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Zero-Trust Architecture Adaptation for Post-Quantum Cryptography: Implementation Roadmap for Critical Infrastructure

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ABSTRACT

The convergence of quantum computing threats and Zero Trust Architecture (ZTA) implementation presents unprecedented challenges for critical infrastructure protection. While quantum computers threaten current cryptographic foundations, Zero Trust frameworks require robust cryptographic mechanisms for continuous verification. This study examines the adaptation challenges and implementation strategies for integrating post-quantum cryptography within Zero Trust architectures across critical infrastructure sectors.

A mixed-methods sequential explanatory design was employed with 147 critical infrastructure organizations across five sectors (energy, transportation, healthcare, financial services, telecommunications). Data collection included the Zero Trust Maturity Assessment Framework (ZTMAF), Post-Quantum Cryptography Readiness Index (PQCRI), Critical Infrastructure Vulnerability Assessment Protocol (CIVAP), semi-structured interviews (n=89), and document analysis (1,247 documents). Statistical analysis employed correlation analysis, ANOVA, and structural equation modeling, while qualitative data underwent thematic analysis.

Zero Trust maturity varied significantly across sectors (M=2.91, SD=0.67), with financial services demonstrating highest maturity (M=3.81) and transportation lowest (M=2.50). Post-quantum cryptography readiness remained concerning across all sectors (M=2.47, SD=0.73), with only 16.3% achieving high readiness levels. Legacy systems prevalence (84.4% of organizations) negatively correlated with both ZTA maturity (r=-0.43) and PQC readiness (r=-0.58). Structural equation modeling revealed significant relationships between organizational factors and implementation success (χ^2/df=2.34, CFI=0.92).

Critical infrastructure organizations face substantial challenges in quantum-safe Zero Trust implementation, with sector-specific barriers requiring targeted intervention strategies. The findings highlight urgent needs for government coordination, technical assistance programs, and accelerated legacy system modernization to ensure national cybersecurity resilience against emerging quantum threats.

INTRODUCTION

The rapid advancement of quantum computing technologies has fundamentally challenged the security assumptions underlying contemporary cybersecurity frameworks, necessitating a

comprehensive reevaluation of cryptographic systems that protect critical infrastructure worldwide. While quantum computers promise revolutionary computational capabilities, they simultaneously pose an existential threat to widely deployed public-key cryptographic algorithms, including RSA, Elliptic Curve Cryptography (ECC), and Diffie-Hellman key exchange protocols, which form the backbone of modern digital communication security. Recent demonstrations by Chinese researchers using D-Wave's Advantage quantum system to successfully factor RSA integers, albeit of limited bit length, underscore the accelerating timeline of quantum threats to cryptographic systems. This quantum threat landscape has catalyzed urgent governmental responses, with the U.S. National Institute of Standards and Technology (NIST) releasing finalized post-quantum cryptography standards in August 2024, including FIPS 203, FIPS 204, and FIPS 205, while simultaneously mandating organizational transitions to quantum-resistant algorithms by 2030.

Concurrently, the cybersecurity paradigm has witnessed a fundamental shift from traditional perimeter-based security models to Zero Trust Architecture (ZTA), which operates on the principle of "never trust, always verify." The White House's 2021 Executive Order on Improving the Nation's Cybersecurity emphasized advancing Zero Trust Architecture, requiring all federal agencies to develop comprehensive ZTA implementation plans. Zero Trust Architecture represents a security framework that assumes no implicit trust within network boundaries, requiring continuous verification of all entities seeking access to system resources. However, the convergence of quantum computing threats with Zero Trust implementation presents unprecedented challenges for critical infrastructure protection. Recent research indicates that while Zero Trust adoption has accelerated, with 61% of organizations reporting defined ZT programs by 2023, the integration of quantum-resistant cryptographic mechanisms remains largely unaddressed.

The intersection of Zero Trust Architecture and post-quantum cryptography presents both technological and operational complexities that extend beyond traditional cryptographic migration challenges. Critical infrastructure systems, characterized by extended operational lifecycles, legacy components, and stringent availability requirements, face unique obstacles in implementing quantum-resistant security frameworks. The explicit verification principle fundamental to ZTA requires robust cryptographic algorithms, protocols, and architectures to perform cryptographic validation essential for guaranteeing confidentiality, integrity, authenticity, availability, and non-repudiation. Furthermore, the heterogeneous nature of critical infrastructure environments, encompassing industrial control systems, supervisory control and data acquisition (SCADA) networks, and interconnected operational technology (OT) systems, necessitates specialized approaches to quantum-safe ZTA implementation.

Despite the growing body of literature addressing Zero Trust Architecture and post-quantum cryptography independently, there exists a significant research gap in understanding the practical challenges, implementation strategies, and operational considerations for integrating quantum-resistant cryptographic mechanisms within Zero Trust frameworks specifically designed for critical infrastructure environments. Existing studies primarily focus on theoretical frameworks or address these technologies in isolation, without considering the complex interdependencies, legacy system constraints, and sector-specific requirements that characterize critical infrastructure operations. Moreover, limited research has examined the performance implications, interoperability challenges,

and risk assessment methodologies necessary for successful quantum-safe ZTA deployment across diverse critical infrastructure sectors.

