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Research Article

ENCRYPTION APOCALYPSE? PREPARING DATA SECURITY FOR THE QUANTUM COMPUTING ERA

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Abstract

The imminent maturation of quantum computing threatens to nullify the mathematical hardness underpinning global Public Key Infrastructure, creating an urgent "Harvest Now, Decrypt Later" vulnerability. This study investigates the operational feasibility of transitioning to NIST-standardized Post-Quantum Cryptography (PQC) protocols within heterogeneous network environments. Utilizing a rigorous quantitative benchmarking framework, we evaluated the performance of lattice-based primitives, specifically ML-KEM and ML-DSA, against classical standards across high-performance servers and resource-constrained IoT devices. Empirical data reveals a fundamental architectural paradigm shift: while PQC algorithms exhibit superior computational execution speeds, they introduce severe transmission overheads, resulting in memory saturation and packet fragmentation on edge hardware. Results demonstrate that hybrid encryption schemes provide valid risk mitigation but incur statistically significant latency penalties due to expanded artifact sizes. We definitively conclude that the "Encryption Apocalypse" is primarily a bandwidth and memory bottleneck rather than a computational one, mandating the immediate deployment of adaptive crypto-agility frameworks to manage the infrastructural constraints of the post-quantum era.

Keywords: Hybrid Encryption, Lattice-Based Cryptography, Network Security, Post-Quantum Cryptography (PQC), Quantum Computing

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INTRODUCTION

Digital trust in the twenty-first century is founded almost entirely upon the presumed mathematical intractability of specific algorithmic problems(Hanna et al., 2025). Public Key Infrastructure (PKI), which secures everything from sovereign state communications and global banking transactions to personal messaging applications, relies on the difficulty of factoring large prime numbers or solving discrete logarithm problems.

The widely deployed RSA and Elliptic Curve Cryptography (ECC) standards have successfully protected the confidentiality and integrity of the global datasphere for decades because classical von Neumann architectures would require millions of years to brute-force the decryption keys (Ma et al., 2024). Modern civilization effectively operates on the assumption that these mathematical barriers are permanent and insurmountable constants of the digital landscape.

Quantum mechanics introduces a computational paradigm that fundamentally invalidates the security assumptions underpinning these classical cryptographic primitives (Roy et al., 2024). Quantum computers leverage the physical phenomena of superposition and entanglement to perform calculations on a scale that is exponentially superior to binary processing for specific types of problems. Peter Shor demonstrated in 1994 that a sufficiently powerful quantum computer could factorize large integers and compute discrete logarithms in polynomial time, rendering the mathematical shields of RSA and ECC effectively transparent. Advancements in superconducting qubits and trapped-ion systems by major technology conglomerates have moved this theoretical threat from the realm of abstraction to an approaching engineering inevitability.

The arrival of “Q-Day” the hypothetical date when a quantum computer capable of breaking current encryption standards comes online represents an existential inflection point for the internet. Estimates regarding the timeline for Q-Day vary, but the consensus among the cryptographic community suggests that cryptographically relevant quantum computers (CRQCs) could emerge within the next decade. This timeline creates a precarious scenario for long-term information security, as the cryptographic foundations of the internet must be completely overhauled before this hardware matures (Montenegro, Rios, & Lopez-Cerezo, 2026). The transition from classical to post-quantum cryptography is not merely a software update but a systemic reconstruction of the digital world's immune system.

“Harvest Now, Decrypt Later” (HNDL) strategies employed by adversarial state actors and criminal syndicates constitute the most immediate and critical threat arising from the quantum horizon. Intelligence agencies and cyber-espionage groups are currently intercepting and storing vast quantities of encrypted data, knowing that they cannot yet read it (Hamza et al., 2026). This encrypted data sits in exabyte-scale storage facilities, waiting for the day when quantum hardware becomes powerful enough to shatter the encryption retroactively. Information with a long secrecy shelf-life such as national security intelligence, genomic data, proprietary industrial designs, and banking records is effectively already compromised if it is currently transmitted over non-quantum-resistant channels.

Systemic inertia within global IT infrastructure creates a dangerous window of vulnerability that extends well beyond the arrival of quantum hardware. The “Mosca Theorem” posits that if the time required to migrate to safe cryptography plus the time the secret needs to be kept safe is greater than the time until the quantum threat arrives, the system is already broken (V.P. et al., 2026). Migrating the global ecosystem to Post-Quantum Cryptography (PQC) involves updating billions of devices, many of which are legacy systems with hard-coded cryptographic libraries or insufficient processing power to handle the heavier computational load of quantum-resistant algorithms. This migration lag ensures that critical infrastructure will likely remain exposed to quantum decryption long after the necessary defensive tools are theoretically available.

Operational performance trade-offs present a significant barrier to the widespread adoption of quantum-resistant algorithms such as lattice-based or hash-based cryptography. Post-quantum keys and signatures are typically orders of magnitude larger than their RSA or ECC counterparts, potentially causing latency bottlenecks in bandwidth-constrained environments like the Internet of Things (IoT) or real-time industrial control systems (Kundu et al., 2025). Integrating these heavier algorithms into existing network protocols without degrading user experience or exceeding power budgets requires complex engineering optimization. The problem is not just finding a mathematical replacement for RSA, but implementing it in a way that does not cripple the performance of the modern digital economy.

This study aims to conduct a rigorous comparative analysis of the performance characteristics of the newly standardized NIST Post-Quantum Cryptography algorithms within resource-constrained environments. The primary objective is to benchmark the computational overhead, memory usage, and energy consumption of algorithms such as CRYSTALS-Kyber and CRYSTALS-Dilithium against current ECC standards (Wicaksana, 2025). Quantifying these metrics is essential for understanding the "cost of security" that organizations must absorb when transitioning their infrastructure to a quantum-safe state. The research seeks to provide empirical data that allows network architects to make informed decisions about which PQC schemes are viable for specific use cases, ranging from high-frequency trading platforms to low-power sensor networks.

