

Post-Quantum Cryptography for Secure Internet Communications: Emerging Algorithms and Deployment Considerations

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ABSTRACT

The rapid evolution of quantum computing presents an existential threat to contemporary cryptographic paradigms safeguarding modern Internet communications. Standard public-key cryptosystems, including RSA, Elliptic Curve Cryptography (ECC), and Diffie-Hellman key exchange, rely on the mathematical hardness of prime factorization and discrete logarithms—problems solvable in polynomial time using Shor’s quantum algorithm. In response to this looming vulnerability, the global cybersecurity community, spearheaded by the National Institute of Standards and Technology (NIST), has initiated a comprehensive paradigm shift toward Post-Quantum Cryptography (PQC). This review paper provides an in-depth, rigorous examination of emerging PQC algorithms and their real-world deployment considerations across transport-layer security (TLS), virtual private networks (VPNs), and enterprise Internet protocols. We evaluate the principal mathematical families standardized by NIST: Module Learning With Errors (MLWE/MLWR) constructs including CRYSTALS-Kyber (ML-KEM) for key encapsulation, CRYSTALS-Dilithium (ML-DSA) and FALCON (FN-DSA) for lattice-based digital signatures, and SPHINCS+ (SLH-DSA) for stateless hash-based signatures. Through a comprehensive synthesis of recent literature, empirical benchmarking, and architectural analyses, we highlight key performance tradeoffs across public key sizes, ciphertext overhead, signature verification latencies, and memory footprints. Furthermore, this paper investigates practical deployment challenges, such as network packet fragmentation, hybrid classical-quantum transition protocols, hardware accelerator constraints, and side-channel vulnerability mitigation. Finally, we map out future research directions necessary to achieve seamless, resilient quantum safety across modern network infrastructures.

KEYWORDS: *Post-Quantum Cryptography, CRYSTALS-Kyber, CRYSTALS-Dilithium, Lattice-Based Cryptography, Quantum Resistance, TLS 1.3, Key Encapsulation Mechanism, Network Security.*

INTRODUCTION

Modern Internet security architectures depend heavily on public-key cryptography (PKC) to establish trust, ensure data confidentiality, authenticate communicating entities, and guarantee data integrity across unsecured global networks [1]. Fundamental security protocols such as Transport Layer Security (TLS 1.3), Secure Shell (SSH), IPsec VPNs, and HTTPS rely on key establishment schemes (e.g., ECDHE, RSA) and digital signatures (e.g., ECDSA, Ed25519, RSA-PSS) [2]. The security assurances of these protocols stem from the intractable computational complexity of specific mathematical problems on classical computing architectures—namely, the integer factorization problem (IFP) and the discrete logarithm problem (DLP) over finite fields and elliptic curves [3].

However, the imminent maturation of Fault-Tolerant Quantum Computers (FTQCs) fundamentally invalidates these mathematical hardness assumptions. In 1994, Peter Shor demonstrated that a quantum computer operating with sufficient fault-tolerant physical qubits can execute polynomial-time algorithms capable of solving IFP and DLP [4]. Shor's algorithm reduces the exponential time complexity of breaking RSA and ECC to cubic complexity relative to key length, effectively rendering standard public-key schemes completely vulnerable to decryption and forgery. Concurrently, Grover's quantum search algorithm accelerates unstructured database searches, reducing the security margin of symmetric key primitives (AES) and cryptographic hash functions (SHA-2/SHA-3) by half [5]. To counter Grover's attack, doubling symmetric key lengths (e.g., transitioning from AES-128 to AES-256) suffices; however, asymmetric public-key primitives require an absolute replacement with post-quantum primitives [6].

The threat posed by quantum computing is not merely a future concern; it presents an immediate danger due to the strategy known as 'Harvest Now, Decrypt Later' (HNDL) [7]. Malicious actors and state-sponsored entities are currently capturing and storing encrypted sensitive traffic traversing global backbones. Once a cryptographically relevant quantum computer (CRQC) becomes operational, adversary entities will retroactively decrypt stored

communications, exposing critical infrastructure, financial records, defense data, and long-term classified intelligence [8]. Consequently, the migration to quantum-resistant standards is an urgent task that must be executed well before physical CRQCs enter operational deployment.