Therefore, this research aims to develop a comprehensive implementation roadmap for adapting Zero Trust Architecture to incorporate post-quantum cryptographic mechanisms within critical infrastructure environments. Specifically, this study seeks to: (1) identify and categorize the technical and operational challenges associated with integrating post-quantum cryptography into existing Zero Trust frameworks; (2) propose a multi-jurisdictional analysis framework for assessing quantum-readiness across different critical infrastructure sectors; (3) develop practical implementation strategies that address legacy system integration, performance optimization, and regulatory compliance requirements; and (4) establish evaluation metrics for measuring the effectiveness of quantum-safe ZTA implementations in real-world critical infrastructure scenarios.

The significance of this research extends beyond academic inquiry, addressing an urgent national security imperative that affects the resilience of essential services including energy distribution, transportation networks, healthcare systems, financial services, and telecommunication infrastructure. As quantum computing capabilities continue to advance, the window for proactive cybersecurity adaptation narrows, making the development of practical, deployable solutions for quantum-safe Zero Trust implementation a critical priority for ensuring the continued security and reliability of critical infrastructure systems that underpin modern society. This research contributes to the emerging field of quantum-safe cybersecurity by providing actionable guidance for organizations tasked with protecting critical infrastructure against evolving quantum threats while maintaining operational continuity and regulatory compliance.

RESEARCH METHOD

Research Design

This study employs a mixed-methods sequential explanatory design (Creswell & Plano Clark, 2017) to comprehensively examine the adaptation of Zero Trust Architecture for post-quantum cryptography implementation in critical infrastructure environments. The research methodology integrates quantitative assessment of cryptographic performance metrics with qualitative analysis of implementation challenges through a multi-phase approach, following established frameworks for cybersecurity research (Heartfield et al., 2021). The sequential design enables the quantitative findings to inform the development of targeted qualitative inquiry instruments, thereby enhancing the depth and validity of the research outcomes (Tashakkori & Teddlie, 2021).

Study Population and Sampling Framework

Target Population

The study population encompasses critical infrastructure organizations across five essential sectors as defined by the U.S. Cybersecurity and Infrastructure Security Agency (CISA, 2023): energy and utilities, transportation systems, healthcare and public health, financial services, and telecommunications. Organizations were selected based on their operational criticality, current cybersecurity maturity levels, and existing Zero Trust implementation status, following sector prioritization guidelines established by NIST (Rose et al., 2020).

Sampling Strategy

A stratified purposive sampling approach was employed to ensure representation across infrastructure sectors and organizational characteristics (Patton, 2015). The sample consisted of 147 organizations distributed as follows: energy sector (n=32), transportation (n=28), healthcare (n=31), financial services (n=29), and telecommunications (n=27). Organizations were required to meet the following inclusion criteria: (1) classified as critical infrastructure under national frameworks (DHS, 2023), (2) annual revenue exceeding $100 million or serving populations greater than 50,000, (3) existing cybersecurity frameworks implementation, and (4) willingness to participate in comprehensive security assessments.

Participant Selection

Within each organization, key informants were identified through snowball sampling, targeting Chief Information Security Officers (CISOs), IT infrastructure managers, cybersecurity architects, and compliance officers. A total of 412 participants were recruited, with each organization contributing 2-4 subject matter experts representing different aspects of cybersecurity implementation and management.

Data Collection Instruments

Quantitative Assessment Tools

Zero Trust Maturity Assessment Framework (ZTMAF): A validated 85-item instrument measuring organizational Zero Trust implementation across seven domains: identity and access management, device security, network segmentation, application security, data protection, threat detection, and governance (Kindervag, 2020; NIST, 2023). Each item employs a 5-point Likert scale ranging from "not implemented" (1) to "fully optimized" (5). The instrument demonstrates strong internal consistency (Cronbach's $\alpha = 0.91$) and has been validated across multiple industry sectors (Zhang et al., 2022).

Post-Quantum Cryptography Readiness Index (PQCRI): A newly developed 62-item assessment tool evaluating organizational preparedness for quantum-safe cryptography implementation, based on NIST post-quantum cryptography standards (NIST, 2024). The instrument measures six dimensions: cryptographic inventory completeness, algorithm migration planning, performance impact assessment, compliance alignment, stakeholder readiness, and resource allocation. Pilot testing with 25 organizations yielded acceptable reliability coefficients ($\alpha = 0.87$-0.94 across subscales), following established psychometric validation procedures (Devellis, 2022).

Critical Infrastructure Vulnerability Assessment Protocol (CIVAP): A standardized checklist comprising 120 technical evaluation criteria addressing system architecture, legacy component identification, network topology analysis, and security control effectiveness. The protocol incorporates automated scanning tools, manual configuration reviews, and penetration testing methodologies aligned with NIST Cybersecurity Framework guidelines (NIST, 2018) and follows established vulnerability assessment best practices (Scarfone et al., 2021).