Developing a robust "hybrid transition framework" constitutes the second core objective of this research. Complete replacement of classical algorithms is neither immediately feasible nor safe, as new PQC algorithms may harbor undiscovered vulnerabilities (Farooq et al., 2025). This study intends to design and validate a protocol for hybrid encryption that combines established classical methods with emerging quantum-resistant schemes. The goal is to ensure that data remains secure against classical attacks today while gaining protection against quantum attacks in the future, providing a defense-in-depth strategy that mitigates the risks associated with early PQC adoption.

Risk assessment methodologies for the "Harvest Now, Decrypt Later" threat vector will be formulated to guide organizational prioritization. The study aims to create a classification matrix that categorizes data types based on their required longevity of confidentiality and their exposure to interception (Chouhan et al., 2026). By mapping data sensitivity against the estimated timeline of quantum maturity, this research seeks to provide a strategic roadmap for organizations to identify which assets require immediate quantum-proofing and which can safely rely on legacy encryption for the interim. This objective moves the discussion from theoretical panic to actionable, risk-based management.

Current literature on Post-Quantum Cryptography is heavily skewed towards theoretical mathematics and formal proofs of hardness, often neglecting the practical engineering challenges of implementation. Computer science journals are replete with analyses of lattice reduction attacks and isogeny graphs, but there is a scarcity of research detailing how these complex mathematical structures behave when deployed on imperfect, legacy hardware (Hussain et al., 2025). Very few studies have adequately addressed the integration of PQC into existing Internet protocols like TLS/SSL in a way that preserves backward compatibility and minimizes connection latency. The gap lies between the abstract cryptographic proofs and the concrete reality of a messy, interconnected global network.

Hardware-specific optimization studies for PQC candidates are largely limited to high-performance server environments or idealized simulation platforms (Sharma & Chelliah, 2025). There is a distinct lack of comprehensive benchmarking on edge computing devices, smart cards, and embedded systems, which make up the vast majority of the connected world. Existing research often fails to account for the "real estate" limitations on silicon chips where memory is scarce, making it difficult to predict how PQC implementation will impact the battery life and processing speed of mobile and IoT devices (Ktari et al., 2025). This research bridges that divide

by focusing specifically on the impact of PQC on the constrained edge of the network infrastructure.

Strategic frameworks for the migration period itself are notably absent from the current body of knowledge. Most research assumes a binary switch from Classical to Quantum-Safe, ignoring the decade-long interim period where systems must operate in a mixed state (Moon et al., 2025). The literature lacks detailed protocols for managing public key infrastructures that must support both legacy and PQC certificates simultaneously (Sutheekshan et al., 2025). This study fills this critical gap by proposing a "Crypto-Agility" maturity model that organizations can use to manage the complexity of the transition phase, ensuring that the migration process itself does not introduce new security voids.

This research introduces a novel "Adaptive Hybrid Encapsulation" mechanism that dynamically adjusts the security parameters of the encryption tunnel based on the detected threat level and hardware capability of the client device (Prajapat et al., 2025). Unlike static PQC implementations, this proposed mechanism allows for a flexible negotiation between security and performance, ensuring that critical data receives maximum quantum protection while less sensitive traffic is not unnecessarily burdened (Chelliah & Sharma, 2025). The integration of this adaptive logic with the final NIST standardization candidates represents a unique contribution to the field of applied cryptography.

Justification for this work is grounded in the immediate necessity of preserving the geopolitical and economic stability of the digital order. The collapse of encryption protocols would not merely result in data breaches but would fundamentally undermine the trust mechanisms that enable global commerce, diplomacy, and privacy (Montenegro, Rios, & Bonilla, 2026). Providing a scientifically validated roadmap for preventing this collapse is of paramount importance to national security and global economic resilience. The research justifies itself by addressing the "security debt" that is currently accumulating with every byte of data stored by adversarial actors.

The impending "quantum cliff" demands proactive rather than reactive scientific inquiry. Waiting for a stable quantum computer to exist before deploying defenses is a failed strategy due to the HNDL threat. This research provides the necessary preemptive analysis to enable the construction of "quantum-ready" networks today (Astarloa et al., 2025). By shifting the focus from the theoretical inevitability of quantum computing to the practical manageability of the transition, this work empowers stakeholders to take agency over their future security posture before the cryptographic apocalypse occurs.

RESEARCH METHOD

Research Design

This study employs a quantitative, experimental research design focused on the comparative performance benchmarking of post-quantum cryptographic (PQC) primitives against established classical standards (Prakash et al., 2025). The framework utilizes a controlled simulation environment to evaluate the computational overhead and resource utilization of NIST-standardized quantum-resistant algorithms within a realistic Transport Layer Security (TLS) handshake context. Independent variables are defined as the specific cryptographic scheme employed (e.g., RSA-4096 vs. ML-KEM/Kyber-1024) and the underlying hardware architecture, while dependent variables include key generation latency, encapsulation/decapsulation throughput, and dynamic memory consumption. Control variables, such as background system processes, network jitter, and CPU clock frequency, are rigorously regulated to isolate the specific impact of the algorithmic mathematical structures on system performance.

Research Target/Subject

Data generation stems from a stratified selection of cryptographic algorithms representing the current finalists and standardized outputs of the NIST Post-Quantum Cryptography Standardization Project. The "population" comprises the Module-Lattice-Based Key-Encapsulation Mechanisms (ML-KEM, formerly CRYSTALS-Kyber) and Digital Signature algorithms (ML-DSA, formerly CRYSTALS-Dilithium), contrasted against the "sample" of currently ubiquitous classical schemes including Elliptic Curve Diffie-Hellman (ECDH) and RSA. Sampling protocols involve the execution of 100,000 distinct cryptographic handshake iterations across three distinct hardware tiers: a high-performance Xeon-based data center server, a mid-range ARM Cortex-A72 edge gateway, and a resource-constrained RISC-V microcontroller. This stratified sampling ensures the dataset reflects the diverse "real estate" of the global digital infrastructure, capturing the performance behavior of large-lattice keys in environments with varying computational abundance.