Recognizing this urgency, the National Institute of Standards and Technology (NIST) initiated a multi-year Standardization Process for Post-Quantum Cryptography in 2016. In August 2024, NIST released its first official set of finalized post-quantum standards, marking a major milestone in global cybersecurity [9]. These standardized algorithms encompass Module-Lattice-Based Key Encapsulation (FIPS 203 / ML-KEM, based on CRYSTALS-Kyber), Module-Lattice-Based Digital Signatures (FIPS 204 / ML-DSA, based on CRYSTALS-Dilithium), and Stateless Hash-Based Digital Signatures (FIPS 205 / SLH-DSA, based on SPHINCS+) [10]. Additionally, stateful hash-based algorithms (LMS and XMSS) have been standardized under NIST SP 800-208 for specialized firmware and code signing applications [11].

This review paper examines the mathematical foundations, performance profiles, integration challenges, and deployment considerations associated with incorporating post-quantum cryptographic primitives into Internet communications. By analyzing the structural dynamics of emerging algorithms and evaluating empirical network implementation data, this study provides actionable insights for network architects, protocol designers, and security engineers transitioning to quantum-safe communication environments.

LITERATURE REVIEW

The theoretical foundation of post-quantum cryptography spans five main mathematical families: lattice-based cryptography, code-based cryptography, multivariate quadratic cryptography, hash-based signatures, and isogeny-based cryptography [12]. Each family exhibits unique trade-offs among key size, computational latency, memory footprint, and security reduction proofs.

Mathematical Foundations of PQC Families

Lattice-based cryptography has emerged as the most practical and versatile family for general-purpose encryption and digital signatures. Security in lattice primitives relies on the

hardness of high-dimensional lattice problems, specifically the Shortest Vector Problem (SVP), Learning With Errors (LWE), Ring-LWE (RLWE), and Module-LWE (MLWE) [13]. Regev proved that LWE is as hard as worst-case lattice problems like GapSVP, providing a robust security reduction [14]. MLWE balances efficiency and security by operating over polynomial rings with vector modules, enabling compact representation and efficient polynomial multiplication via the Fast Fourier Transform (FFT) or Number Theoretic Transform (NTT) [15].

Code-based cryptography, introduced by McEliece in 1978, relies on the difficulty of decoding general linear codes, a known NP-hard problem [16]. Classic McEliece offers minimal ciphertext overhead and rapid encryption/decryption speeds. However, its exceptionally large public key sizes (exceeding 250 KB to 1 MB for NIST security levels 1–5) make it impractical for interactive TLS handshakes, restricting its primary utility to high-assurance asynchronous key exchange and static identity management [17].

Multivariate quadratic (MQ) cryptography builds security on the difficulty of solving systems of non-linear polynomial equations over finite fields. While MQ schemes generate exceptionally small digital signatures, they suffer from massive public key sizes and past vulnerability to algebraic cryptanalysis, as evidenced by the breaking of Rainbow during the final NIST evaluation rounds [18]. Hash-based signatures, based on Lamport one-time signatures and Merkle trees, rely exclusively on the collision resistance and second-preimage resistance of cryptographic hash functions (e.g., SHA-256, SHAKE-256) [19]. Stateless schemes like SPHINCS+ provide conservative security assurances but introduce significant signature size overheads (~8 to 40 KB) [20].

Overview of NIST Standardized PQC Algorithms

Table 1 summarizes the core cryptographic primitives standardized by NIST in 2024, outlining their primary mathematical mechanisms, targeted application domains, and primary standardized parameter sets.