Qualitative Data Collection Methods

Semi-Structured Interview Protocol: In-depth interviews were conducted using a standardized protocol addressing implementation challenges, organizational barriers, technical constraints, and strategic considerations related to quantum-safe Zero Trust deployment (Kvale & Brinkmann, 2015). The interview guide contained 28 open-ended questions organized across four thematic areas: technical implementation, organizational readiness, regulatory compliance, and future planning considerations, following established qualitative research methodologies for cybersecurity studies (Williams & Nurse, 2020).

Focus Group Discussion Framework: Structured focus groups were facilitated with cross-functional teams to explore collective perspectives on implementation strategies, risk assessment approaches, and operational considerations. Each 90-minute session followed a predetermined moderator guide addressing stakeholder alignment, resource requirements, and change management strategies.

Document Analysis Protocol: Systematic review of organizational cybersecurity policies, technical documentation, compliance reports, and strategic planning documents was conducted using a structured content analysis framework (Krippendorff, 2018). Documents were coded according to predetermined categories related to Zero Trust principles, cryptographic standards, and implementation timelines, following established document analysis procedures for organizational research (Bowen, 2009).

Data Collection Procedure

Phase 1: Organizational Assessment (Months 1-4)

Initial organizational recruitment was conducted through professional networks, industry associations, and cybersecurity conferences. Following institutional review board approval and organizational consent, baseline assessments were administered through secure online platforms. The ZTMAF and PQCRI instruments were deployed simultaneously to minimize participant burden while ensuring data quality through built-in validation checks and completion monitoring.

Phase 2: Technical Evaluation (Months 3-8)

On-site technical assessments were conducted by certified cybersecurity professionals using the CIVAP methodology. Each evaluation required 2-3 days of intensive system analysis, including network architecture documentation, cryptographic implementation review, and security control testing. All technical assessments adhered to non-disclosure agreements and followed established penetration testing ethical guidelines.

Phase 3: Qualitative Data Collection (Months 6-10)

Individual interviews were conducted via secure video conferencing platforms, with each session lasting 45-60 minutes. All interviews were audio-recorded with participant consent and transcribed verbatim by professional transcription services. Focus groups were facilitated in-person when possible, with hybrid participation accommodated through secure collaboration platforms. Document collection occurred continuously throughout the study period, with organizations providing materials through encrypted file transfer systems.

Data Analysis Techniques

Quantitative Analysis

Descriptive statistics were calculated for all continuous variables, including measures of central tendency, variability, and distribution characteristics. Zero Trust maturity scores and post-quantum readiness indices were analyzed using multiple regression analysis to identify significant predictors of implementation success. Sector-specific differences were examined through one-way ANOVA with post-hoc Tukey's HSD tests for pairwise comparisons. Correlation analysis was employed to assess relationships between organizational characteristics, maturity levels, and readiness indicators. Advanced statistical techniques included structural equation modeling (SEM) to test hypothesized relationships between latent constructs representing Zero Trust implementation domains and post-quantum cryptography readiness factors, following established SEM methodologies (Hair et al., 2021). Model fit was evaluated using standard goodness-of-fit indices, including χ^2/df ratio, Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), and Root Mean Square Error of Approximation (RMSEA), with recommended thresholds as specified by Hu and Bentler (1999).

Qualitative Analysis

Qualitative data analysis followed Braun and Clarke's (2006) thematic analysis framework, employing both inductive and deductive coding approaches. Initial coding was conducted independently by two researchers using NVivo 14 software, with intercoder reliability assessed through Cohen's kappa coefficient (target threshold $\kappa \geq 0.80$) as recommended by McHugh (2012). Themes were developed through iterative analysis cycles, with regular team meetings to discuss emerging patterns and resolve coding discrepancies (Nowell et al., 2017).

Member checking was conducted with 15% of interview participants to validate thematic interpretations and ensure analytical accuracy (Lincoln & Guba, 1985). Triangulation across data sources (interviews, focus groups, documents) enhanced the credibility and trustworthiness of qualitative findings, following established criteria for qualitative research rigor (Shenton, 2004).

Mixed-Methods Integration

Quantitative and qualitative datasets were integrated through joint displays, mixed-methods matrices, and convergent synthesis techniques, following established mixed-methods integration procedures (Fetters et al., 2013). Priority was given to identifying areas of convergence and divergence between statistical findings and qualitative insights, with particular attention to sector-specific implementation patterns and organizational contextual factors (Schoonenboom & Johnson, 2017).

Ethical Considerations

This research was conducted in accordance with the Declaration of Helsinki (World Medical Association, 2013) and received approval from the Institutional Review Board (IRB Protocol #2024-IR-0892). All participants provided informed consent prior to data collection, with explicit acknowledgment of voluntary participation and withdrawal rights, following established ethical guidelines for cybersecurity research (Kenneally & Dittrich, 2012). Organizational data confidentiality was maintained through de-identification protocols, secure data storage systems, and restricted access procedures (Barocas & Nissenbaum, 2014).

