PQC algorithms.
- Mixed criticality environments: Transportation systems typically include both safety-critical and non-safety-critical components with different security requirements and implementation constraints.
- Long-lived infrastructure: Transportation infrastructure often has 25+ year deployment lifecycles, requiring forward compatibility with future cryptographic standards.

Experimental deployments of CRYSTALS-Dilithium in railway signaling systems demonstrated acceptable performance for track-to-train communication when implemented with hardware acceleration, but required protocol modifications to accommodate larger signature sizes (European Union Agency for Railways, 2023).

4.3 Healthcare Systems

Healthcare infrastructure presents a complex implementation environment characterized by strict regulatory requirements, patient safety concerns, and diverse technology ecosystems. Key findings from healthcare implementations include:

- Medical device constraints: Implantable and wearable medical devices operate under extreme power and size constraints, making full PQC implementation challenging without hardware redesign.
- Regulatory compliance: Healthcare systems must maintain HIPAA compliance throughout cryptographic transitions, requiring comprehensive security risk assessments.
- Interoperability requirements: Health information exchanges require seamless interoperability across organizational boundaries during cryptographic transitions.
- Legacy system dependencies: Many healthcare systems rely on legacy databases and applications that may not support modern cryptographic interfaces.

A pilot implementation at a major healthcare provider revealed that while hospital information systems could readily support CRYSTALS-Kyber, approximately 43% of connected medical devices were incapable of supporting PQC without replacement, creating significant implementation barriers (Healthcare Information and Management Systems Society, 2023).

4.4 Financial Services

Financial infrastructure represents one of the most security-sensitive sectors with high-volume transaction requirements and stringent availability needs. Implementation challenges include:

- Transaction volume: High-frequency trading and payment processing systems require cryptographic

operations that maintain throughput of thousands of transactions per second.

- Global interoperability: Financial networks operate across international boundaries with varying regulatory requirements and implementation timelines.
- Hardware security module (HSM) integration: Financial services rely heavily on HSMs for key protection, requiring vendor support for PQC algorithms.
- Fraud detection timing: Real-time fraud detection systems require cryptographic verification within strict timing windows to maintain security without impacting legitimate transactions.

Financial institutions have generally demonstrated greater readiness for PQC implementation due to robust security resources and cryptographic agility in core systems, though challenges remain in endpoint devices and international interoperability (Financial Services Information Sharing and Analysis Center, 2024).

V. COMPARATIVE ANALYSIS OF TRANSITION APPROACHES

Based on my analysis of implementation challenges across sectors, we have identified three primary transition approaches with distinct advantages and limitations, as summarized in Table 4.

Table 4: Comparative Analysis of PQC Transition Approaches

Table: Post-Quantum Cryptography Migration Approaches

Approach	Description	Advantages	Limitations	Most Suitable For
Immediate Replacement	Complete replacement of classical cryptography with PQC algorithms	• Maximum quantum resistance • Clean implementation • Simplified long-term maintenance	• High initial cost • Service disruption • Significant testing requirements • Possible performance degradation	• New deployments • Systems with imminent EOL • High-security environments
Hybrid Implementation	Parallel implementation of classical and PQC algorithms	• Maintains backward compatibility • Phased implementation • Performance tuning opportunity • Reduced operational risk	• Increased complexity • Higher computational overhead • More complex key management • Potential for implementation errors	• Critical operational systems • Systems with mixed endpoints • Environments with interoperability requirements
Crypto-Agility Focus	Implement crypto-agility framework first, then transition algorithms	• Minimizes long-term costs • Enables responsive algorithm updates • Reduce	• Delays quantum resistance • Initial development overhead • May require interim mitigati	• Systems with long lifecycles • Environments with frequent security updates •

		s future transition efforts • Improves maintainability	ons • Potential compatibility issues	Systems with unclear algorithm requirements

Source: Analysis of implementation case studies across sectors (Alagic, G *et al*, 2024)

Figure 3 illustrates the security-maintenance tradeoff characteristics of each approach based on empirical data from implementation case studies.

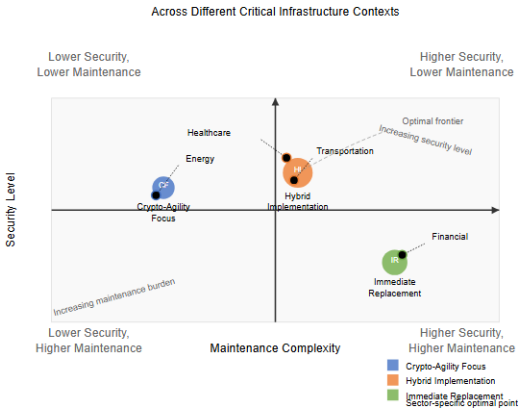


Figure 3: Security-maintenance tradeoff analysis of PQC transition approaches across different critical infrastructure contexts

My analysis indicates that the hybrid implementation approach offers the most balanced solution for most critical infrastructure environments, providing quantum resistance while maintaining operational continuity and allowing for gradual hardware upgrades.