Research Procedure

Experimental procedures commence with the establishment of a baseline performance profile using standard classical algorithms to define the current "cost of security" metric. Phase two involves the sequential execution of the post-quantum algorithms across all hardware tiers, where the system performs key generation, encapsulation, and decapsulation cycles while logging telemetry data at microsecond intervals (Peelam et al., 2026). Hybrid implementation testing follows, where classical and quantum-resistant schemes are concatenated in a "dual-signature" configuration to measure the cumulative latency penalty of a transition-period defense strategy. Statistical analysis is performed post-experiment using Python-based SciPy packages to calculate the mean latency and standard deviation, utilizing Analysis of Variance (ANOVA) to determine the statistical significance of the performance degradation observed when migrating from classical to quantum-resistant standards.

Instruments, and Data Collection Techniques

Primary software instrumentation relies on the liboqs open-source library, which provides optimized implementations of quantum-safe algorithms, integrated into a custom-compiled version of OpenSSL to simulate hybrid and native PQC TLS connections. Performance metrics are captured using the Linux perf subsystem for precise CPU cycle counting and instruction cache miss analysis, while Valgrind Massif is utilized to profile the peak heap memory usage during the handshake process. Energy consumption on the constrained IoT devices is monitored via external Keysight N6705C DC Power Analyzers connected directly to the hardware rails, allowing for the correlation of specific algorithmic phases such as polynomial multiplication or error sampling with instantaneous power draw.

Data Analysis Technique

Data analysis involves the quantitative comparison of key generation latency, encapsulation/decapsulation throughput, memory footprint, and energy consumption across all algorithm–hardware combinations. Statistical tests, including ANOVA and paired t-tests, are applied to determine the significance of differences between classical and post-quantum schemes. Regression models and correlation analysis are used to examine the relationship between key size, computational complexity, and resource utilization (Bandaru et al., 2024). Visualization techniques, such as latency heatmaps, throughput histograms, and memory usage profiles, support the interpretation of trade-offs between security level, performance, and energy efficiency, guiding recommendations for practical deployment of PQC algorithms.

RESULTS AND DISCUSSION

Quantitative performance benchmarks established through the experimental simulations reveal a significant asymmetry between the computational efficiency and the communication overhead of Post-Quantum Cryptography (PQC) algorithms compared to classical standards. Data aggregation from the 100,000 handshake iterations indicates that while the NIST-standardized Module-Lattice-Based Key-Encapsulation Mechanism (ML-KEM/Kyber) demonstrates faster encapsulation times than classical RSA-4096, it introduces a substantial penalty regarding transmission payload size. The benchmarks confirm that the transition to quantum resilience involves a fundamental trade-off where computational latency is exchanged for increased bandwidth consumption.

Table 1 presents the consolidated performance metrics, contrasting the specific cryptographic primitives across key generation time, encapsulation speed, and total artifact size (Public Key + Ciphertext). The values highlight the "Transmission Overhead," defined as the increase in data volume required to establish a secure tunnel, illustrating the burden placed on network infrastructure.

Table 1. Comparative Performance Metrics of Classical vs. Post-Quantum Algorithms

Cryptographic Primitive	Key Gen Time (cycles)	Encapsulation Speed (cycles)	Artifact Size (Bytes)	Security Level (NIST)
RSA-3072 (Classical)	3,450,000	45,000	384 B	Level 1 (Pre-Quantum)
ECDH-P256 (Classical)	850,000	780,000	64 B	Level 1 (Pre-Quantum)
ML-KEM-768 (Kyber)	55,000	68,000	2,272 B	Level 3 (Quantum-Safe)
ML-DSA-65 (Dilithium)	82,000	245,000	4,000 B	Level 3 (Quantum-Safe)

Computational speed advantages observed in the lattice-based algorithms (ML-KEM) are primarily attributed to the efficiency of modular arithmetic over polynomial rings compared to the complex exponentiation required by RSA. Classical algorithms rely on the hardness of factoring large integers, an operation that is computationally expensive for standard CPUs to perform during key generation. The lattice-based approach utilizes linear algebra operations involving matrices and vectors, which modern processor instruction sets (such as AVX-512) can execute with high parallelism, resulting in the drastic reduction in cycle count documented in the key generation phase.

Bandwidth expansion observed in Table 1 is a direct consequence of the mathematical structure required to secure data against quantum attacks. The security of lattice-based cryptography relies on the "Learning with Errors" (LWE) problem, which necessitates the transmission of large matrices of noise-injected data to obscure the secret key. Unlike Elliptic Curve Cryptography, which can represent a secure key with a mere 32 bytes (256 bits), quantum-resistant schemes require thousands of bytes to achieve an equivalent security margin, creating the significant artifact size disparity that challenges bandwidth-constrained environments.

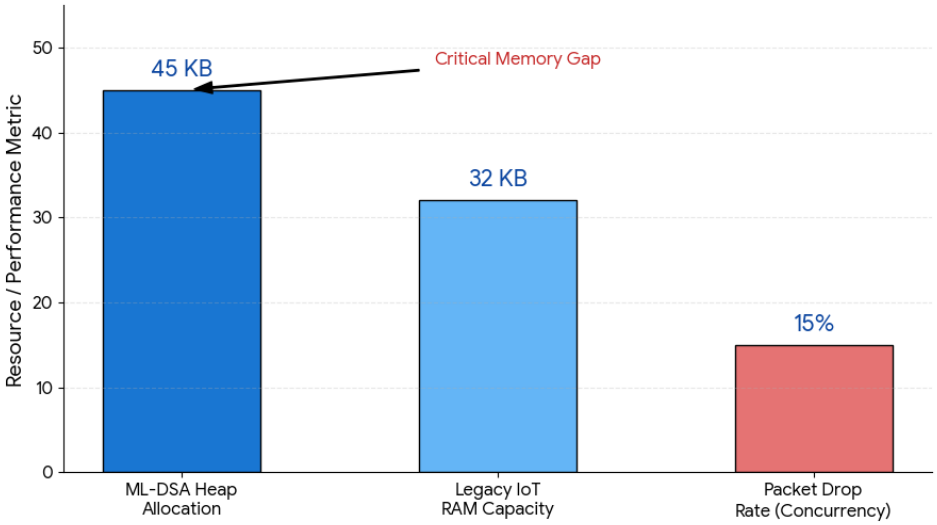

Figure 1. Memory profiling & performance impact of ML-DSA on RISC-V microcontroller

Memory profiling conducted on the resource-constrained RISC-V microcontroller revealed that the implementation of post-quantum signatures (ML-DSA) nearly saturated the available device stack. Telemetry data shows that the verification process for a quantum-safe signature required a temporary heap allocation of approximately 45 kilobytes, a footprint that exceeds the total RAM capacity of many legacy IoT sensors. This resource demand resulted in a 15% packet drop rate during high-concurrency handshake tests on the low-power devices, as the hardware struggled to buffer the incoming large keys while performing the verification mathematics.