Given the sensitive nature of critical infrastructure cybersecurity information, additional safeguards included: (1) execution of comprehensive non-disclosure agreements, (2) implementation of data minimization principles, (3) secure destruction of identifiable information following analysis completion, and (4) provision of aggregated findings reports to participating organizations while maintaining individual confidentiality.

Research team members completed specialized training in cybersecurity research ethics and critical infrastructure protection protocols. All data collection activities were conducted in compliance with relevant federal regulations, including the Federal Information Security Modernization Act (FISMA) and sector-specific cybersecurity frameworks.

RESULTS AND DISCUSSION

Results

Participant Demographics and Organizational Characteristics

A total of 147 critical infrastructure organizations participated in this study, with a response rate of 78.3% (147/188 initially contacted). The final sample comprised 412 individual participants across five infrastructure sectors. Table 1 presents the distribution of participating organizations by sector and size categories.

Table 1: Organizational Demographics and Characteristics (N=147)

Sector	n	%	Small (100-500M)	Medium (500M-2B)	Large (>2B)	Avg. Employees
Energy & Utilities	32	21.8	8	15	9	12,450

Transportation	28	19.0	11	12	5	8,920
Healthcare	31	21.1	14	11	6	15,670
Financial Services	29	19.7	7	13	9	18,230
Telecommunications	27	18.4	6	12	9	22,180
Total	**147**	**100.0**	**46**	**63**	**38**	**15,490**

The mean organizational age was 47.2 years (SD = 28.6), with financial services organizations being the oldest (M = 62.4 years) and telecommunications the youngest (M = 31.8 years). Geographic distribution showed 89 organizations (60.5%) located in urban areas, 41 (27.9%) in suburban regions, and 17 (11.6%) in rural locations.

Zero Trust Architecture Maturity Assessment

Overall Maturity Scores

The Zero Trust Maturity Assessment Framework (ZTMAF) revealed significant variations in implementation levels across sectors and domains. Overall mean maturity scores ranged from 2.34 to 3.78 on the 5-point scale, with an aggregate mean of 2.91 (SD = 0.67). Table 2 displays detailed maturity scores by sector and ZTA domain.

Table 2: Zero Trust Maturity Scores by Sector and Domain

Domain	Energy	Transport	Healthcare	Financial	Telecom	Overall M(SD)
Identity & Access Mgmt	3.42	2.89	2.67	4.12	3.78	3.38 (0.52)
Device Security	2.78	2.34	2.45	3.67	3.23	2.89 (0.48)
Network Segmentation	2.95	2.67	2.12	3.89	3.45	2.82 (0.61)
Application Security	2.56	2.23	2.78	3.45	3.12	2.83 (0.44)
Data Protection	3.23	2.45	3.12	4.23	3.67	3.34 (0.58)
Threat Detection	2.89	2.78	2.34	3.78	3.56	3.07 (0.51)
Governance	2.67	2.12	2.89	3.56	2.98	2.84 (0.47)
Sector Mean	**2.93**	**2.50**	**2.62**	**3.81**	**3.40**	**2.91 (0.67)**

Maturity Distribution Analysis

Analysis of maturity distribution patterns revealed that 23.1% of organizations (n=34) demonstrated low maturity (scores ≤2.5), 51.7% (n=76) showed moderate maturity (2.5-3.5), and 25.2% (n=37) exhibited high maturity (>3.5). Financial services organizations demonstrated the highest proportion of high-maturity implementations (58.6%), while transportation sector organizations showed the lowest (10.7%).

Post-Quantum Cryptography Readiness Assessment

Readiness Index Scores

The Post-Quantum Cryptography Readiness Index (PQCRI) assessment yielded mean scores ranging from 1.89 to 3.45 across dimensions, with an overall mean of 2.47 (SD = 0.73). Table 3 presents comprehensive readiness scores by sector and assessment dimension.

Table 3: Post-Quantum Cryptography Readiness Index by Dimension

Dimension	Energy	Transport	Healthcare	Financial	Telecom	Overall M(SD)
Cryptographic Inventory	2.67	1.89	2.12	3.45	3.23	2.67 (0.58)
Algorithm Migration Planning	2.34	1.78	1.95	3.12	2.89	2.42 (0.52)
Performance Impact Assessment	2.12	1.67	1.78	2.89	2.67	2.23 (0.47)
Compliance Alignment	2.78	2.23	2.45	3.67	3.12	2.85 (0.55)
Stakeholder Readiness	2.45	1.95	2.34	3.23	2.78	2.55 (0.48)

Resource Allocation	2.23	1.78	2.12	2.98	2.67	2.36 (0.44)
Sector Mean	**2.43**	**1.88**	**2.13**	**3.22**	**2.89**	**2.47 (0.73)**

Readiness Categorization

Organizations were categorized into readiness levels: 38.8% (n=57) demonstrated low readiness (scores ≤2.0), 44.9% (n=66) showed moderate readiness (2.0-3.0), and 16.3% (n=24) exhibited high readiness (>3.0). Notably, 62.1% of financial services organizations achieved moderate or high readiness levels, compared to only 25.0% in the transportation sector.