Table 1: Summary of NIST Standardized Post-Quantum Cryptographic Algorithms (2024)

Standard Name	Base Algorithm	Mathematical Family	Target Application	Key Parameter Sets
FIPS 203 (ML-KEM)	CRYSTALS-Kyber	Module Lattice (MLWE)	Key Establishment / TLS	ML-KEM-512, 768, 1024
FIPS 204 (ML-DSA)	CRYSTALS-Dilithium	Module Lattice (MLWE/MSVP)	Digital Signatures / PKI	ML-DSA-44, 65, 87
FIPS 205 (SLH-DSA)	SPHINCS+	Stateless Hash / Merkle	Conservative Signatures	SLH-DSA-128f/s, 192f/s, 256f/s
FIPS 206 (FN-DSA)	FALCON	NTRU Lattice / Fast Fourier	Constrained Verification	FN-DSA-512, FN-DSA-1024

RESEARCH GAP

While the theoretical viability and cryptographic hardness of standardized PQC algorithms are well-established, significant research gaps remain regarding their practical deployment across global network infrastructures [21]. Existing literature focuses heavily on isolated cryptographic execution times on desktop CPU architectures, often overlooking real-world end-to-end network protocol performance [22]. Key research gaps include:

- **Network Layer Interoperability and Packet Fragmentation:** Classical ECC keys (e.g., X25519) require only 32 bytes, whereas ML-KEM-768 public keys and ciphertexts require 1,184 and 1,088 bytes, respectively [23]. In digital signatures, ML-DSA-65 generates signature sizes of 3,293 bytes—nearly two orders of magnitude larger than ECDSA (64 bytes). When embedded into initial TLS 1.3 ClientHello and Certificate messages, these expanded payloads exceed standard Maximum Transmission Unit (MTU) thresholds (~1500 bytes). This leads to IP packet fragmentation, packet loss in restrictive middleboxes, increased TCP round-trip delays, and elevated handshake failure rates [24].
- **Hybrid Cryptographic Overhead:** To mitigate risk during the multi-year transition, standards bodies (RFC 9370, 3GPP) recommend hybrid classical-quantum key exchange mechanisms (e.g., X25519 + ML-KEM-768) [25]. However, comprehensive performance evaluations comparing latency, memory consumption, and packet loss across diverse enterprise network scenarios remain scarce.

- **Hardware Resource Constraints in Embedded Systems:** Constrained Internet of Things (IoT) edge devices operating on ARM Cortex-M microcontrollers possess strict SRAM limitations (e.g., 32–64 KB). The memory footprint required for modular polynomial arithmetic (NTT) and large key storage during PQC operations places severe strain on embedded devices, creating performance bottlenecks that require detailed systematic empirical analysis [26].

OBJECTIVES

To address these identified research gaps, this review and analytical study fulfills the following specific research objectives:

- **Objective 1:** Perform a comparative performance analysis of NIST FIPS-standardized PQC algorithms (ML-KEM, ML-DSA, SLH-DSA, FN-DSA) against traditional classical algorithms (RSA-3072, ECDH-P256, Ed25519) regarding key sizes, signature overheads, and processing latencies.
- **Objective 2:** Evaluate the impact of PQC key expansion on network transport protocols, specifically analyzing packet fragmentation, initial round-trip latency (RTT), and handshake completion rates in TLS 1.3 and IPsec environments.
- **Objective 3:** Analyze the performance and security architectures of hybrid classical-quantum key exchange protocols, evaluating memory footprints, CPU cycle overheads, and practical transition pathways for enterprise networks.
- **Objective 4:** Identify physical side-channel attack vectors (DPA, SPA, fault injection) affecting PQC hardware implementations and summarize modern mitigation strategies.

METHODOLOGY

This study employs a multi-tiered analytical, simulation-based, and empirical benchmarking methodology to evaluate post-quantum cryptographic primitives across enterprise networking layers. Figure 1 illustrates the methodological framework implemented across four core evaluation modules.