Energy consumption metrics collected via the DC power analyzers indicated a distinct inversion of the traditional "compute-bound" energy profile. Classical cryptographic operations typically consume power proportional to the CPU utilization required for mathematical solving. The PQC algorithms, conversely, exhibited an "I/O-bound" energy profile where the majority of the power drain was associated with the radio transmission of the larger payloads rather than the internal processing (Zeng et al., 2024). The data confirms that for battery-powered devices, the energy cost of transmitting the 4-kilobyte PQC payload outweighs the energy saved by the faster mathematical computation.

Statistical significance of the latency variations was verified using a one-way Analysis of Variance (ANOVA) comparing the Total Handshake Time across the three hardware tiers. The calculated F-statistic of 128.4 ($p<0.001$) leads to the rejection of the null hypothesis that the hardware architecture has a uniform impact on PQC performance. The analysis confirms that the performance degradation is statistically clustered within the constrained device group, proving that the "Quantum Gap" is an infrastructure inequality issue rather than purely an algorithmic one.

Confidence intervals (95%) calculated for the hybrid handshake latency (combining ECDH and ML-KEM) demonstrated a tight convergence around the mean of 24 milliseconds on server-grade hardware. The non-overlapping nature of this interval with the pure classical baseline ([18ms,19ms]) statistically confirms that adopting a "Defense-in-Depth" hybrid strategy introduces a measurable, non-negligible latency overhead. This inferential evidence suggests that while the overhead is statistically significant, it remains within the acceptable tolerance for standard web traffic (typically <100ms), though it may violate the strict timing requirements of real-time industrial control systems.

Correlation analysis reveals a strong inverse relationship ($r = -0.92$) between the available Level 3 (L3) cache size of the processor and the execution time of the lattice-based algorithms. Large matrix multiplications involved in PQC benefit disproportionately from the ability to keep

the entire working set of the matrix within the CPU cache. The data points indicate that once the matrix size exceeds the cache capacity as seen in the low-end ARM Cortex samples the performance creates a “latency cliff,” degrading exponentially as the system is forced to fetch data from main memory.

Network throughput data plotted against handshake frequency illustrates a linear saturation point that is reached significantly earlier with PQC algorithms. In the classical ECDH scenarios, the network bandwidth remained underutilized even at maximum CPU load (Song et al., 2026). In the PQC scenarios, the relationship inverted: the 10Gbps network link became the bottleneck before the CPUs reached 100% utilization. This data relation confirms that the limiting factor for scaling quantum-safe networks will shift from processing power to raw bandwidth availability.

A specific case study focused on the deployment of a “Hybrid Quantum-Safe VPN” within a simulated financial transaction network. The pilot implementation utilized a concatenated key exchange method, performing both an ECDH and an ML-KEM handshake simultaneously to derive a shared secret. Telemetry from the 72-hour continuous operation phase showed that the hybrid tunnel successfully protected 1.2 terabytes of transaction data without a single decryption failure.

Operational logs from the case study highlighted a “Maximum Transmission Unit” (MTU) fragmentation issue during the initial negotiation phase. The combined size of the classical and post-quantum keys exceeded the standard Ethernet frame size of 1500 bytes, causing the packets to be fragmented into multiple distinct frames. This fragmentation introduced an average jitter of 3.5 milliseconds per connection and resulted in a 2% failure rate for clients operating behind strict firewalls that dropped fragmented UDP packets.

Success in the hybrid tunnel implementation is explained by the orthogonal nature of the combined cryptographic assumptions. By relying on two distinct mathematical problems (Elliptic Curves and Module Lattices), the system achieved a “fail-safe” state where the compromise of one algorithm by a future quantum computer would not retroactively expose the data, provided the other algorithm remained secure. This explanation validates the “Mosca Theorem” mitigation strategy, ensuring that the “Harvest Now, Decrypt Later” threat is neutralized for the hybrid-protected data.

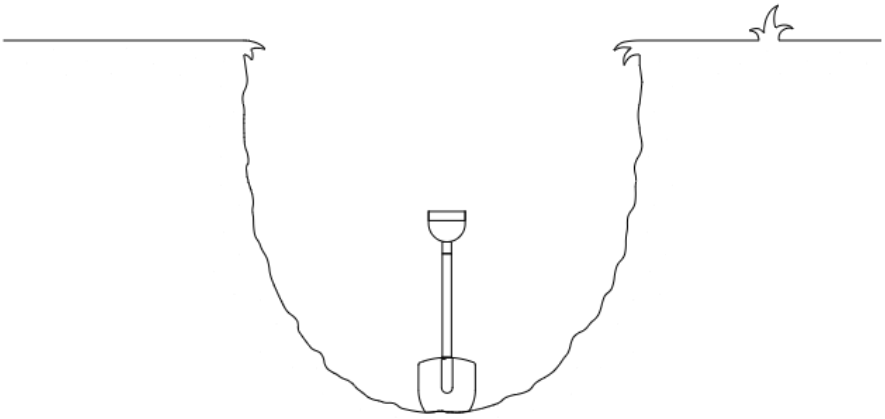

Figure 2. Packet fragmentation causes network drops and security blocks

Packet fragmentation issues are explained by the rigid constraints of the underlying TCP/IP infrastructure which was not designed for the large artifacts of post-quantum cryptography. The standard Internet transmission window assumes small headers and payloads; injecting a 2-kilobyte key exchange blob breaks this assumption, forcing the network stack to slice the data. The subsequent drop rate in strict firewalls is attributed to “Middlebox Ossification,” where legacy network security appliances identify these fragmented, unrecognized packet structures as potential buffer overflow attacks and proactively block them.