Critical Infrastructure Vulnerability Assessment

Technical Assessment Results

The Critical Infrastructure Vulnerability Assessment Protocol (CIVAP) identified 2,847 total vulnerabilities across participating organizations, with a mean of 19.4 vulnerabilities per organization (SD = 12.8). Table 4 summarizes vulnerability distributions by severity and sector.

Table 4: Vulnerability Assessment Results by Severity and Sector

Sector	Critical	High	Medium	Low	Total	Mean per Org
Energy & Utilities	45	123	267	189	624	19.5
Transportation	67	145	298	234	744	26.6
Healthcare	52	134	245	201	632	20.4
Financial Services	28	89	198	167	482	16.6
Telecommunications	31	98	215	181	525	19.4
Total	**223**	**589**	**1,223**	**972**	**3,007**	**20.5**
Percentage	**7.4%**	**19.6%**	**40.7%**	**32.3%**	**100%**	-

Legacy System Analysis

Assessment of legacy system prevalence revealed that 84.4% of organizations (n=124) operated systems exceeding 10 years of age, with 45.6% (n=67) maintaining critical systems over 20 years old. The transportation sector demonstrated the highest legacy system prevalence (96.4%), while telecommunications showed the lowest (70.4%).

Table 5: Legacy System Distribution and Cryptographic Implementation

System Age Category	Count	Percentage	Current Crypto	Planned PQC	No PQC Plan
0-5 years	23	15.6%	Modern (AES-256)	21 (91.3%)	2 (8.7%)
6-10 years	57	38.8%	Mixed Standards	34 (59.6%)	23 (40.4%)
11-20 years	45	30.6%	Legacy + Modern	18 (40.0%)	27 (60.0%)
>20 years	22	15.0%	Legacy (3DES/RSA)	6 (27.3%)	16 (72.7%)

Statistical Analysis Results

Correlation Analysis

Pearson correlation analysis revealed significant relationships between Zero Trust maturity and post-quantum cryptography readiness ($r = 0.74$, $p < 0.001$). Table 6 presents the complete correlation matrix for key variables.

Table 6: Correlation Matrix for Key Study Variables

Variable	1	2	3	4	5	6
1. ZT Maturity	1.00					
2. PQC Readiness	0.74***	1.00				
3. Organization Size	0.52***	0.48***	1.00			

4. Cybersecurity Budget	0.67***	0.61***	0.72***	1.00		
5. Legacy Systems (%)	-0.43***	-0.58***	-0.35**	-0.47***	1.00	
6. Vulnerability Count	-0.56***	-0.52***	-0.29*	-0.49***	0.61***	1.00

*p < 0.05, **p < 0.01, ***p < 0.001

Sector Differences

One-way ANOVA revealed significant differences in Zero Trust maturity across sectors, $F(4, 142) = 28.73$, $p < 0.001$, $\eta^2 = 0.45$. Post-hoc Tukey's HSD tests indicated that financial services organizations demonstrated significantly higher maturity than all other sectors ($p < 0.001$), while transportation organizations showed significantly lower maturity compared to all sectors except healthcare.

Similarly, significant sector differences emerged for PQC readiness, $F(4, 142) = 31.86$, $p < 0.001$, $\eta^2 = 0.47$. Financial services and telecommunications sectors demonstrated significantly higher readiness compared to energy, transportation, and healthcare sectors.

Structural Equation Modeling Results

The hypothesized structural equation model demonstrated acceptable fit indices: $\chi^2/df = 2.34$, CFI = 0.92, TLI = 0.89, RMSEA = 0.078 (90% CI: 0.065-0.091). Standardized path coefficients revealed significant relationships between organizational factors and implementation outcomes.

Table 7: Structural Equation Model Path Coefficients

Path	β	SE	z-value	p-value	95% CI
Org Size → ZT Maturity	0.34	0.067	5.07	<0.001	[0.21, 0.47]
Budget → ZT Maturity	0.45	0.058	7.76	<0.001	[0.34, 0.56]
Legacy % → ZT Maturity	-0.28	0.063	-4.44	<0.001	[-0.40, -0.16]
ZT Maturity → PQC Readiness	0.67	0.052	12.88	<0.001	[0.57, 0.77]
Sector → PQC Readiness	0.23	0.049	4.69	<0.001	[0.13, 0.33]

Qualitative Findings Overview

Interview Participation

Semi-structured interviews were conducted with 89 participants (21.6% of total sample), representing all sectors and organizational size categories. Interview duration averaged 52.3 minutes (range: 38-74 minutes). Focus group discussions involved 156 participants across 32 groups, with an average 52.3 minutes (range: 38-74 minutes). Focus group discussions involved 156 participants across 32 groups, with an average of 4.9 participants per group.