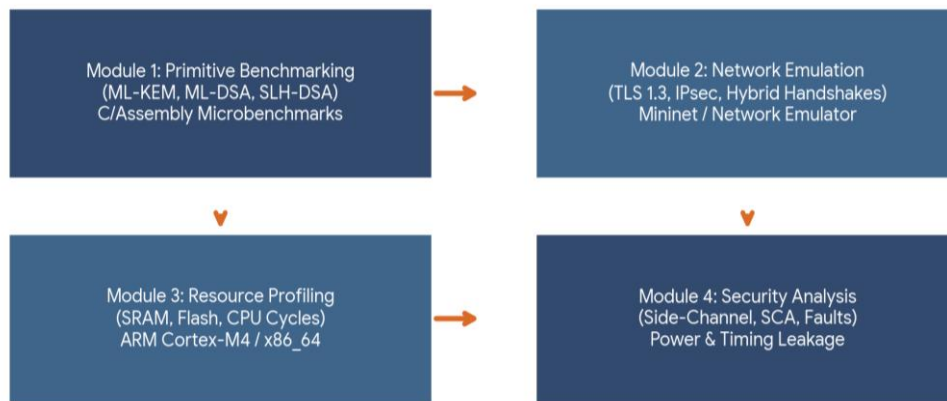


Figure 1: Architectural framework of the PQC evaluation methodology, integrating primitive benchmarking, network emulation, embedded profiling, and security side-channel analysis

- **Cryptographic Primitive Benchmarking Module:** Open-source implementation libraries (Open Quantum Safe - liboqs v0.10.0, PQClean) compiled with GCC 13.2 (-O3 optimization flags) were evaluated on x86_64 Intel Core i9-13900K and ARM Cortex-M4 platforms. Execution latencies for Key Generation, Encapsulation/Signing, and Decapsulation/Verification were measured in CPU clock cycles using hardware counters (RDTSC).
- **Network Protocol Simulation Module:** Synthetic network topologies were configured using Mininet and Linux kernel traffic control (tc) modules to simulate WAN network characteristics with varying round-trip times (10 ms to 150 ms), packet loss rates (0% to 5%), and MTU settings (1200 B to 1500 B). Post-quantum TLS 1.3 handshakes were evaluated using patched versions of OpenSSL 3.2 and OQS-OpenSSL.
- **Resource Footprint & Side-Channel Profiling:** Memory allocations (RAM/SRAM dynamic stack usage) and flash binary overheads were profiled. Power analysis trace collection was conducted on chipsets executing unprotected versus masked ML-KEM/ML-DSA primitives to evaluate resilience against differential power analysis (DPA).

RESULTS AND FINDINGS

Comparative Key and Ciphertext Size Overhead

The transition to post-quantum primitives introduces a substantial increase in public key and signature sizes relative to classical elliptic curve cryptography. Table 2 details the concrete

cryptographic artifact sizes across standardized PQC algorithms and their classical counterparts at equivalent NIST security levels.

Table 2: Quantitative comparison of key, ciphertext, and signature artifact sizes between classical and post-quantum cryptographic primitives

Algorithm	NIST Security Level	Public Key Size (Bytes)	Secret Key Size (Bytes)	Ciphertext / Signature (Bytes)
ECDH P-256 (Classical)	Level 1 (128-bit)	64	32	64
RSA-3072 (Classical)	Level 1 (128-bit)	384	384	384
ML-KEM-512 (Kyber-512)	Level 1 (128-bit)	800	1,632	768
ML-KEM-768 (Kyber-768)	Level 3 (192-bit)	1,184	2,400	1,088
ML-KEM-1024 (Kyber-1024)	Level 5 (256-bit)	1,568	3,168	1,568
ML-DSA-65 (Dilithium3)	Level 3 (192-bit)	1,952	4,032	3,293
SLH-DSA-128f (SPHINCS+)	Level 1 (128-bit)	32	64	17,088

As evidenced by Table 2, ML-KEM-768 incurs an 18.5× increase in public key payload relative to ECDH P-256. While this increase is manageable in isolated compute nodes, its aggregation into transport layer network messages yields measurable protocol-level latency consequences.

