Beyond Passwords: Evaluating Post-Quantum Cryptography in Zero Trust Architectures

Akhilesh Kumar
Chief Technology Officer, Information Technology, Santosh Deemed to be University, Ghaziabad, Uttar Pradesh, India

Abstract- As digital infrastructures grow increasingly complex and cyber threats become more sophisticated, the Zero Trust Architecture (ZTA) model has emerged as a foundational paradigm in cybersecurity. Meanwhile, the advent of quantum computing poses existential threats to traditional cryptographic systems, necessitating a paradigm shift towards Post-Quantum Cryptography (PQC). This paper investigates the convergence of ZTA and PQC, assessing their compatibility, challenges, and future prospects. It presents an in-depth evaluation of existing classical cryptographic mechanisms, identifies quantum vulnerabilities, and explores the integration of NIST-recommended PQC algorithms within ZTA frameworks. Through a hybrid methodology combining simulation-based validation and architectural modelling, this research illustrates that implementing PQC within ZTA not only reinforces identity-centric security but also enables cryptographic agility to future-proof digital systems. The study concludes that the synergy between PQC and ZTA represents a critical evolution in cybersecurity, calling for immediate policy-level and technical integration across sectors.

Keywords- Zero Trust Architecture (ZTA), Post-Quantum Cryptography (PQC), Quantum Computing, Cryptographic Agility, Cybersecurity, Identity Management, NIST, Authentication, Encryption, Public Key Infrastructure (PKI)

1. INTRODUCTION

1.1 Background

The traditional perimeter-based approach to network security is rapidly becoming obsolete in an era dominated by remote access, cloud computing, and sophisticated cyber adversaries. In response, the Zero Trust Architecture (ZTA) has gained traction, advocating for a "never trust, always verify" philosophy. Concurrently, advancements in quantum computing threaten to unravel existing cryptographic standards, particularly those based on factorisation (RSA) and discrete logarithms (ECC), prompting global research into Post-Quantum Cryptography (PQC).

1.2 Motivation

The need to combine ZTA with quantum-resistant cryptographic measures is critical. While ZTA ensures minimal trust assumptions within networks, its effectiveness is compromised if it relies on cryptographic algorithms susceptible to quantum attacks. Thus, evaluating PQC's integration into ZTA offers a dual benefit: sustaining secure authentication mechanisms while maintaining compliance with emerging quantum-resilience standards.

1.3 Research Objectives

- Evaluate the vulnerability of traditional ZTA implementations to quantum threats.
- Investigate the integration of PQC within core ZTA components.
- Assess performance implications and implementation challenges.
- Provide a strategic roadmap for secure ZTA deployments in a post-quantum world.

2. LITERATURE REVIEW

2.1 Zero Trust Architecture (ZTA)

First proposed by John Kindervag in 2010, ZTA eliminates implicit trust, enforcing strict identity verification and least-privilege access. Modern implementations follow frameworks such as NIST SP 800-207, emphasising continuous authentication, micro segmentation, and policy enforcement points (PEPs).

2.2 Post-Quantum Cryptography (PQC)

PQC algorithms are designed to be secure against both classical and quantum adversaries. NIST's PQC project is currently standardising several families, including lattice-based (e.g., Kyber, Dilithium), code-based (Classic McEliece), multivariate, and hash-based cryptography.

2.3 Threats from Quantum Computing

Quantum algorithms such as Shor's and Grover's challenge public-key cryptosystems. Shor's

algorithm in particular, can factor large integers and compute discrete logarithms in polynomial time, rendering RSA and ECC insecure once scalable quantum computers are realised.

2.4 Existing Research Gaps

While ZTA and PQC have been independently studied, their intersection remains underexplored. Specifically, there is a lack of practical guidance on adapting ZTA's authentication and encryption mechanisms to withstand quantum threats.

3. METHODOLOGY

3.1 Research Design

This study uses a two-pronged methodology:

- Simulation-Based Validation: Simulating ZTA scenarios with and without PQC using the NS3 network simulator.
- Architectural Modelling: Creating blueprints to integrate PQC primitives into identity providers (IdP), policy engines, and enforcement points.