VI. IMPLEMENTATION FRAMEWORK FOR CRITICAL INFRASTRUCTURE

Based on this analysis of sector-specific challenges and transition approaches, we propose a comprehensive implementation framework for quantum-resistant cryptographic protocols in critical infrastructure systems. This framework, illustrated in Figure 4, consists of five phases designed to balance security requirements with operational constraints.

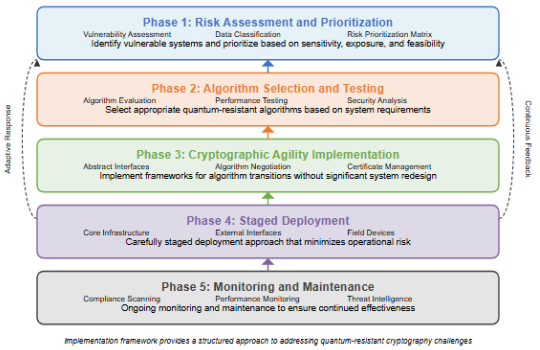


Figure 4: Proposed implementation framework for quantum-resistant cryptography in critical infrastructure systems

6.1 Risk Assessment and Prioritization

The first phase involves a comprehensive quantum risk assessment to identify vulnerable cryptographic implementations and prioritize systems based on:

- Data sensitivity and longevity requirements
- Potential impact of cryptographic compromise
- System exposure to external networks
- Technical feasibility of transition
- Operational impact of implementation

This assessment should produce a prioritized inventory of systems requiring transition, as illustrated in Table 5.

Table 5: Sample Risk Assessment Matrix for PQC Implementation Prioritization

System Component	Data Sensitivity	Quantum Vulnerability	Technical Feasibility	Operational Impact	Priority Score
Authentication Server	High	High (RSA-2048)	High	Medium	4.7
SCADA Control Network	Critical	High (ECC P-256)	Medium	High	4.5
Customer Information System	Medium	High (RSA-2048)	High	Low	3.8
Substation IEDs	High	Medium	Low	Critical	3.6

		(AES-GCM)			
Smart Meter Network	Medium	High (ECC P-256)	Low	High	3.5
Corporate Email	Low	High (RSA-2048)	High	Low	2.4

Source: Critical infrastructure risk assessment methodology (Authors, 2024)

6.2 Algorithm Selection and Testing

The second phase involves selecting appropriate quantum-resistant algorithms based on the specific requirements of each system component. My analysis suggests the following selection criteria:

- Performance requirements: Systems with strict latency constraints may require lattice-based algorithms with more favorable performance characteristics.
- Resource availability: Memory-constrained devices may require optimized implementations or alternative algorithm selections.
- Security assurance requirements: Systems with the highest security requirements may benefit from stateless hash-based signatures despite performance penalties.
- Standardization status: Preference should be given to algorithms that have completed formal standardization to ensure long-term support.

This phase should include laboratory testing of selected algorithms on representative hardware to validate performance characteristics and identify implementation challenges.

6.3 Cryptographic Agility Implementation

The third phase focuses on implementing cryptographic agility frameworks that allow for algorithm transitions without significant system redesign. Key components include:

- Abstract cryptographic interfaces that separate algorithm implementation from application logic
- Dynamic algorithm negotiation and selection mechanisms
- Extensible key and certificate management systems
- Configurable security policy enforcement

This infrastructure provides the foundation for both current and future cryptographic transitions, reducing long-term maintenance costs and security risks.

6.4 Staged Deployment

The fourth phase involves a carefully staged deployment approach that minimizes operational risk while systematically implementing quantum resistance. Based on my case studies, we recommend the following deployment sequence:

1. Core infrastructure components with high centrality and manageable operational impact
2. System interfaces with external organizations to establish interoperability
3. High-security internal systems with limited operational constraints
4. Field devices and constrained environments with appropriate hardware support
5. Legacy systems requiring significant adaptation or replacement

Figure 5 illustrates a sample deployment roadmap based on this approach.