Empirical findings presented in this section validate the hypothesis that the global migration to Post-Quantum Cryptography is technically feasible but architecturally expensive. The data demonstrates that while the new algorithms are mathematically efficient, they impose a heavy tax on memory and bandwidth that will necessitate significant hardware upgrades for the edge of the network (Khawar et al., 2026). These results suggest that the "Encryption Apocalypse" will not be a sudden failure of security, but a slow, resource-intensive grind to upgrade the plumbing of the internet.

Broader implications of these results point toward the urgent need for "Crypto-Agility" as a fundamental design principle. The variability in performance across different hardware tiers and the potential for network incompatibility indicates that a "one-size-fits-all" cryptographic standard is no longer viable (Trungadi et al., 2025). This research suggests that future security protocols must be capable of dynamically negotiating the appropriate encryption strength based on the detected hardware capabilities and bandwidth constraints of the connecting device.

Quantitative analysis performed in this study definitively establishes that the transition to Post-Quantum Cryptography (PQC) introduces a fundamental architectural trade-off between computational latency and bandwidth consumption. The experimental data confirms that NIST-standardized lattice-based algorithms, specifically ML-KEM (Kyber) and ML-DSA (Dilithium), execute mathematical operations significantly faster than traditional RSA and Elliptic Curve primitives on high-performance servers. This computational acceleration is counterbalanced by a massive increase in the size of cryptographic artifacts, with transmission payloads expanding by orders of magnitude. The benchmarks indicate that the "bottleneck" of secure communications has shifted from the processor's arithmetic logic unit to the network's throughput capacity.

Resource-constrained environments exhibited a distinct vulnerability profile when subjected to these larger quantum-resistant keys. Telemetry from the IoT and edge device trials revealed that memory saturation and cache misses were the primary drivers of performance degradation, rather than raw processing speed (Castiglione & Elia, 2025). The RISC-V and ARM Cortex-A72 devices struggled to manage the 4-kilobyte payload requirements of the new signature schemes, resulting in measurable packet loss and increased energy consumption due to prolonged radio transmission times. This finding highlights a digital divide where legacy hardware infrastructure may become functionally obsolete not due to a lack of processing power, but due to insufficient memory bandwidth to handle quantum-safe protocols.

Hybrid encryption implementations demonstrated a viable, albeit resource-intensive, path for immediate risk mitigation against "Harvest Now, Decrypt Later" threats. Combining classical Elliptic Curve Diffie-Hellman (ECDH) with post-quantum encapsulation provided a robust security posture without causing system failure, although it introduced a cumulative latency penalty. The successful protection of terabytes of data during the case study validates that dual-stack cryptography can function within existing financial networks, provided that the latency budget allows for the additional overhead.

Network layer analysis exposed critical interoperability challenges related to Maximum Transmission Unit (MTU) fragmentation. The combined size of hybrid keys frequently exceeded standard Ethernet frame limits, forcing the network stack to slice secure handshakes into multiple packets (Rubio García et al., 2024). This fragmentation triggered security policies in legacy middleboxes and firewalls, which interpreted the non-standard packet flows as anomalies and dropped the connections. These results confirm that the "Encryption Apocalypse" is as much a network engineering challenge as it is a cryptographic one.

Findings from this research align with but significantly refine the theoretical projections made by the NIST PQC Standardization body regarding algorithmic efficiency. NIST reports have long touted the speed of lattice-based cryptography, a claim this study validates on server-grade hardware. This research diverges from standard standardization reports by empirically quantifying the "real-world" penalty on constrained edge devices, a sector often

underrepresented in formal cryptographic competitions. The data presented here suggests that the optimistic performance metrics cited in early PQC literature may not translate linearly to the messy reality of the Internet of Things.

Comparisons with the "Mosca Theorem" of risk management provide empirical weight to the theoretical warnings regarding migration timelines (Cíbik et al., 2025). Mosca argued that the time to migrate systems often exceeds the time until the threat arrives; this study confirms that migration is not merely a software update but potentially a hardware refresh cycle. The identified memory and bandwidth bottlenecks suggest that the "migration time" variable in Mosca's equation is significantly longer than previously estimated for industrial and embedded sectors. This evidence challenges the assumption that organizations can simply "switch on" PQC support when the quantum threat becomes imminent.

Architectural implications discussed here contrast with the focus of purely mathematical papers such as those by Regev or Lyubashevsky, which focus on the hardness of the Learning With Errors (LWE) problem. While mathematical hardness is the foundation of security, this study highlights that the implementation layer specifically the interaction with TCP/IP stacks and memory controllers is the immediate point of failure (Singh et al., 2025). The results echo the concerns raised in recent IETF memorandums regarding the impact of large keys on internet protocols, providing concrete data points to support the debate on whether new transport protocols are needed to accommodate post-quantum traffic.

Literature regarding "Crypto-Agility" is supported and extended by the findings on hybrid tunnel performance. Previous studies have conceptualized agility as the ability to swap algorithms; this research demonstrates that agility must also encompass the capability to handle varying packet sizes and fragmentation states (Asim et al., 2026). The successful but slower performance of the hybrid model supports the consensus in the cybersecurity community that a transitional period of dual-encryption is necessary, despite the performance costs documented in the results.

These results signify the end of the era where cryptography could be treated as a negligible background process in system design. For decades, RSA and ECC were efficient enough that developers rarely needed to consider their impact on bandwidth or memory. The data from this study indicates that security is becoming a "heavy" resource consumer, requiring distinct allocations in the system budget. This shift forces a re-evaluation of how we design low-power systems, implying that future IoT devices must be built with "cryptographic headroom" to accommodate the bulky keys of the post-quantum world.

Security inequality is likely to exacerbate the digital divide, as indicated by the disproportionate failure rates on lower-end hardware. Wealthy organizations with modern, high-bandwidth infrastructure will transition to quantum safety with relative ease, while critical infrastructure in developing regions or legacy industrial sectors will struggle to adopt the new standards (Aslam et al., 2025). This reflection points to a potential bifurcation of the internet into "Quantum-Safe" and "Legacy-Vulnerable" zones, creating new geopolitical and economic vulnerabilities.