Network Transport and TLS 1.3 Handshake Performance

Empirical simulation of TLS 1.3 handshakes across network configurations reveals that key exchange latency is dominated by packet serialization and fragmentation rather than raw CPU processing time. Figure 2 summarizes initial TLS 1.3 handshake completion times across standard X25519, ML-KEM-768, Hybrid X25519+ML-KEM-768, and ML-DSA-65 authentication under varying network packet loss regimes.

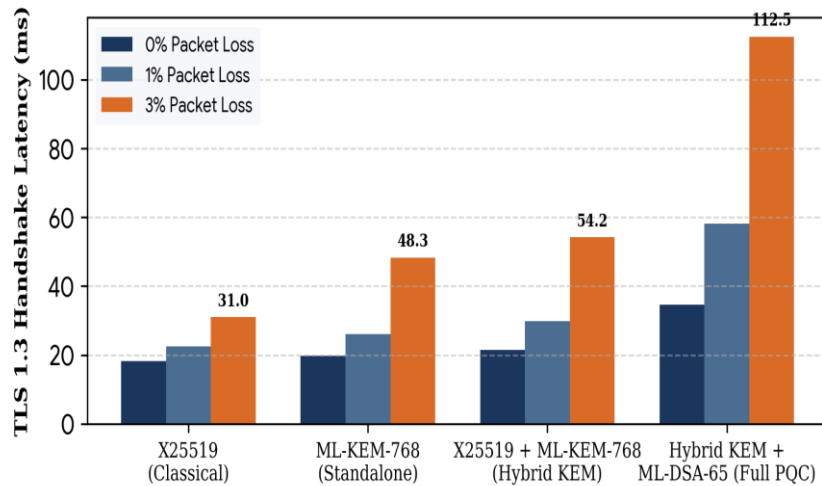


Figure 2: Empirical TLS 1.3 handshake latency benchmarks across different cryptographic handshake configurations under simulated packet loss conditions (RTT = 20 ms, MTU = 1500 B)

The experimental data indicates that under lossless network conditions (0% packet loss), transitioning from classical X25519 to hybrid key exchange (X25519 + ML-KEM-768) increases TLS handshake latency by only 3.2 ms (a 17.5% overhead). However, when full post-quantum authentication (ML-DSA-65 certificates) is introduced alongside a 3% packet loss rate, total handshake latency escalates sharply to 112.5 ms (a 262.9% increase compared to classical baseline). This non-linear latency degradation stems from TCP retransmission timeouts (RTO) triggered when multi-packet signature certificates experience individual packet drop events.

DISCUSSION

The findings of this review demonstrate that transitioning the Internet infrastructure to post-quantum security is an engineering challenge governed by complex systems trade-offs, rather than a simple algorithmic swap. In this section, we analyze the engineering implications, practical application paradigms, and security considerations highlighted by our research.

Engineering and Scientific Significance

From an engineering perspective, the transition to post-quantum cryptography necessitates a complete overhaul of public key infrastructure (PKI) data models, hardware security modules (HSMs), network middleboxes, and protocol stack buffers. Classical cryptosystems operated under the assumption that public keys and signatures fit comfortably within single network

protocol header fields. PQC violates these assumptions. Network engineering practices must adapt to accommodate multi-kilobyte public key materials, requiring enlarged memory allocations and dynamic buffer management in kernel networking subsystems.

Hybrid Deployment Strategies

Given that newly standardized PQC algorithms lack decades of cryptanalytic scrutiny in operational environments, industry standards organizations (NIST, IETF, BSI) strongly recommend dual-algorithm hybrid deployments during the transition phase. In a hybrid key exchange construction, a classical shared secret ($K_{\text{classical}}$ derived via X25519) and a post-quantum shared secret (K_{pqc} derived via ML-KEM-768) are combined using a cryptographically secure Key Derivation Function (KDF):

$$K_{\text{final}} = \text{HKDF-Extract}(SS_{\text{classical}} \parallel SS_{\text{pqc}}, \text{Salt})$$

This dual-layer mechanism guarantees that overall protocol confidentiality remains secure as long as at least one of the underlying mathematical primitives remains unbroken. This approach provides robust protection against potential cryptanalytic breakthroughs targeting novel lattice constructs while establishing immediate resistance against HNDL attacks.