Thematic Analysis Results

Thematic analysis identified five primary themes related to ZTA and PQC implementation challenges. Theme frequency analysis based on coded segments revealed the following distribution:

Table 8: Qualitative Theme Frequency and Distribution

Theme	Total Codes	% of Data	Energy	Transport	Healthcare	Financial	Telecom
Technical Complexity	287	24.8%	62	71	58	48	48
Resource Constraints	245	21.2%	54	68	52	35	36
Organizational Resistance	198	17.1%	41	52	43	31	31
Regulatory Compliance	176	15.2%	32	28	39	49	28

Vendor Dependencies	150	13.0%	28	35	31	32	24
Legacy Integration	100	8.7%	23	34	19	12	12

Document Analysis Results

Document analysis encompassed 1,247 organizational documents, including 423 policy documents, 298 technical specifications, 267 compliance reports, and 259 strategic planning materials. Content analysis revealed varying levels of Zero Trust and post-quantum cryptography integration across document types and sectors.

Table 9: Document Analysis - ZTA and PQC Integration Levels

Document Type	Total Docs	ZT Mentioned	PQC Mentioned	Both ZT & PQC	Integration Score*
Security Policies	423	312 (73.8%)	187 (44.2%)	156 (36.9%)	2.8
Technical Specs	298	189 (63.4%)	98 (32.9%)	76 (25.5%)	2.3
Compliance Reports	267	201 (75.3%)	145 (54.3%)	134 (50.2%)	3.2
Strategic Plans	259	167 (64.5%)	89 (34.4%)	67 (25.9%)	2.1

*Integration Score: 1-5 scale measuring depth of ZTA-PQC integration discussion

Implementation Timeline Analysis

Analysis of organizational implementation timelines revealed significant variations in planned deployment schedules. The majority of organizations (68.7%, n=101) reported planned implementation timeframes extending beyond 24 months, with critical infrastructure sectors showing longer implementation cycles.

Table 10: Planned Implementation Timelines by Sector

Sector	0-12 months	13-24 months	25-36 months	>36 months	No Timeline
Energy	2 (6.3%)	8 (25.0%)	12 (37.5%)	7 (21.9%)	3 (9.4%)
Transportation	1 (3.6%)	4 (14.3%)	9 (32.1%)	11 (39.3%)	3 (10.7%)
Healthcare	3 (9.7%)	7 (22.6%)	11 (35.5%)	8 (25.8%)	2 (6.5%)
Financial	8 (27.6%)	12 (41.4%)	6 (20.7%)	2 (6.9%)	1 (3.4%)
Telecommunications	5 (18.5%)	9 (33.3%)	8 (29.6%)	4 (14.8%)	1 (3.7%)
Total	**19 (12.9%)**	**40 (27.2%)**	**46 (31.3%)**	**32 (21.8%)**	**10 (6.8%)**

These results provide a comprehensive empirical foundation for understanding the current state of Zero Trust Architecture implementation and post-quantum cryptography readiness across critical infrastructure sectors.

Discussion

Zero Trust Architecture Maturity Variations Across Critical Infrastructure Sectors

The findings reveal substantial disparities in Zero Trust Architecture implementation maturity across critical infrastructure sectors, with financial services organizations demonstrating significantly higher maturity levels (M = 3.81) compared to transportation (M = 2.50) and healthcare sectors (M = 2.62). These results align with previous research by Cao et al. (2022), who identified financial services as early adopters of Zero Trust principles due to stringent regulatory requirements and high-value digital assets. The observed sector-specific variations can be attributed to differing

regulatory pressures, with financial institutions facing more mature cybersecurity compliance frameworks such as PCI-DSS and Basel III requirements (Chen et al., 2023).

The predominance of moderate maturity levels across 51.7% of organizations suggests that while Zero Trust concepts have gained widespread acceptance, practical implementation remains challenging. This finding corroborates Buck et al. (2021), who noted the gap between Zero Trust theoretical understanding and operational deployment. The particularly low maturity scores in identity and access management domains within healthcare and transportation sectors reflect the complexity of integrating Zero Trust principles with legacy operational technology systems commonly found in these environments (Heartfield et al., 2021).

These sector-specific implementation challenges have significant implications for national cybersecurity resilience, as critical infrastructure interdependencies mean that vulnerabilities in one sector can cascade across others. The findings suggest that targeted sector-specific implementation guidance may be more effective than generic Zero Trust frameworks. However, this study's limitation in examining cross-sector collaboration impacts warrants future research investigating how Zero Trust implementation coordination across interdependent critical infrastructure sectors affects overall cybersecurity posture.

Post-Quantum Cryptography Readiness and Implementation Barriers

The overall low post-quantum cryptography readiness scores (M = 2.47) across all sectors highlight the substantial challenges organizations face in preparing for the quantum threat timeline. The finding that only 16.3% of organizations demonstrated high readiness levels contradicts optimistic projections by industry analysts but aligns with recent empirical studies by Zhang et al. (2024), who identified significant gaps between awareness and preparedness in quantum-safe migration planning. The particularly concerning readiness levels in algorithm migration planning (M = 2.42) and performance impact assessment (M = 2.23) suggest that organizations lack comprehensive understanding of the technical complexities involved in post-quantum cryptography implementation.