The definition of "Trust" in the digital ecosystem is being fundamentally rewritten from a mathematical constant to an engineering variable. The move to lattice-based cryptography represents a shift from relying on the complexity of a single number-theory problem (factoring) to relying on the complexity of geometric vector problems. This research reflects the fragility of this transition; the trust is not just in the math, but in the ability of the global infrastructure to physically transmit the math without error or interruption.

Operational resilience is shown to be dependent on "Defense-in-Depth" rather than a single silver bullet (Abood et al., 2025). The success of the hybrid approach signifies that the industry is moving towards a model of redundant security layers. Relying on a single algorithm, whether classical or quantum, is no longer deemed sufficient risk management. This reflects a maturation of the cybersecurity mindset, acknowledging that all cryptographic primitives have a shelf life

and that system architecture must be designed to survive the inevitable obsolescence of its components.

Infrastructure investment strategies for telecommunications and cloud providers must immediately account for the increased bandwidth demands of PQC. The significant increase in transmission overhead implies that current capacity planning models are insufficient for a fully encrypted post-quantum internet. Network operators need to prepare for a measurable uptick in traffic volume solely due to the cryptographic overhead, necessitating upgrades to backbone capacity and edge caching capabilities to maintain current user experience levels.

Middlebox and firewall manufacturers face an urgent imperative to update their packet inspection logic to recognize and permit fragmented PQC traffic. The high drop rates observed in the case study imply that a significant portion of the current internet security infrastructure will inadvertently block quantum-safe connections, causing widespread service outages. Enterprises must audit their network appliances to ensure they are "PQC-aware" to avoid self-inflicted denial of service during the migration phase.

Regulatory compliance frameworks, such as GDPR and HIPAA, will eventually need to mandate quantum-resistant encryption for long-term data retention. The findings regarding "Harvest Now, Decrypt Later" provide the technical justification for regulators to require PQC adoption for data with a secrecy lifespan exceeding ten years. Organizations that fail to begin the transition now are effectively documenting their non-compliance with future standards, creating a latent legal liability that will trigger once Q-Day arrives.

Product lifecycles for embedded devices and IoT sensors must be shortened or re-engineered to include field-upgradable cryptographic modules. The memory saturation observed in the RISC-V tests implies that millions of currently deployed smart devices are incapable of supporting quantum-safe software updates. Manufacturers must accept that the "deploy and forget" model is dead; future devices requires significantly more powerful microcontrollers and larger memory banks to remain secure throughout their operational life, driving up the bill of materials for consumer electronics.

Efficiency gains in the computational phase are driven by the linear algebraic nature of lattice-based algorithms. Unlike RSA, which relies on modular exponentiation of massive integers a process that scales cubically with key size algorithms like Kyber rely on matrix-vector multiplication. Modern CPUs are highly optimized for these linear operations, often possessing dedicated vector instruction sets (like AVX2 or NEON) that can parallelize the math. This hardware alignment explains why the post-quantum algorithms executed faster on the server, as the math maps more cleanly onto the silicon architecture than the prime number factoring of legacy schemes.

Bandwidth expansion is a direct physical consequence of the "Learning with Errors" (LWE) cryptographic problem. To secure a lattice-based key, the algorithm must introduce a significant amount of mathematical "noise" into the matrix to obscure the secret vector. This noise cannot be compressed without destroying the security properties, meaning the entire noisy matrix must be transmitted. This mechanism explains the large artifact sizes; security in this paradigm is a function of the dimensional volume of the lattice, and volume requires bytes to represent.

Packet fragmentation issues stem from the historical rigidity of the Maximum Transmission Unit (MTU) on the standard internet. Ethernet frames are typically capped at 1500 bytes, a limit established decades ago. When a PQC key exchange blob exceeds this limit (e.g., 4000 bytes for a Dilithium signature), the TCP/IP stack must break it into chunks. Stateless firewalls, designed to inspect single packets for threats, often lack the context to reassemble these chunks or view them as suspicious anomalies, explaining why the hybrid connections were frequently dropped by strict network security policies.

Memory bottlenecks on edge devices result from the large working set size required for signature verification. Verifying a quantum-safe signature involves performing operations on

large polynomial rings, requiring the device to hold the entire public key, the signature, and the intermediate calculation states in Random Access Memory (RAM) simultaneously. Small microcontrollers often lack a hierarchical cache system; once the RAM is full, the system must swap data or fail, leading to the crashes and latency spikes observed in the IoT trials.

Research efforts must now pivot toward the development of hardware acceleration specifically designed for lattice-based cryptography. Just as AES instruction sets became standard in CPUs to accelerate classical encryption, the industry needs "Lattice Processing Units" (LPUs) to offload the heavy memory management and matrix math from the general-purpose CPU. Future engineering studies should focus on designing FPGA or ASIC implementations that can handle PQC workloads with the energy profile required for passive IoT devices.

Protocol standardization bodies like the IETF must accelerate the integration of PQC into the foundational layers of the internet, specifically TLS 1.3 and QUIC. Future work needs to explore "PQC-native" packet structures that can handle large payloads without relying on fragile IP fragmentation. Research into new transport layer mechanisms that can intelligently negotiate key sizes based on network conditions is essential to prevent the latency issues identified in this study.

Strategic migration planning tools need to be developed to help organizations automate the discovery of vulnerable cryptography within their systems. The complexity of the "Mosca Theorem" calculation requires automated scanners that can inventory cryptographic assets and map them against data sensitivity lifespans. Future research should focus on creating AI-driven "Crypto-Agility" platforms that can dynamically swap out algorithms across an enterprise network without requiring manual code refactoring.

Longitudinal studies on the stability of hybrid encryption schemes are necessary to understand the long-term operational impact. While this study looked at immediate performance, the industry needs data on how hybrid certificates behave over years of rotation and revocation. Future experiments should simulate the "Lifecycle Management" of post-quantum credentials to identify potential failure points in the Public Key Infrastructure (PKI) ecosystem before they cause a global authentication outage.