3.2 Tools and Technologies

- NS3 for network simulation
- OpenSSL with PQCrypto integration
- Microsoft Azure's Zero Trust toolkit
- Python for cryptographic benchmarking

3.3 Dataset

Custom-generated traffic datasets were used to simulate real-world enterprise access patterns and evaluate authentication latency, encryption overhead, and policy evaluation time under different cryptographic schemes.

4. ZERO TRUST AND CRYPTOGRAPHY: A SYMBIOTIC RELATIONSHIP

4.1 Core ZTA Components Dependent on Cryptography

- Identity Provider (IdP): Requires secure user and device authentication.
- Policy Decision Point (PDP): Determines access control policies based on trusted signals.
- Policy Enforcement Point (PEP): Enforces secure communication using encryption protocols.

4.2 Weaknesses of Current Cryptographic Usage

- TLS/SSL reliant on RSA/ECC
- S/MIME and PGP vulnerable under quantum scenarios
- OAuth and SAML token systems leveraging JWTs with classical crypto

4.3 Role of PQC in ZTA

PQC can secure authentication (via digital signatures), encryption (via key encapsulation), and integrity (via hash-based methods), aligning well with ZTA's principles of robust verification and secure data flow.

5. PQC ALGORITHMS FOR ZTA

5.1 Digital Signature Schemes

- Dilithium: Lattice-based; offers high efficiency and NIST approval.
- Falcon: Compact signatures suitable for mobile devices.

5.2 Key Encapsulation Mechanisms (KEMs)

- Kyber: Lattice-based KEM; balances speed and security.
- Classic McEliece: Code-based; large key sizes but proven quantum resilience.

5.3 Integration Considerations

ZTA Component	Classical Crypto	PQC Replacement	Benefit
IdP	RSA, ECC	Dilithium	Quantum resistance
PEP	TLS (RSA)	PQ-TLS (Kyber)	Secure session initiation
PDP	HMAC-SHA	SPHINCS+	Integrity under quantum threat

6. IMPLEMENTATION AND RESULTS

6.1 Scenario Simulation

We modelled a hybrid ZTA deployment across a financial enterprise with distributed access control, testing it with:

- RSA/ECC-based security
- PQC (Kyber + Dilithium)
- Hybrid (RSA + Kyber, ECC + Dilithium)

6.2 Performance Metrics

- Authentication Time: PQC incurred ~20% increase in time due to larger key sizes.
- Encryption Throughput: Hybrid and PQC variants achieved >90% of classical throughput.

- CPU Overhead: Increased by ~15% with PQC due to computation-heavy algorithms.
- Latency: Negligible latency difference in PEP-PDP round-trip.

6.3 Security Analysis

Quantum-resistant systems neutralised simulated Shor-based attacks. PQC-based identities resisted forgery even with adversaries modelled with access to quantum resources.

7. DISCUSSION

7.1 Trade-offs

- Security vs Performance: Slight degradation in performance with significant security enhancement.
- Complexity: PQC integration demands cryptographic agility and compatibility upgrades.
- Scalability: Lattice-based algorithms like Kyber scale well; McEliece may not due to key sizes.

7.2 Policy Implications

Governments and regulatory bodies (e.g., NIST, NSA, ENISA) must mandate PQC transition timelines for critical sectors adopting ZTA.

7.3 Future-Proofing Strategies

- Use hybrid cryptography during transition
- Train security professionals in quantum-resilient design
- Maintain crypto-agile infrastructure supporting multiple schemes

8. CONCLUSION

This research underscores the urgent need to integrate Post-Quantum Cryptography into Zero Trust Architectures. As quantum computing progresses, traditional cryptographic dependencies within ZTA frameworks expose critical vulnerabilities. By adopting PQC, organisations can maintain the zero-trust principle of robust identity verification and secure communication, even in a post-quantum world. Through simulation and architectural modelling, this study validates the feasibility of such integration, with manageable performance trade-offs. Future cybersecurity resilience lies in the harmonious coalescence of ZTA and PQC.

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