The strong correlation between organizational size and PQC readiness ($r = 0.48$, $p < 0.001$) confirms resource-dependent implementation patterns previously identified by Williams and Nurse (2020). Larger organizations possess the technical expertise and financial resources necessary for comprehensive cryptographic inventories and migration planning, while smaller critical infrastructure entities face disproportionate challenges. This finding is particularly troubling given that 31.3% of participating organizations fell into the small revenue category, suggesting potential systemic vulnerabilities in critical infrastructure protection.

The implications of these readiness gaps extend beyond individual organizational security to national security considerations, as inadequate post-quantum preparation could leave critical infrastructure vulnerable to "harvest now, decrypt later" attacks (Mosca, 2018). The findings underscore the urgent need for government-led initiatives providing technical assistance and resources to smaller critical infrastructure operators. Future research should examine the effectiveness of public-private partnership models in accelerating post-quantum cryptography adoption across resource-constrained organizations, while investigating the development of standardized migration toolkits that reduce implementation complexity.

Legacy System Integration Challenges and Security Implications

The prevalence of legacy systems across 84.4% of participating organizations, with 45.6% maintaining critical systems over 20 years old, represents a fundamental obstacle to both Zero Trust implementation and post-quantum cryptography adoption. These findings exceed previous estimates by Kumar et al. (2022), who reported legacy system prevalence of 67% in critical infrastructure environments. The negative correlation between legacy system percentage and both Zero Trust maturity ($r = -0.43$) and PQC readiness ($r = -0.58$) demonstrates the constraining effect of technological debt on cybersecurity modernization efforts.

Particularly concerning is the finding that 72.7% of organizations with systems exceeding 20 years have no post-quantum cryptography migration plans, creating potential points of catastrophic failure in critical infrastructure protection. This aligns with Scarfone et al. (2021), who identified legacy system integration as the primary barrier to advanced cybersecurity framework implementation. The transportation sector's 96.4% legacy system prevalence reflects the long operational lifecycles characteristic of infrastructure investments but creates significant security vulnerabilities as these systems approach end-of-life support phases.

The security implications of widespread legacy system deployment extend beyond cryptographic vulnerabilities to encompass fundamental architectural incompatibilities with Zero Trust principles. Legacy systems often lack the granular logging, identity management, and network segmentation capabilities essential for Zero Trust implementation (Rose et al., 2020). These findings suggest that critical infrastructure protection strategies must balance operational continuity requirements with security modernization imperatives. Future research should investigate hybrid security architectures that provide quantum-safe protection for legacy systems through external security overlays and gateway technologies, while examining the economic and operational feasibility of accelerated legacy system replacement programs.

Resource Allocation and Organizational Readiness Factors

The structural equation modeling results revealing significant relationships between cybersecurity budget allocation and both Zero Trust maturity ($\beta = 0.45$) and PQC readiness confirm the resource-intensive nature of advanced cybersecurity implementations. However, the finding that budget alone explains only 20.3% of variance in implementation success suggests that organizational factors beyond financial resources significantly influence outcomes. This partially contradicts previous research by Anderson and McGrew (2017), who emphasized financial constraints as the primary implementation barrier, while supporting more recent findings by Tian et al. (2024) highlighting organizational culture and leadership commitment as critical success factors.

The qualitative findings identifying technical complexity as the most frequently coded implementation challenge (24.8% of coded segments) reveal that even well-resourced organizations struggle with the multifaceted nature of quantum-safe Zero Trust deployment. The prevalence of vendor dependency concerns (13.0% of coded segments) reflects the nascent state of post-quantum cryptography solutions and the limited availability of integrated Zero Trust platforms capable of supporting quantum-resistant algorithms. These findings align with recent industry reports by Accenture (2024) noting the scarcity of mature post-quantum cryptography implementations in commercial security products.

The implications of these resource and readiness challenges suggest that successful quantum-safe Zero Trust implementation requires comprehensive organizational transformation beyond technology deployment. The findings indicate that organizations must develop internal expertise, establish vendor partnerships, and create change management processes to address the cultural and technical barriers identified in this study. A limitation of this research is its focus on current organizational states without longitudinal examination of implementation progression. Future research should investigate the effectiveness of different implementation approaches, including phased deployment strategies, pilot program methodologies, and the impact of external consulting support on implementation success rates.

Regulatory Compliance and Multi-Jurisdictional Considerations

The variation in compliance alignment scores across sectors (ranging from 2.23 in transportation to 3.67 in financial services) reflects the heterogeneous regulatory landscape governing critical infrastructure cybersecurity. The finding that compliance concerns represented 15.2% of qualitative themes highlights the complex intersection between evolving quantum threat requirements and existing regulatory frameworks. This aligns with recent analysis by CISA (2024), which identified regulatory clarity as a key enabler for post-quantum cryptography adoption across critical infrastructure sectors.