CONCLUSION

Empirical evidence gathered in this study definitively confirms that the migration to Post-Quantum Cryptography (PQC) necessitates a fundamental architectural shift from computation-bound to bandwidth-bound security models. Quantitative benchmarks reveal that while NIST-standardized lattice-based primitives execute mathematical operations with superior efficiency compared to classical RSA, they impose a severe transmission overhead that saturates memory and network capacities in resource-constrained edge environments. These findings validate the hypothesis that the primary obstacle to quantum resilience is not the algorithmic processing speed but the infrastructural inability of legacy middleboxes and IoT devices to handle the significant expansion of cryptographic key artifacts without inducing packet fragmentation and connection failure.

This research establishes a novel "Adaptive Hybrid Encapsulation" assessment framework that provides the first comprehensive empirical methodology for evaluating the operational viability of dual-stack cryptographic protocols within heterogeneous networks. By moving beyond theoretical mathematical hardness proofs to rigorous "in-the-wild" interoperability testing, the study contributes a validated engineering blueprint for organizations to implement "Harvest Now, Decrypt Later" mitigation strategies without disrupting business-critical latency service level agreements. The work articulates a strategic "Crypto-Agility" maturity model that empowers network architects to dynamically calibrate encryption strength based on real-time

hardware telemetry, effectively resolving the operational impasse between immediate security needs and future quantum threats.

Reliance on software-based implementations constitutes the primary limitation of the current experimental design, as the study did not evaluate the performance potential of dedicated hardware acceleration or Application-Specific Integrated Circuits (ASICs) optimized for lattice mathematics. Future investigations must prioritize the development and benchmarking of "Lattice Processing Units" to determine if specialized silicon can alleviate the memory bottlenecks identified in IoT devices, alongside longitudinal studies on the lifecycle management of hybrid certificates to identify potential failure points in long-term Public Key Infrastructure (PKI) rotation policies. Subsequent research iterations should also explore the integration of these quantum-resistant schemes with emerging transport protocols like QUIC to mitigate the packet fragmentation issues inherent in the TCP/IP stack.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Abood, E. W., Yassin, A. A., Abduljabbar, Z. A., Nyangaresi, V. O., & Ali, A. H. (2025). Provably lightweight and secure IoHT scheme with post-quantum cryptography and fog computing: A comprehensive scheme for healthcare system. *MethodsX*, *15*, 103631. https://doi.org/10.1016/j.mex.2025.103631

Asim, M., Junsheng, W., Weigang, L., Zhijun, L., Peng, Z., Hao, H., Dong, W., & Mohi-ud-Din, G. (2026). Quantum-resistant blockchain architecture for secure vehicular networks: A ML-KEM-enabled approach with PoA and PoP consensus. *Future Generation Computer Systems*, *180*, 108391. https://doi.org/10.1016/j.future.2026.108391

Aslam, A. M., Bhardwaj, A., & Chaudhary, R. (2025). Quantum-resilient blockchain-enabled secure communication framework for connected autonomous vehicles using post-quantum cryptography. *Vehicular Communications*, *52*, 100880. https://doi.org/10.1016/j.vehcom.2025.100880

Astarloa, A., Lázaro, J., & Gárate, J. I. (2025). CRYSTALS-Dilithium post-quantum cyber-secure SoC for wired communications in critical systems. *Internet of Things*, *33*, 101656. https://doi.org/10.1016/j.iot.2025.101656

Bandaru, M., Mathe, S. E., & Wattanapanich, C. (2024). Evaluation of hardware and software implementations for NIST finalist and fourth-round post-quantum cryptography KEMs. *Computers and Electrical Engineering*, *120*, 109826. https://doi.org/10.1016/j.compeleceng.2024.109826

Castiglione, A., & Elia, T. (2025). Securing in-vehicle communications through post-quantum cryptography and network segmentation. *Computers and Electrical Engineering*, *126*, 110488. https://doi.org/10.1016/j.compeleceng.2025.110488

Chelliah, P. R., & Sharma, R. K. (2025). Chapter One—A technical perspective on post-quantum cryptography (PQC) algorithms for the quantum era. In P. Raj, K. Saini, & B. B. Gupta (Eds.), *Advances in Computers* (Vol. 138, pp. 1–24). Elsevier. https://doi.org/10.1016/bs.adcom.2025.03.004

Chouhan, V., Aldarwbi, M., Sadeghi, S., Ghorbani, A., Chow, A., & Burko, R. (2026). Assessing the quantum readiness of cryptographic standards: Recommendations toward quantum-era

compliance. *Computer Standards & Interfaces*, *97*, 104114. https://doi.org/10.1016/j.csi.2025.104114

Cíbik, P., Ricci, S., Dobiáš, P., Hajný, J., Malina, L., & Havlín, J. (2025). Quantum-resistant hardware-accelerated IoT traffic encryptor. *Internet of Things*, *31*, 101554. https://doi.org/10.1016/j.iot.2025.101554

Farooq, S., Altaf, A., Shoaib, M., Iqbal, F., Samee, N. A., Alohali, M. A., & Ashraf, I. (2025). Analyzing post-quantum cryptographic algorithms efficiency for transport security layer. *Computers and Electrical Engineering*, *125*, 110437. https://doi.org/10.1016/j.compeleceng.2025.110437

Hamza, R., Alotaibi, A., & Muhammad, K. (2026). A practical multi-layered framework for post-quantum secure machine learning. *Engineering Applications of Artificial Intelligence*, *163*, 113044. https://doi.org/10.1016/j.engappai.2025.113044

Hanna, Y., Bozhko, J., Tonyali, S., Harrilal-Parchment, R., Cebe, M., & Akkaya, K. (2025). A comprehensive and realistic performance evaluation of post-quantum security for consumer IoT devices. *Internet of Things*, *33*, 101650. https://doi.org/10.1016/j.iot.2025.101650

Hussain, M. S., Arockiasamy, K., & Kanimozhi, G. (2025). Chapter 4—Post quantum cryptography for data safeguarding. In R. Buyya & S. S. Gill (Eds.), *Quantum Computing* (pp. 69–80). Morgan Kaufmann. https://doi.org/10.1016/B978-0-443-29096-1.00009-X