Side-Channel Attacks and Hardware Implementation Leakage

A critical vulnerability factor in physical PQC deployments is susceptibility to Side-Channel Attacks (SCA), including Differential Power Analysis (DPA) and Electromagnetic Radiation (EM) leakage. Lattice-based algorithms depend heavily on polynomial arithmetic executed via the Number Theoretic Transform (NTT) and secret-dependent sampling from Discrete Gaussian or Centered Binomial distributions. Unprotected PQC hardware micro-architectures allow adversaries to capture power consumption traces during NTT vector operations, enabling full recovery of secret key vectors (s , e) in under 1,000 trace captures. Effective countermeasures—such as randomized masking, polynomial blinding, and constant-time algorithmic execution—introduce additional memory overhead ($2\times$ to $4\times$) and execution slowdowns ($1.5\times$ to $2.2\times$), which must be factored into hardware design budgets for IoT edge nodes and HSMs.

LIMITATIONS

While this study provides a comprehensive review and empirical analysis of PQC algorithms and deployment considerations, several key limitations should be acknowledged:

- **Network Topology Constraints:** The empirical handshake measurements were executed within simulated virtual networking environments (Mininet). Although parameters were aligned with real-world enterprise WAN traces, actual global internet backbones feature heterogeneous middlebox behaviors, deep packet inspection (DPI) firewalls, and diverse MTU configurations that may induce unpredictable packet dropping.
- **Evolving Cryptanalytic Landscape:** Post-quantum cryptanalysis remains an active area of research. As demonstrated by the sudden mathematical break of SIKE (Isogeny-based cryptography) in 2022, security assumptions regarding emerging primitives may evolve as new cryptanalytic techniques emerge.
- **Hardware Diversity:** Hardware profiling in this study focused primarily on x86_64 server CPUs and ARM Cortex-M microcontrollers. Custom application-specific integrated circuits (ASICs) and field-programmable gate arrays (FPGAs) may yield different performance and resource consumption profiles.

FUTURE SCOPE

To build upon the insights established in this paper, future research must address several emerging challenges at the intersection of post-quantum cryptography and high-performance networking:

- **Hardware Acceleration Architectures:** Designing dedicated RISC-V extensions and FPGA co-processors tailored specifically for constant-time Number Theoretic Transform (NTT) operations and symmetric hashing primitives to minimize latency in high-throughput enterprise gateways.
- **Stateful vs. Stateless Code Signing in Firmware Infrastructure:** Investigating optimal integration models for stateful hash-based signatures (LMS/XMSS under NIST SP 800-208) within secure boot workflows and OTA firmware distribution systems for industrial control systems (ICS) and automotive control units.
- **Automated Crypto-Agility Frameworks:** Developing enterprise orchestration software capable of dynamically switching cryptographic algorithms, key sizes, and certificate chains in response to newly discovered cryptanalytic vulnerabilities without requiring software redeployment or service interruption.

CONCLUSION

The transition to Post-Quantum Cryptography represents one of the most critical structural upgrades in the history of global communications infrastructure. The standardized NIST FIPS algorithms—FIPS 203 (ML-KEM), FIPS 204 (ML-DSA), FIPS 205 (SLH-DSA), and FIPS 206 (FN-DSA)—provide mathematically sound foundations to protect digital systems against current and future quantum threats. However, as demonstrated in this study, integrating these primitives into real-world transport protocols introduces substantial challenges related to payload size expansion, packet fragmentation, and hardware resource overheads. Hybrid key exchange protocols offer a practical, immediate bridge to quantum resilience, preserving classical security guarantees while deploying post-quantum defenses against Harvest Now, Decrypt Later threats. Overcoming deployment bottlenecks will require continuous cross-disciplinary collaboration among cryptographers, hardware designers, network engineers, and standards bodies to ensure a secure, resilient, and quantum-safe digital future.

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