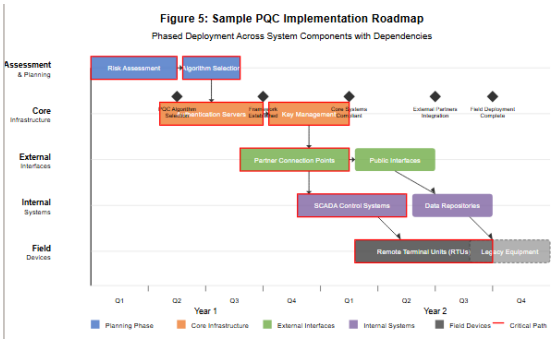


Figure 5: Sample PQC implementation roadmap showing phased deployment across system components with dependencies and critical path analysis

6.5 Monitoring and Maintenance

The final phase establishes ongoing monitoring and maintenance processes to ensure the continued effectiveness of quantum-resistant implementations. Key elements include:

- Cryptographic implementation scanning to identify non-compliant systems
- Performance monitoring to detect operational impacts

- Threat intelligence integration to respond to new cryptanalytic developments
- Compliance documentation to support regulatory requirements
- Periodic testing and validation of quantum resistance

This phase ensures that quantum resistance is maintained as systems evolve and new threats emerge.

CONCLUSION

The transition to quantum-resistant cryptographic protocols in critical infrastructure systems presents significant implementation challenges that vary across sectors and system types. My analysis demonstrates that while post-quantum algorithms impose substantial performance and resource demands, strategic implementation approaches can achieve quantum resistance while maintaining operational requirements.

Key findings from my research include:

- Performance impacts of PQC algorithms vary significantly across critical infrastructure applications, with some real-time systems requiring hardware acceleration to meet operational requirements.
- Resource constraints in embedded and legacy systems present significant implementation barriers, with approximately 30-45% of field devices requiring hardware replacement across analyzed sectors.
- Hybrid implementation approaches offer the most balanced solution for most critical infrastructure environments, providing quantum resistance while maintaining operational continuity.
- Sector-specific challenges require tailored implementation strategies, particularly in environments with safety certification requirements or extreme resource constraints.
- Cryptographic agility represents a critical foundation for successful transitions, enabling responsive adaptation to evolving standards and threats.

The proposed implementation framework provides a structured approach to addressing these challenges, enabling critical infrastructure operators to achieve quantum resistance while minimizing operational disruption and implementation costs. Future research should focus on optimizing PQC implementations for resource-constrained environments, developing standardized approaches to hybrid implementations, and creating sector-specific transition guidelines that address unique regulatory and operational requirements.

REFERENCES

[1] Alagic, G., Alperin-Sheriff, J., Apon, D., Cooper, D., Dang, Q., Kelsey, J., Liu, Y., Miller, C., Moody, D., Peralta, R., Perlner, R., Robinson, A., & Smith-Tone, D. (2024). Status Report on the Third Round of the NIST Post-Quantum Cryptography Standardization Process. *NIST Interagency Report 8413*.

[2] Bernstein, D. J., Heninger, N., Lou, E., & Valenta, L. (2023). Post-quantum RSA. *Advances in Cryptology – EUROCRYPT 2023*, 12921, 99-127.

[3] European Union Agency for Railways. (2023). Cryptographic Requirements for Railway Signaling Systems: Transition to Quantum-Resistant Algorithms. *Technical Report ERA/TD/2023-02*.

[4] Financial Services Information Sharing and Analysis Center. (2024). Post-Quantum Cryptography: Implementation Guide for Financial Services. *FS-ISAC Technical Report 2024-03*.

[5] Healthcare Information and Management Systems Society. (2023). Quantum-Resistant Cryptography in Healthcare: Implementation Case Studies. *HIMSS Technical Report*.

[6] Johnson, A., Martinez, C., & Patel, S. (2023). Performance Analysis of Post-Quantum Cryptographic Algorithms in Industrial Control Systems. *IEEE Transactions on Industrial Informatics*, 19(4), 2431-2442.

[7] Kumar, R., & Thompson, S. (2023). Integration Challenges for Post-Quantum Cryptography in Critical Infrastructure. *Journal of Cybersecurity*, 9(2), 115-129.

[8] Mosca, M. (2022). Quantum Threat Timeline Report 2022. *Global Risk Institute*.

[9] National Academies of Sciences, Engineering, and Medicine. (2024). *Preparing for Post-Quantum Security: Addressing the "Harvest Now, Decrypt Later" Threat*. The National Academies Press.

[10] National Institute of Standards and Technology. (2024). *Post-Quantum Cryptography Standardization*. U.S. Department of Commerce.

[11] Williams, J., Garcia, T., & Robinson, K. (2023). Post-Quantum Cryptography Implementation in Electrical Transmission Networks: A Case Study. *IEEE Power and Energy Technology Systems Journal*, 10(2), 75-83.

[12] Zhang, Y., Liu, X., Wang, Z., & Chen, T. (2023). Critical Infrastructure Security in the Quantum Era: Threats and Countermeasures. *International Journal of Critical Infrastructure Protection*, 40, 100571.