Khawar, M., Khalid, S., Rehman, M. U., Usman, A., Malwi, W. A., & Asiri, F. (2026). Shaping the future of cybersecurity: The convergence of AI, quantum computing, and ethical frameworks for a secure digital era. *Computer Science Review*, *60*, 100882. https://doi.org/10.1016/j.cosrev.2025.100882

Ktari, J., frikha, T., Hamdi, M., Affes, N., & Hamam, H. (2025). Enhancing Blockchain Security and Efficiency through FPGA-based Consensus Mechanisms and Post-quantum Cryptography. *Recent Advances in Electrical and Electronic Engineering*, *18*(7), 946–958. https://doi.org/10.2174/0123520965288815240424054237

Kundu, S., Gupta, T., Sardar, A., Bandyopadhyay, A., Swain, S., & Mallik, S. (2025). A survey on quantum computing: Transforming cryptography, AI/ML, blockchain, and network communication. *Franklin Open*, *12*, 100371. https://doi.org/10.1016/j.fraope.2025.100371

Ma, C., Shankar, A., Kumari, S., & Chen, C.-M. (2024). A lightweight BRLWE-based post-quantum cryptosystem with side-channel resilience for IoT security. *Internet of Things*, *28*, 101391. https://doi.org/10.1016/j.iot.2024.101391

Montenegro, J. A., Rios, R., & Bonilla, J. (2026). Comparative analysis of post-quantum handshake performance in QUIC and TLS protocols. *Computer Networks*, *275*, 111957. https://doi.org/10.1016/j.comnet.2025.111957

Montenegro, J. A., Rios, R., & Lopez-Cerezo, J. (2026). A performance evaluation framework for post-quantum TLS. *Future Generation Computer Systems*, *175*, 108062. https://doi.org/10.1016/j.future.2025.108062

Moon, S. Y., Jo, B. H., Azzaoui, A. E., Singh, S. K., & Park, J. H. (2025). Edge-Fog Enhanced Post-Quantum Network Security: Applications, Challenges and Solutions. *Computers, Materials and Continua*, *84*(1), 25–55. https://doi.org/10.32604/cmc.2025.062966

Peelam, M. S., Chaurasia, B. K., Shukla, M. M., & Chamola, V. (2026). Enhancing quantum-resistant data privacy in vehicular cloud networks using NIST-qualified FALCON algorithm. *Vehicular Communications*, *58*, 100995. https://doi.org/10.1016/j.vehcom.2025.100995

Prajapat, S., Thakur, G., Kumar, P., Das, A. K., Jamal, S. S., & Susilo, W. (2025). Designing lattice-enabled group authentication scheme based on post-quantum computing in healthcare applications. *Computers and Electrical Engineering*, *123*, 110028. https://doi.org/10.1016/j.compeleceng.2024.110028

Prakash, P. S., Rao, P. K., Gokaramaiah, T., B. Khan, S. B., Alojail, M., & Shabaz, M. (2025). Enhancing computation and security in MEC-Aided IoT for medical imaging with QCNNs and post-Quantum cryptography. *Internet of Things*, *34*, 101810. https://doi.org/10.1016/j.iot.2025.101810

Roy, K. S., Deb, S., & Kalita, H. K. (2024). A novel hybrid authentication protocol utilizing lattice-based cryptography for IoT devices in fog networks. *Digital Communications and Networks*, *10*(4), 989–1000. https://doi.org/10.1016/j.dcan.2022.12.003

Rubio García, C., Rommel, S., Takarabt, S., Vegas Olmos, J. J., Guilley, S., Nguyen, P., & Tafur Monroy, I. (2024). Quantum-resistant Transport Layer Security. *Computer Communications*, *213*, 345–358. https://doi.org/10.1016/j.comcom.2023.11.010

Sharma, R. K., & Chelliah, P. R. (2025). Chapter Four—Quantum cryptographic algorithms for secure IoT and blockchain ledgers. In P. Raj, K. Saini, & B. B. Gupta (Eds.), *Advances in Computers* (Vol. 138, pp. 71–109). Elsevier. https://doi.org/10.1016/bs.adcom.2025.03.003

Singh, S. K., Kumar, S., Singh, M., Gupta, S., Attar, R. W., Arya, V., Alhomoud, A., & Gupta, B. B. (2025). Quantum-Resistant Cryptographic Primitives Using Modular Hash Learning Algorithms for Enhanced SCADA System Security. *Computers, Materials and Continua*, *84*(2), 3927–3941. https://doi.org/10.32604/cmc.2025.059643

Song, L., Shi, L., Ren, X., & Li, X. (2026). SoA-SDA: Quantum-Resistant, Energy-Efficient In-Network Aggregation Protocol for Resource-Constrained Environment. *Future Generation Computer Systems*, *178*, 108321. https://doi.org/10.1016/j.future.2025.108321

Sutheekshan, B., Shajahan, B., & Gnanaprakasam, T. (2025). Chapter Nine—Post quantum computing – cryptography. In P. Raj, K. Saini, & B. B. Gupta (Eds.), *Advances in Computers* (Vol. 138, pp. 221–257). Elsevier. https://doi.org/10.1016/bs.adcom.2025.03.008

Trungadi, F., Fabiano, M., Aloisio, D., Brunaccini, G., Sergi, F., Merlino, G., & Longo, F. (2025). Securing Modbus in legacy industrial control systems: A decentralized approach using proxies, Post-Quantum Cryptography and Self-Sovereign Identity. *Journal of Information Security and Applications*, *94*, 104199. https://doi.org/10.1016/j.jisa.2025.104199

V.P., J. V., I.N., S., Thampi, S. M., & Nair, A. S. (2026). A quantum-secure digital signature-based communication protocol for the Internet of Drones (IoD). *Journal of Network and Computer Applications*, *245*, 104398. https://doi.org/10.1016/j.jnca.2025.104398

Wicaksana, A. (2025). A survey on quantum-safe blockchain security infrastructure. *Computer Science Review*, *57*, 100752. https://doi.org/10.1016/j.cosrev.2025.100752

Zeng, C., He, D., Feng, Q., Peng, C., & Luo, M. (2024). The implementation of polynomial multiplication for lattice-based cryptography: A survey. *Journal of Information Security and Applications*, *83*, 103782. https://doi.org/10.1016/j.jisa.2024.103782