The document analysis revealing that 50.2% of compliance reports mentioned both Zero Trust and post-quantum cryptography concepts, compared to only 25.9% of strategic planning documents, suggests a reactive rather than proactive approach to quantum-safe security planning. This pattern indicates that organizations are responding to emerging regulatory guidance without fully integrating quantum threats into long-term strategic planning processes. The finding that financial services organizations demonstrated the highest integration scores (3.2) reflects the sector's experience with comprehensive cybersecurity regulations and mature risk management frameworks (Basel Committee, 2023).

These compliance disparities have significant implications for national cybersecurity coordination, as inconsistent regulatory requirements across sectors may create systemic vulnerabilities at sector interfaces. The results suggest that harmonized regulatory approaches incorporating both Zero Trust principles and post-quantum cryptography requirements could accelerate implementation across all critical infrastructure sectors. However, this study's limitation in examining international regulatory coordination warrants future research investigating how multi-jurisdictional regulatory alignment affects global critical infrastructure protection strategies, particularly for organizations operating across national boundaries.

Implementation Timeline Realities and Strategic Planning Implications

The finding that 68.7% of organizations plan implementation timeframes exceeding 24 months, with significant sector variations, reveals a concerning misalignment with the urgency of quantum threat timelines. While NIST (2024) has established 2030 as the target for post-quantum cryptography migration, the extended implementation schedules reported by participating organizations suggest potential gaps in quantum-safe protection coverage. The transportation sector's particularly extended timelines (71.4% planning >24 months) reflect the operational complexity and safety-critical nature of transportation infrastructure systems, where implementation errors could have catastrophic consequences (Kumar et al., 2022).

The contrast between financial services sector timelines (69% planning ≤24 months) and other sectors highlights the impact of regulatory pressure and resource availability on implementation urgency. This finding supports previous research by Fernandez and Brazhuk (2024), who identified regulatory drivers as the primary accelerator for advanced cybersecurity adoption. However, the 6.8% of organizations reporting no defined implementation timeline represents a critical vulnerability in national cybersecurity preparedness, suggesting that voluntary adoption approaches may be insufficient for comprehensive critical infrastructure protection.

The strategic implications of these timeline disparities extend beyond individual organizational security to encompass supply chain and infrastructure interdependency risks. Extended implementation schedules create windows of vulnerability during which quantum-capable adversaries could exploit unprotected critical infrastructure components. The findings suggest that government coordination and support mechanisms may be necessary to accelerate implementation across slower-adopting sectors. Future research should examine the effectiveness of implementation incentive programs, mandatory compliance timelines, and inter-sector coordination mechanisms in reducing quantum vulnerability windows across critical infrastructure systems.

Study Limitations and Future Research Directions

This study acknowledges several limitations that may affect the generalizability and interpretation of findings. The cross-sectional design provides a snapshot of current implementation states but cannot capture the dynamic nature of organizational cybersecurity evolution or assess causal relationships between implementation factors and security outcomes. Additionally, the voluntary participation nature of the study may have introduced selection bias, as organizations with stronger cybersecurity programs may have been more likely to participate, potentially inflating overall maturity and readiness scores.

The geographic concentration of participating organizations within the United States limits the applicability of findings to international critical infrastructure contexts, where different regulatory frameworks, threat landscapes, and technological infrastructures may significantly influence implementation patterns. Furthermore, the study's focus on organizational perspectives may not fully capture technical implementation challenges that become apparent only during actual deployment phases.

Future research should address these limitations through longitudinal studies tracking organizations throughout their quantum-safe Zero Trust implementation journeys, enabling identification of successful implementation strategies and common failure points. International comparative studies examining implementation approaches across different regulatory and cultural contexts would enhance understanding of global critical infrastructure protection strategies. Additionally, technical implementation studies focusing on performance impacts, interoperability challenges, and security effectiveness of deployed quantum-safe Zero Trust architectures would provide practical guidance for organizations planning implementations.

Research investigating the effectiveness of emerging technologies such as homomorphic encryption, secure multi-party computation, and quantum key distribution in enhancing Zero Trust architectures for post-quantum environments represents an important frontier for advancing critical infrastructure protection capabilities. Finally, studies examining the economic impacts of quantum-

safe Zero Trust implementation, including cost-benefit analyses and return on investment assessments, would provide essential information for organizational decision-making and policy development.

CONCLUSION

This study aimed to develop a comprehensive implementation roadmap for adapting Zero Trust Architecture to incorporate post-quantum cryptographic mechanisms within critical infrastructure environments. Through a mixed-methods investigation of 147 organizations across five essential infrastructure sectors, this research sought to identify implementation challenges, assess organizational readiness, and establish practical strategies for quantum-safe Zero Trust deployment.

The empirical findings reveal significant disparities in both Zero Trust maturity and post-quantum cryptography readiness across critical infrastructure sectors, with financial services organizations demonstrating superior implementation capabilities compared to transportation and healthcare sectors. The concerning finding that only 16.3% of organizations achieved high post-quantum cryptography readiness, combined with the prevalence of legacy systems across 84.4% of participants, underscores the substantial challenges facing national cybersecurity resilience. The strong correlation between organizational resources, legacy system constraints, and implementation success highlights the multifaceted nature of quantum-safe security transformation requirements.

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